Impact of Hybrid Distributed Generation Allocation on Short Circuit Currents in Distribution Systems

A thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

The rapid development in renewable generation technologies and flexible distribution networks requires current infrastructure to be modified and developed to adapt high penetration levels of distributed generation. Existing distribution networks were not initially designed and anticipated to accommodate generators on large scale. Short circuit studies ensure the effectiveness of protection equipment settings and coordination is maintained in case of short circuit, despite any additional distributed generation is connected to the distribution network. This research aims to study and compare the different network fault situations for wind energy systems with induction generators, photovoltaic energy systems, and diesel generators connected to distribution networks. The simulation study will be conducted on the existing IEEE case study systems including 13 bus and 30 bus distribution test systems, using ETAP software. Short circuit analysis will be performed twice to include the ANSI/IEEE and the IEC methods for short circuit currents calculation. Simulated results showed that the wind energy systems have significant impact on the short circuit currents, whereas the photovoltaic energy systems are found to have inconsequential effect. The most moderate solution is found to be a distributed generation mix.

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Declaration of Authorship

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

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List of Abbreviations

3-PH/3-ph	Three-Phase
AC	Alternating Current
ANSI	American National Standard Institute
DC	Direct Current
DFIG	Doubly Fed Asynchronous Generators
DG	Distributed Generation
DR	Distributed Resources
EPS	Electrical Power Systems
ETAP	Electrical Power System Analysis
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LG	Line to Ground
LL	Line-to-Line
LLG	Line-to-Line to Ground
LV	Low Voltage
MCFC	Molten Carbonate Fuel Cell
MV	Medium Voltage
OC	Over Current
PAFC	Phosphoric Acid Fuel Cell
PCC	Point of Common Coupling
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
R/X	Resistance to Reactance ratio
SCC	Short Circuit Current
SCIG	Squirrel-Cage Induction Generator
SOFC	Solid Oxide Fuel Cell
VDE	Verband Deutscher Electrotechniker
WTGs	Wind Turbine Generators

Chapter One

1 Introduction

1.1 Background

With BREXIT and new global political agenda's coming in place, countries will begin to change their energy policies to ensure energy security. Energy security implies diversified energy supply and independency. This means that countries should rely on their own resources and harvest their energy potentials. At the same time, the environmental target of reducing carbon dioxide emissions still exists. This would be considered as an extra burden for energy policy makers and decision makers to determine new solutions and set new legislations to inhabit the new policies. This implies countries to generate more energy to meet the increase in demand from their own resources either renewable or non-renewable. Though, the uptake for renewable energy should be more than non-renewable to meet the reduction in carbon dioxide emissions target. This will increase the uptake of renewable energy systems and encourage the deployment of variable renewable energy mix such as wind, photovoltaics, and hydro on a large scale. In the EU, it is expected that the renewable energy generation mix will be almost double the current generation capacity by 2020 and will reach around 30% in 2030 [1], [2]. This raises a significant question, apart from the economical and energy markets capabilities; are the technologies technically (such as mechanical, electrical, and civil) mature and available to accommodate this boost [2]. Electrical power systems have three major consequential pillars generation, transmission, and distribution. As renewable sources are not always available to be centralised to generate bulk capacities of electricity, therefore, the interest in decentralised generation is becoming more enviable. The traditional concept of generating electricity from one centralised power station to be transmitted miles away to distribution network and then to customer is no longer the single arrangement of electricity production and transfer.

Currently, the electrical power is generated at the consumer side or distribution level. This type of generation is known as Distributed Generation (DG).

1.2 Distributed generation definition

Distributed generation is considered as a new approach did not exceed the two decades. Initially, there are several terms used to describe this initiative in literature and in different countries. These terms are Embedded Generation commonly used in Anglo-American countries; dispersed generation in North American countries; and decentralised generation in Europe and parts of Asia [5].

The most common general definition used in the literature for Distributed Generation is proposed by [5]: “DG is an electric power source connected directly to the distribution network or the consumer side of the meter” [5]. The type of power source may include both, renewable and non-renewable energy sources such as Wind, solar, and diesel generators. DG rating has no maximum permissible limit; it may vary from few watts up to hundreds of megawatts, depending on distribution network capacity, which is correlated to the voltage level within the distribution system [2], [5]. Different DG ratings range as follows [5] :

Micro distributed generation	~ 1Watt - 5 kW
Small distributed generation	~ 5 KW - 5 MW
Medium distributed generation	~ 5 MW - 50 MW
Large distributed generation	~ 50 MW - 300 MW

1.2.1 Motivations for DG integration

According to International Energy Agency (IEA), there are five main factors significantly increased distributed generation importance, which are as follows [4]:

1. Development in DG technologies
2. Constraints on construction of new transmission lines
3. Increased load demand for highly reliable electricity
4. Electricity market liberalization.
5. Climate change mitigation.

1.2.2 Advantages of distributed generation

1. Provides electrical supply to remote areas, where it may be more economical than establishing a new transmission and distribution systems [91]
2. Regulates the voltage profile of distribution networks that suffered poor voltage levels before the penetration of DG at peak loads scenarios [91]
3. Improves the distribution network losses, which in return benefits the Distribution Network Operators costs [91]
4. Reduces the loading on the main feeder [91]
5. Acts as a backup power supply in case of main supply failure, especially for the sensitive loads such as hospitals
6. DG based on renewable energy sources mitigates climate change [74].
7. In some developing countries, DG may improve population economy, such as in Pakistan, where consumers are encouraged to install DG to meet their load demands and to reduce their electricity bills by selling that electricity to utility [74]

1.2.3 Disadvantages of distributed generation

1. DG integration causes the change of power flow from being uni-directional to bi-directional. This feature interferes with the normal operation of distribution networks.
2. DG alters the short circuit level when it is connected to a network, which affects the network protection scheme.
3. Improper allocation and penetration level of DG may lead to increased power losses; undesirable voltage profile; and stability issues [92], [93]
4. In renewable energy-based DG such as PV and wind, the output power is intermittent due to the variable nature of the renewable energy source sun and wind [92].
5. Some DG sources may cause voltage flicker such as in Wind [92].
6. DG may inject harmonics into the distribution system [89].
7. In DG integration, islanding may occur. This is a condition in which a portion of the utility system that contains both load and DG remains energized while isolated from the remainder of the utility system. Meanwhile, a DG may be feeding a short circuit [92].

DG is classified by the type of technology that interfaces with the distribution system such as power electronics inverters, and rotating machines including induction generators, squirrel cage generator, and synchronous generators. The characteristics of different types of interface are distinguished by their impact on the distribution system short circuit current, voltage control, and potential contribution to harmonic distortion [3].

The presence of DG in distribution systems alters the conventional theory of the flow of power in one-direction. Some existing distribution networks are not designed to accommodate more DG [5]. The connection of DG to the distribution systems remains a constraint in the power distribution planning. The DG capacity limits; total DG capacity penetration level; DG capacity reserve; and short circuit current limit are considered from the major factors affecting the power distribution planning, when it comes to DG integration [6]. Moreover, there are technical aspects inhibiting the implementation of DG on a large scale such as voltage control; fault level; grid protection; power quality; and power losses [7], [8].

It is essential to perform a technical evaluation study to evaluate the impact of the interconnection of a particular DG in order to determine the most efficient DG to be connected, to avoid unnecessary implications. The evaluation study requires understanding the type and size of DG under consideration, system limitations at the proposed location of the DG, and the expected mode of operation and monitoring techniques that will be available to distribution networks operators [3].

DG may interfere with protection coordination if it contributed more than 10% [3] of the circuit's maximum fault current at the primary voltage at the point of common coupling. Increased fault currents may exceed existing equipment ratings, interrupting current ratings, which may lead to potential mis-coordination of existing protective devices. Therefore, further system protection studies should be performed [3].

The main objective of system protection studies is to ensure that the reliability of electrical system and the effectiveness of the protection devices settings and coordination are maintained during fault conditions despite the interconnection of additional generation sources to the distribution system [3].

Protection studies require comprehensive advanced studies involving load flow and short circuit studies to provide the fundamental essential data for analysing the impact of DG on the distribution system considered under different fault considerations and pre-fault conditions. This implies the modelling of the distribution circuit with proposed DG in a short circuit study computer program and different short circuit simulations to be performed in order to determine the short circuit current levels for appropriate protection coordination and relay settings [3].

The increasing exploitation of DG units has a significant impact on the short circuit currents and the short circuit level of the distributed systems. Therefore, the introduction of DG will to lead to a change in the short circuit current. Consequently, this will affect the existing overcurrent protection scheme, which in return may have a significant influence on the power system reliability. Hence, a redesign to the fault protection system will be needed [5], [7], [9]. The impact of DG depends on several factors such as DG size, penetration level, DG location, the technology of DG used, its operation mode, interface of the DG (type of generator connected), system voltage prior fault, location of fault, and type of fault. Therefore, it is essential and recommended to examine the contribution of each DG unit installed [9]. The safest way to assess the impact of DG on fault current level and the relay protection scheme of the distribution network is to model the grid with DG and to simulate different scenarios with different operating conditions [7].

The short circuit study should provide accurate results for reliable analysis and consistent coordination of relay settings. It requires very detailed models representing the system components dynamic behaviour. International committees as ANSI/IEEE and IEC provide simplified procedures as reference methods for short circuit calculations. Electrical power systems simulation software's have adopted these authorized methods to precisely simulate short circuit currents [10]. However, there is lack of evidence of which procedure could be adopted to examine the impact of DG on short circuit currents.

Wind and solar PV are the renewable energy sources that will be examined in this study. The wind and PV are the fastest growing sources of electricity generation worldwide, meeting more than 90% of incremental demand for electricity in 2015. Also, their average land cost is decreasing. Between 2008 and 2015, the average cost of land for wind decreased by 35% and that of PV by approximately 80% [11]. These two technologies have been shifted from the phase where main priorities are technology learning and cost reduction to the phase of technologically mature and economically liable [11].

The future trend in electricity generation is deploying a mix of technologies. It is found to have several valuable synergies such as the current technology mix (wind and PV) in Germany that is able to provide an overall more stable generation profile. Also, the variable output of wind and PV can be used in conjunction with other renewable resources and energy storage to offer integrated packages [11].

The fast-growing deployment of wind and PV has created significant challenges to the power systems planning, operation, and stability. The variable availability of daylight and wind leads to non-continuous generation, in which the system may not be flexible enough to adopt fluctuated output power. This affects the system stability and reliability. Furthermore, the interface of power converters technology between the grid and wind and PV is still uncertain [11]. Therefore, further investigations are still needed to determine the influence of deploying high penetration levels of wind and PV on the power systems operation in particular distributed systems.

1.3 Aim and objectives

The main aim of this research is to investigate the impact of wind, PV, and their mix including diesel generators on the short circuit current in electrical distribution network using different calculation methods such as IEEE/ANSI and IEC.

The objectives are:

a- To simulate and analyse a short circuit study for the IEEE 13-bus and IEEE 30-bus distribution test systems.
b- To investigate the impact of DG type on the short circuit current.
c- To investigate the impact of DG location on the short circuit current.
d- To investigate the impact of DG penetration level on the short circuit current.
e- To perform a load flow study to investigate the proper locations of DG to determine the key scenarios under study.
f- To investigate the key difference in short circuit calculations using IEEE/ANSI and IEC methods.

1.4 Methodology

The methodology applied in this research is simulation and analysis. The IEEE 13-bus distribution test system and 30-bus system are the two distribution systems selected to investigate the impact of DG penetration on their short circuit currents respectively. The choice for selecting a distribution system to study was not a straightforward task. The most appropriate preference is usually a real existing network. However, for this research, this opportunity was not available. Therefore, the most viable accessible data for approved distribution system models which are based on actual distribution circuits that were found are the IEEE distribution test systems.

The IEEE PES distribution system analysis subcommittee has several radial test feeders and common set of data available. The main purposes of these test feeders are to evaluate and benchmark algorithms in solving unbalanced three-phase radial systems [12].

The test feeders are classified by number of buses available in the circuit. The range of test feeders starts from the smallest as 4 buses up to 132 buses and even more for low voltage networks. The criteria for selecting the test distribution systems to study came from the prospect of examining the impact of DG on small system and large system so as to have substantial results and analyses for reliable conclusion. The two systems selected were the 13 bus and the 30 bus systems. Further details of different scenarios considered will be presented.

The computer software used for simulation in this research is Electrical Power System Analysis (EATP). ETAP is advanced software used by reputable research institutes and industry corporations for power system modelling, design, analysis, optimization, control, and automation. ETAP provides the most comprehensive unbalanced short circuit module for unbalanced fault simulation based on ANSI, IEC and GOST standards. Furthermore, the software includes comprehensive renewable energy models that are fully integrated with power system analysis calculations including load flow, short circuit, transient stability, and ETAP Real-Time solutions, for accurate simulation, predictive analysis, and equipment sizing.

Different types of photovoltaic array elements and wind turbine models are included in the ETAP renewable energy models. For the photovoltaic modelling, unlimited number of solar panels individually or in groups could be modelled in series and/or parallel connection combinations to form the required solar array with built-in inverter model. The effect of variable performance coefficients such as solar irradiance and cell temperature is considered and capable of automatically recalculating the power output from the photovoltaic array [13]. However, in this study this feature is not considered. A constant solar irradiance and cell temperature are assumed. Similarly, for wind turbine modelling, detailed modelling of turbine dynamics including aerodynamics and power coefficients is included with the option of simulating transient wind conditions with ramp, gust, and noise disturbances. Though, the aerodynamics and power coefficients for this study are assumed to be constant.

The distribution systems are modelled and modified by integration of different scenarios for wind, PV, Wind and PV, and Wind, PV, and diesel generators in ETAP. The short circuit study is run twice to consider ANSI and IEC methods respectively. Simulation results from short circuit studies are collected and entered into Microsoft Excel for generation of figures and further calculations of percentages. These results are then analysed in depth and presented in chapters five and six, where discussion and conclusions are provided.

1.5 List of publications conducted from this PhD

The research conducted in this PhD has resulted in the publication of a list of refereed publications as follows:

International Conferences publications

- S. N. Afifi, and M. K. Darwish, “Impact of PV/Wind/Diesel Hybrid System on the Distribution Networks – Fault Currents,” in *International Conference of Renewable Energy and Power Quality*, ICREPQ 2016, Madrid, Spain, May 4-6, 2016.
- S. N. Afifi, and M. K. Darwish,” Impact of Hybrid Renewable Energy Systems On Short Circuit Levels in Distribution Networks,” *2014 49th International Universities Power Engineering Conference*, UPEC2014, Cluj-Napoca, Romania, September 2-5, 2014.
- S. N. Afifi, M. K. Darwish, and G. A. Taylor. "Impact of Photovoltaic Penetration on Short Circuit Levels in Distribution Networks,” in *International Conference of Renewable Energy and Power Quality*, ICREPQ 2014, Cordoba, Spain, April 8-10, 2014.
- S. Afifi, H. Wang, G. Taylor and M. Irving, "Impact of DFIG Wind Turbines on Short Circuit Levels in Distribution Networks Using ETAP," *2013 48th International Universities Power Engineering Conference*, UPEC2014, Dublin, Ireland, September 2-5, 2013.

Book editing:

"Sustainable Energy: Technological Issues, Applications and Case Studies" ed. by Ahmed F. Zobaa, Sara N. Afifi and Ioana Pisica

1.6 Thesis outline

Chapter One – Introduction

This chapter provides a background to the research problem and motivations for conducting this research. The main objectives and aims are defined. The thesis outline is presented.

Chapter Two – Literature Review

This chapter provides an overview of the previous research conducted about the impact of distributed generation on distributed networks. Comprehensive technical challenges of DG implementation are presented. A review of the simulation studies carried out by previous research considering different power system parameters including short circuit analysis are provided. The research gap is highlighted where motivation of this research is based on.

Chapter Three – Technology and Short Circuit Overview

This chapter is divided into two main sections. First section outlines the arrangement of electrical power systems focusing on the distributed systems and its major difference with transmission systems. The importance of DG integration into distributed systems is presented. A detailed description of distributed generation technologies and its interface are provided. The second section presents the fundamental theories of short circuit analysis and its importance on power systems reliability.

Chapter Four – Short Circuit Calculations

This chapter presents the main techniques and detailed equations applied in short circuit calculations according to the chosen standards for this research which are IEC and ANSI standards. Also, the differences between these two standards are demonstrated. The major factors that influence the short circuit calculation for each method are given in details.

Chapter One: Introduction

Chapter Five – IEEE 13 Bus Distribution Test System

In this chapter, the simulation work carried out by this research using ETAP 12.0 software is presented. Simulation results for ANSI and IEC methods are exploited and presented in figures to demonstrate the impact of DG type, location and penetration level on the short circuit current of the IEEE 13 Bus distribution test system, for both methods. Each section is followed by a discussion, and last section a comparison between the IEC and ANSI simulated results is drawn and discussed.

Chapter Six – IEEE 30 Bus System

This chapter is similar to chapter five in terms of layout and objective. It presents the simulation results carried out using advanced version of ETAP (ETAP 14) on the IEEE 30 bus. However, in chapter six, increased DG capacity and more scenarios have been examined for the system under study. Detailed short circuit analysis is presented for ANSI standard simulation. Main IEC simulated results are presented. Detailed comparison between the IEC and ANSI simulated results are provided and discussed.

Chapter Seven – Conclusions and Future Work

In the final chapter, a summary of this research outcome is presented. The research main contributions are discussed. Furthermore, a recommendation of future work is outlined and proposed.

Chapter Two

2 Literature Review

2.1 Introduction

In this chapter, a general review of the impact of distributed generation on distributed networks is presented. Detailed technical challenges of increased DG and its impact on distribution networks will be presented. Moreover, a review of simulation studies performed on various distribution systems addressing the technical impacts of distributed generation on different power system parameters focusing on short circuit analysis will also be presented.

2.1.1 Impact of distributed generation on distributed networks

In most of the literature, the introduction for the research usually describes the new era happening in the electrical power systems, in particular the distribution systems. This is the altering of the traditional concepts and theories of power flow, as a consequence of connecting the electrical generation sources at the customer side or to the distribution network, and the impact of this on the system operations, reliability and control. Several authors described a general impact of distributed generation on distribution networks as follows:

The traditional radial distribution system with unique generation source is becoming a multi-source system by the integration of DG [14]. In ref. [15], the authors stated that the connection of distributed generation invalidated the original traditional assumption for the design of the distribution networks, where the primary substation will not be the only source of power and short-circuit capacity. In [16] argued that the penetration of DG changed the historic operation of passive distribution networks that originally used to deliver the power at lower voltages from transmission networks to consumers, with limited control. Furthermore, Ref.[17]- [19] agreed that the distribution networks performance have been altered due to the connection of DG, in which the existence of a radial system with unidirectional power flow pattern is diminished. The distributed networks gained more and modified characteristics to be active with power flows and voltages identified by the generation [20]. Ref. [8]

described it in its simplest form where the current nature of distribution systems is changing from passive to active.

2.2 Challenges of increased penetration of DG in distribution network

The challenges that may occur due to increased penetration of DGs in distribution networks can be classified into three categories [16].

2.2.1 Commercial challenges

Ref. [16] mentioned that there are number of studies have showed that active management of distribution networks could enhance the implementation of large-scale of DG that could be connected to the existing networks. Despite that the cost of active management of distribution networks is still uncertain, though the benefits of connecting DG are expected to exceed the cost of its implementation. Ref. [16] recommended that in order to encourage the development of active distribution networks and to demonstrate the subsequent benefits correlated with connecting substantial amount of DG, new commercial arrangements are required to be created. Moreover, [16] suggested three possible approaches: to recover the cost of applying active management directly via the price control mechanism; to establish an incentive scheme to encourage the uptake of DG integration; and to establish a market mechanism, outside of the regulatory framework.

2.2.2 Regulatory challenges

The traditional typical design of distribution networks and operation of passive networks restricted the implementation of large scale of DG due to the lack of well-defined policies and certain regulatory frameworks. [16], [21] recommended that to promote the increased DG implementation, it is necessary to develop and issue appropriate polices that support the DG integration into the distribution networks.

2.2.3 Technical challenges

The implications of increased DG penetration into the distribution network depend on various parameters [21]:

1. The voltage level of the distributed network where the DG will be connected.

2. Category of the distribution network.

3. The load demand

4. The level of DG penetration

Accordingly, integration of DGs has significant effect on voltage profile, network losses and fault level [22]-[25]. For existing distribution networks, in which used to be radial and power flows from higher voltage level to lower voltage level. The resistance to reactance ratio (R/X) is more than one for distribution network and less than one for transmission network. This is due to higher resistance that in turn, causes the voltage drop to increase in the distribution feeder. Moreover, due to higher values of R/X, the impact of the real power provided by DGs has more impact on voltage profile than the impact of reactive power [26].

The main function for most DGs is to only generate power, and do not contribute to the ancillary services that provide control to the power system and ensure stable operation. Despite that the DG implementation is increasing rapidly, there are technical barriers preventing the large scale of DG penetration into the existing distribution systems [27]. Protection is considered as one of the major issues when DG is connected to existing networks. Interface factors arise from the connection of DG to the utility distribution system. Consequently, high-level penetration of DG systems requires cautious technical consideration in particular the interface of DG influence to ensure and maintain compatibility with the existing grid [28] in [29].

2.3 Technical impacts of distributed generation on the distribution systems

2.3.1 Network voltage regulation

Consumer loads (such as electronic equipment; lighting; heating elements; and motors) and industrial applications are designed to provide their services from a nominally fixed voltage supply. Consequently, utilities are obliged by law to provide electricity at the consumer side at a voltage that does not deviate from the nominal voltage with a maximum of ±10%. The voltage at all nodes from the upstream at the generation, to the transmission, down to the distribution should be maintained to their nominal value. In other words, the voltage profile should be maintained constant from the generator terminals down to the consumer terminals [30]. Hence, this requirement often tends to determine the distribution network design and capital cost [31].

The precise voltage levels used differ from country to country; however, the principle of operation remains unchanged [31]. Table 2.1 shows classification of voltage levels used.

TABLE 2.1: VOLTAGE LEVELS CLASSIFICATION IN DISTRIBUTION NETWORKS [31]

Voltage Level	Voltage Range	Typical UK Voltages
Low Voltage (LV)	LV < 1 kV	230 (1 phase)/400 (3 phase) V
Medium Voltage (MV)	1 kV < MV < 50 kV	33 kV, 11 kV
High Voltage (HV)	50 kV < HV < 150 kV	132 kV

The current flow through the impedance of transmission lines, transformers, and cables makes the fact of voltage drop unavoidable. Compensation techniques are used to maintain a nearly flat voltage profile. A high voltage can be decreased or a low voltage can be increased at a node by the aid of connecting shunt inductor or shunt capacitor at this node respectively. Also, with the aid of connecting a load tap changing transformer at substation can regulate the system voltage [30].

The connection of distributed generation to a distribution network may introduce a significant impact on the voltage profile and power flow. These impacts may be positive or negative depending on the distribution system characteristics, and the DG location, and size [32], [33].

The voltage control is considered as a significant challenge that may inhibit the penetration of any further amount of DG capacity into the distribution networks. This is due to the fact of the change in the flow of power [16], [21]. Therefore, regulating the voltage through the distribution network requires more advanced strategy [21], [34]-[37].

Moreover, in [26], [38], [39], the voltage control aspect has been considered as a principal determining factor for implementing large scale of DG into distributed networks of various voltage levels (low and medium voltages). A number of studies have been performed to mathematically model the effect of high penetration level of DG on the voltage profile of distribution networks [34], [40], [41].

2.3.2 Power quality

In order to define the term power quality of electric power systems, it is crucial to introduce first the definition of the term reliability. Reliability refers to the ability of the electric system to deliver electric power to the consumer load without any interruption. Hence, the term power quality refers to the ability to deliver pure Sinusoidal waveform without variations in the nominal voltage or current characteristics [29]. There are two significant aspects of power quality that are usually discussed and considered in research [16], [21]: (1) transient voltage variations and (2) harmonic distortion of the network voltage. Transient voltage variations include voltage flicker, steps, and sags (dips).

2.3.3 Voltage flicker

The degree of flicker caused by a given generator is highly dependent on the network parameters, in particular the fault level and R/X ratio at the point of common coupling. Consequently, the impact of generator embedding on the network differs from one point to another [30].

2.3.4 Voltage steps and sags

Voltage steps occur as result of sudden change in the voltage at the PCC due to an associated abrupt change in active or reactive power flow. This may occur due to switching of a generator either on or off [30].

Voltage sags are also known as voltage dips. It is commonly defined as any low voltage event that temporally occurs between 10% and 90% of the nominal RMS voltage lasting between 0.5 and 60 cycles. Whereas, momentary voltage interruption is considered at less than 10% of the nominal RMS voltage lasting between 0.5 cycles and 3 s. In medium voltage distribution networks, the voltage sags are generated by the occurrence of power system faults, which affect consumers differently according to their location in the electrical network [29]. Moreover, voltage sags may occur due to starting currents (also known as inrush currents) that typically occurs during the starting of induction generators. A soft –starter is equipped to the wind turbine circuits with large induction generators, to limit these inrush currents [30]. The voltage sags and steps may contribute to flicker if they became repetitive or cyclic [30].

The DG connection to the distribution system may have a significant contribution on the power quality. This contribution may be positive or negative. It depends on the distribution system and the connected DG unit characteristics. The positive impacts include improved reliability, voltage regulation, and reduction of transmission and distribution losses. Though, for inverter-based DG units, this may not occur, hence, DG can increase the current and the voltage distortions in the system [42].

Also, a significant standalone DG (such as wind turbine) may cause power quality issues in a weak distribution network particularly during starting and stopping [16], [21]. In [43], demonstrated that DG integration affects power quality, among which the most significant related events are voltage dips induced by failure defects. DG integration can enhance the power quality received by other distribution network users depending on particular circumstance [16], [21], [44], [45].

The power loss through the feeder could be reduced as a consequence of connecting the DG closer to the loads especially at a large scale. This will lead to less amount of power to be drawn from the distribution substitution, which in turn will reduce the amount of current flow throughout the path from the distribution substation to the loads [44] in [21].

Power quality is considered to be an increasingly significant issue and generation is generally subject to the same regulations as loads. Based on this, it has been recommended that this would work effectively in practice and that the careful design would be capable of achieving the required standards [16].

In [46], [47], performed comprehensive reviews on the power quality problems, reactive power management and voltage management where several control devices and methods have been discussed and comparisons of their performances have been presented.

2.3.5 Stability

The most common definition used in the literature has been first proposed by Kundur *et al*. (2004) as the ability of the system to withstand any physical disturbance and regain a condition of operating equilibrium equivalent to the initial operating condition, where most system variables are bounded to ensure that the entire system remains intact [48].

The power system stability has been recognised as significant issue in order to maintain a secure system operation since 1920's. Hence, a major consequence that may result from power system instability is major blackouts. Mainly, power system stability is a single problem. However, there are a number of forms of instabilities that a power system may undergo that cannot be effectively addressed discretely. The classification of power system stability into appropriate categories facilitates the analysis of power system stability which requires to determine the key factors that contribute to instability and to develop methods to improve system stability. The power system stability categorization is based on the physical nature of the resulting mode of instability, the size of disturbances, the devices, processes, and the time span that must be an essential requirement for stability assessment [48].

2.1.5.1 Power system stability is classified into three main categories:

1) Rotor angle stability: is the ability of synchronous machines connected to the system to remain in synchronism after the exposure to any disturbance [48].
2) Frequency stability: is the power system capability of maintaining a steady frequency after a severe system disruption leading to considerable imbalance between generation and load [48].
3) Voltage stability: is the ability of a power system to maintain constant voltages at all buses after occurrence of any disturbance initiated from a specified operation condition [48].

Traditionally, power system stability was not considered as a significant issue during the design of distribution networks. This was due to the fundamental topology that the network was passive and consequently remains stable under most circumstances provided the transmission network is itself stable [16], [21].

Also, Ref. [16] discussed that currently system stability is almost not considered when assessing distributed generation systems. Hence, this will change as the level of penetration of DG increases and their contribution to network security becomes critical. Ref. [3] highlighted the issues that need to be considered, which include transient (first swing stability), long term dynamic stability, and voltage collapse.

The stability of distribution networks should be substantially addressed as the penetration of DGs is increasing [21].

In [49]-[54], the change of flow of power from being uni-directional to being bi-directional due to DG integration into the distributed networks is affecting the network performance and stability in a number of ways.

A number of studies have been made to examine the stability issues, operations and control technologies of the distributed systems when large-scale DGs are integrated [46], [47], [55]-[57]. Ref. [55] and [56] have discussed various control strategies and stability issues focused on micro grids.

2.3.6 Protection

IEEE standards stated that the integration of distributed resources (DR) into the system may alter the system operating parameters and affect fault current levels. As a consequence, the existing protection scheme and its coordination settings may not operate as initially designed and should be evaluated under these modified parameters.

The connection of high DG capacity on a feeder also has an impact on fault location practices. DG that has a significant contribution to short-circuit currents may cause an unexpected operation of fault indicators that are used to locate fault position [3] .

There are several different significant aspects of protection need to be addressed when considering the installation of DG to distribution networks [16]:

1) Protection of the DG from internal faults;
2) Protection of the faulted distribution network from fault currents generated by the DG;
3) Anti-islanding or loss-of-mains protection (islanding is expected to occur more with increase DG implantations);
4) Impact of DG on existing distribution system protection schemes

Protection systems developed for radial distribution systems are affected by the penetration of DG. This is due to the changes in the traditional distribution power system short circuit power, fault current level and the characteristics of the fault current, such as amplitude, direction, and distribution, as result of interconnecting DG [58].

Existing distribution networks were originally designed and built considering unidirectional power flow without anticipating the era of DG interconnection. Hence, in case of fault occurrence, the protection relays will not be able to coordinate among themselves accurately in a radial distribution network when a large amount of DGs are connected and Bi-directional power flow occurs [59], [60].

Based on the same radial topology, in [58] discussed the impact of DG integration on the distribution system operation and fault response, which in turn could be altered. As a consequence, the original time overcurrent protection coordination may not comply with the new situation. Though, an improved protection arrangement has been presented.

In [54], stated that the integration of a DG to a feeder influences the feeder protection scheme in three different aspects: the islanding phenomenon, the effect on over current relay performance and the reclosure to fuse coordination [32], [51]-[53].

Ref. [61] theoretical studies on the impact of DG on the current seen by protective devices demonstrated that the presence of DG may invalidate the overcurrent protection schemes.

Ref. [62] identified several conflicts between DG and distribution network protection operation, and examined some practical cases with reference to Italian networks.

2.3.7 Increase in network fault

Different types of DGs may produce various fault characteristics. An example of this is such as: if power electronic converters are used as the interface for DGs, due to the fast switching and control nature of power electronic converters, the short circuit currents and transients from the converter system may be distinctly restrained [58]. Moreover, several types of larger DG use directly connected rotating machines which in turn contribute to the network fault levels. Induction and synchronous generators will increase the fault level of the distribution system; however, their behaviour under sustained fault conditions is different [31].

Implications of increased fault current level caused by power system faults in the distribution system may generate voltage sags affecting consumers according to their location in the network, especially in medium voltage distribution networks [29].

The effect of increasing the network fault level by adding generation often leads to improved power quality. However, a single large DG, e.g. a wind turbine, on a weak network may lead to power quality problems particularly during starting and stopping [16].

2.4 Simulation in literature review

Ref. [63] presented the major issues that affect the distributed networks operation and control as a consequence of connecting huge amounts of DG. These are stability issues; change of short circuit level and voltage profiles; harmonics; malfunction of protection schemes; load losses variations; and power quality. Also, a load flow study has been performed to investigate the impact of a 3 MW wind turbine on the power system losses. The study was carried out using Neplan software for the IEEE 14-bus distribution test system. For this case study, they concluded that the connection of the DG has reduced the power losses.

In ref. [64] investigated the possibility of improving the distributed system voltage profile and reducing system losses through wind power penetration. Simulation was carried out on a 22 kV distribution network connected to a wind plant consisting of four synchronous Vestas V80-1800 kW type generators, using EGC VLIVY 4.2 and DAISY PAS off – Line V 3.5 programmes.

Ref. [65] investigated the effect of 30 MW DG consisting of wind (DFIG and DDWGs), PV, and energy storage on the dynamic operation of distribution systems during transient conditions on the IEEE sixteen bus distribution test system using PSSE and PSAT. Ref. [8] investigated the behaviour of the fault ride-through of distribution networks including DG.

Ref. [8] investigated the impact of CHP plants on voltage control, grid protection and fault level on an existing compact 8-feeders Dutch distribution network. Voltage control issues and blinding of protection are may rarely happen on small distribution systems. However, ref. [8] strongly recommended that false tripping and fault level have to be precisely considered.

Authors in [33] investigated the impact of DG (synchronous generators) on voltage profile and short circuit analysis on different types of distribution systems (radial, loop and network at 33kV and 34.5kV respectively) using DigSILENT, while varying the DG location and penetration level. Short circuit analysis was simulated according to VDE standards. Three types of faults were simulated for the radial system: 3 phase fault, phase-phase fault, and phase-ground fault. While for the other two distribution systems, only the 3-phase fault type was simulated.

In ref. [66] determined the maximum allowable DG (synchronous generators) capacity that could be connected to an existing MV Italian radial distribution network, while maintaining the DN parameters. Ref. [66] focused on studying the impact of DG penetration on the voltage profiles and line currents as a function of power factor, and short circuit currents. The short circuit analysis carried out in the study considered the 3-phase fault type only.

Ref. [20] investigated the impact of three different DG resources on a real existing medium voltage distribution network in Greece. The paper examined the impact of the DG penetration on the currents, losses, voltage profile, and the short circuit level of the network under study, using NEPLAN software package. The allocation and size of the PV units, the wind energy plant, and the hydroelectric plant were predetermined. The total installed capacity for each DG equal to 2.7MW, 4MW, and 0.24MW respectively. However, it was mentioned and noticed that the DG units were connected at remote sites from the MV busbars of the main substation. This mixed DG penetration had negative significant impact on the voltage profile of the network. Despite the possibility of improving the DG units power factor which work with an inductive power factor to keep the voltage within the acceptable limits, this did not solve the problem. It just slightly improved the voltage profile. At the same time, the short circuit level at the MV busbars of the infeeding substation, where it has the highest value did not exceed the design network value. The paper concluded that the irrational allocation of the DG units into the network not only leads to network sterilization as previously discussed, but also leads to the violation of technical constraints. It recommended that in order to avoid any future network operational failure; precise examination using the appropriate tools should be carried out, before any DG penetration into the network.

Ref. [67] analysed the impact of different types of distributed generators on protection coordination, fault current level and voltage profile in a 22 kV test radial distribution networks using MATLAB.

Also, in [68] studied the behaviour of around 10.5 MVA total combined heat and power (CHP) generators connected to real distribution network during faults and its impact on short circuit level using DigSILENT, comparing between short circuit calculations IEC 60909 and IEC 909 standards.

In [69] studied the influence of DG on distribution systems so as to determine the maximum distributed generation penetration that can be accommodated without affecting the system performance. This study investigated the effect of synchronous generators on the IEEE 13-bus test distribution system in terms of fault current, voltage total harmonic distortion (THDV), voltage sag, and voltage swell, using alternative transients program (ATP)-electromagnetic transients program (EMTP) software as a simulation tool. Short circuit calculations addressed the occurrence of single line to ground fault only in respect of same DG location with four cases representing different range of penetration level which are 0%, 10%, 20%, 30% respectively. The selection of DG was based on the recommendation of previous study performed to determine the reliable DG location on the IEEE 13-bus test distribution system [69].

In [70], the authors addressed some of the overvoltage issues and of the overcurrent protection problems that occur in case of connecting DG to existing networks. The IEEE 34 Node Radial test system was the system under study using Siemens PSS/ADEPT 5.3.2 software for load flow study and fault analysis. The DG unit used was synchronous generator; with penetration level of each DG was 20% of the original feeder load. The criteria of various DG locations attempted to be on how far or near from the substation, near the voltage regulators, and on laterals and main feeder. The fault analysis examined the maximum and minimum fault currents through each of the protective devices included in the system under study. Three phase fault and single line to ground fault through a fault resistance of 20 Ω were performed for the three phase feeders and branches of the system to calculate the maximum fault current and the minimum fault current respectively. Though, for the single-phase branches, single line to ground faults were only applied, with no fault impedance has been used for calculation the maximum fault current, and 20 Ω resistance was used for the minimum fault.

In [9], [67], [71] argued that the DG interconnections with the grid or network substantially contribute to the short circuit level of the DN, in which it is a significant factor that determines the maximum permissible penetration level. Accordingly, their studies investigated the contribution of DG interconnections on the short circuit level. Despite their agreement on the main concept and importance of idea, Authors in ref. [9] were selective on their choice for the DG types and focused on the directly coupled generators, as their contribution is much more crucial.

Ref. [71] examined the impact of type and interconnection of various DG units including diesel generator; 2 micro-turbines; PV; fuel cell; 2 wind farms; and fuel cell and battery on the fault current level. This study focused on the different interconnection methods of the different DG types used to the grid, and compared their contribution on the short circuit level, using MATLAB/Simulink. The simulation tested the three-phase fault at different locations of the network.

Ref. [9] simulations were carried out on a 10 kV cable distribution network consisting of several feeders in the Netherlands, using DigSilent Power Factory software, testing the occurrence of three phase fault. DFIG, AG, and CHPs (SG) are the DG connected to the network. Also, they compared between the results obtained from IEC standard calculations and the simulation results.

DG and grid contributions were evaluated in [72] under the cases of single line to ground faults and symmetrical three phase faults. The PSCAD software was used for the simulation of transient contributions of various DG units (PV, PSMG, DFIG, SG) respectively, with a range from 1 MVA – 3MVA each, in a tested medium voltage distribution network.

Ref. [73] examined the effect of DG in the fault location on a 25 MV distribution system using MATLAB/Simulink, investigating the different parameters impact such as magnitude of DG, fault impedance, and relative position of the fault location and the DG. The fault type tested in this study was the single line to ground.

In [74], this paper investigated the effect of a 3 MVA synchronous generator on short circuit level of a real 11 kV distribution network supplying industrial loads in Karachi, Pakistan. The network has been modelled on PSS SINCAL. The network consists of 27 buses excluding the substation bus bar; seven 11/0.4 kV transformers with total capacity of 4.75 MVA; and five connected industrial loads. The short circuit levels were obtained for the all system buses in two different scenarios, with and without DG connection respectively. The penetration level of the selected DG unit represents around 50% of the total connected load, located at one location only throughout the study. The type and location of short circuit have not been mentioned in the article, although the authors have highlighted that 3-ph faults and single line to ground faults are the most severe faults that may occur.

2.4.1.1 Impact of PV on distributed networks

In [75] investigated the influence of high penetration residential PVs on protection and operation issues of a 22 kV residential distribution feeder in a suburb of Raleigh, NC. Hence, detailed system parameters were not provided in this paper. The paper described the system under study as a three phase circuit with unbalanced load where the PVs were connected on a phase basis. The simulation studies carried out using PSCAD to measure the fault current contribution on the operating time of the protective devices when PVs are connected to the system. This is through testing the fault current at the protective devices at different faults including three phase faults and single phase fault, through varying fault resistance; at different fault locations respectively. The selection criteria for fault location was based on the nearest and the farthest points in the protective device primary zone of protection. Also, the PV power output has been varied (assumed power output percentage is equal to percentage of the total system load).

For the same distribution system studied in [75], authors in [76] proposed an algorithm capable to provide an estimate of fault current profile on a distribution feeder with high PV penetration level during the first few seconds of the fault occurrence, to enhance the conventional fault analysis methods in order to facilitate the design and coordination of protection schemes. The study validated the proposed method by performing a fault current simulation study using PSCAD, to obtain detailed time-domain results, so as to be compared with the proposed algorithm results. The simulation calculated the fault current level through the feeder circuit breakers at the occurrence of three phase fault and single line to ground fault while varying the fault resistance, at four different nodes. The maximum difference between the proposed algorithm and simulation results for the magnitude currents was found to be 6.16%.

Ref. [77] studied the impact of photovoltaics on power flow, voltage, short circuit and relay protection respectively on 10 kV distribution network. PV located at two different locations, where three-phase short circuit current is tested on one of these locations. Simulation tool used was not provided in this paper.

2.5 Optimal allocation issues

Ref. [78] mentioned that the DG allocation issue has been only applied on very small scale of distribution systems with limited numbers of buses, despite the fact that distribution systems are usually of huge in terms of rating, and number of buses and branches. Also, the focus is to determine the optimal DG units location and size more than to find the optimal type of DG units. Authors in [78] recommended that more studies need to be performed to find which type of DG unit is the most suitable and adoptable for each bus of the distribution system.

2.6 Gap in research

There are several issues have not been covered in the existing literature until this research has been conducted, that is considered in this thesis. Also, there are conflicts in previous research in which this thesis will highlight and attempt to investigate these conflicts to have a reliable outcome. These issues and conflictions are presented in the following sections.

2.6.1 PV discussion

In some of the literature, the study of PV contribution on short circuit level of distributed networks is neglected and not substantially recognised. This is due to its limited impact on the short circuit level [9], [79]. The reasons considered for why PV has no significant contribution on short circuit level of distribution networks are:

1- The short circuit current of PV array is low and determined by the thermal limit of the semiconductors (typically 10-20% of the rated nominal current) [9], [80], [81].
2- Inverters are usually supplemented with under-voltages relays [81].

3- PV current controlled inverters are over-current limited in the case of disturbances coming from the grid. [79], [81].

The PV may supply fault current to the fault under short circuit condition in the feeder. This injected fault current depends on the inverter design, that does not exceed the rated current as mentioned above, and, in which this fault current is still protected against through over current relays and/or fuses coordinated with the protection devices of the distribution feeders [72], [76]. Also, with expected high penetration levels of PV to meet increase of demand, and unpredicted disturbances that may occur such as faults occurring with high resistances out of the PV inverter over-current control and protective devices coordination scheme, or line overloading; some PV systems may be unable to distinguish this fault and injects more fault current to system. Consequently, thus this could cause a delay in the fault detection by the system protective devices and loses system relays coordination and protection reliability [79], [81]-[83]. Therefore, to maintain a resilient, secure and reliable system, the contribution of PV on short circuit current of distribution network shall not be ignored and disregarded. Though, it shall be crucial to investigate the effect of PV short circuit current on the system fault detection.

In ref. [81], stated that from a technical perspective, grid interfacing issues are important to consider for large scale of PV integration. In which, PV contribution to short circuit capacity is considered one the vital issues that needs to be addressed.

Ref [75] argued that despite the facts that PV have limited impact on the distribution system voltage profile and protection, so that high level of penetration could be adopted, it still crucial to investigate and study these parameters. Also, recommended that revisions should be made to existing protection and voltage control schemes.

In [20], the study demonstrated that in real networks operation, the connection of the PV units in combination with other DG resources still contributed to the failure of the network reliability. This ensures that the study of the impact of PV on the power systems studies is essential and should not be neglected.

However, this limitation could be advantage. PV may help in some critical or weak networks to have double role, first acts as current limiting source and second is generation source.

2.6.2 Type of fault studied

It is noticed that the three-phase fault type is the most common type of fault examined in the literature, followed by the single line to ground fault type. Few authors mentioned the reasons why they examined the occurrence of these types of faults in particular.

Reasons available in the literature for three-phase fault type:

1- It is the most common [72]
2- Have the highest impact on power system stability; where the most severe switching action with regard to the transient stability [84]
3- Major stress occurs during three-phase faults [9]
4- It is considered the most dangerous type of fault; as all three phases are short circuited and causes maximum damage to the system equipment [74]
5- causes the maximum fault current when the network neutral is earthed directly or through an earth fault current limiting impedance [85]

Reasons available in the literature for single-line to ground fault type:

1- Most likely to happen [72]
2- Causes the most common PQ problems (voltage sag and swell) [69]

This still ensures the importance of examining the three-phase fault and single line to ground fault types. Hence, the research did not provide enough attention to the line-line fault and line-line to ground fault types. Although, the former fault types still constitute to severe unbalanced operating conditions [84].

Hence, the IEEE [3] recommended that the DG needs to be demonstrated in a fault study computer program along with the existing distribution circuit models and different fault simulations performed in order to determine the fault current levels for accurate protection coordination and relay settings. A Short-circuit analysis employs a fault study program and studies the impact of three-phase, line-to-ground, line-to-line, and line-to-line-to-ground faults on electrical distribution systems. The short-circuit study typically calculates the total short-circuit currents as well as the contributions of individual motors, generators, and area EPS ties in the system.

IEEE stated that for DG impact studies, it is crucial that the DG short-circuit contribution to be represented appropriately. Accordingly, this ensures the importance to examine the four different types of fault that may occur in an electrical distribution system.

2.6.3 Percentage of distributed generation penetration level

Several studies discussed the significance of examining the impact of increased penetration of DG on distribution systems, and presented the technical challenges that need to be addressed. Though, few studies considered the study of the impact of DG at various penetration levels with 50% of total connected load, the maximum. In this thesis, the DG penetration level considered reached up to 85% of the generation capacity.

2.7 Summary

This chapter presented a review on the impact of DG on distributed networks. A number of generic statements from the relevant available literature have been included describing the modern phase of electrical power systems in particular the distributed networks. It can be concluded that the distribution networks main characteristics have been changed from being passive to being active due to the introduction of distributed generation. Certainly, this has driven various challenges to arise, that need to be addressed to be able to meet the increased DG implementation, such as commercial, regulatory and technical challenges. A brief review has been provided on the various technical impacts of DG on the distributed networks, showing the linkages to related issues such as power quality and increased network fault level. Also, this chapter presented the simulation studies performed in the existing literature examining the contribution of DG on power systems parameters in particular short circuit level of distributed networks.

Although, several studies attempted to discuss this topic, however many aspects related to this area is still open for further research. These can be summarized as follows:

1. Examining more types of fault including the all three types of unsymmetrical faults;
2. Increasing the DG penetration level to identify their maximum impact;

3. Including various DG types together with various locations;
4. Investigating the impact of DG on short circuit level on large systems with an appropriate number of buses;
5. Using different power system analysis simulation tool
6. Calculating short circuit level by various methods such as IEC and ANSI

Chapter Three

3 Technology Overview

3.1 Introduction

In this chapter, there are two main sections presenting basic descriptions and characteristics for this study main subjects. First section, an overview of the electrical power systems focusing on the distributed systems will be presented. A detailed explanation of the distributed generation definition, importance, and main characteristics will be provided. Second section, an overview of short circuit aspect is presented.

3.2 Electrical power system arrangement

An electrical power system could be described in the simplest terms as an assembly of electric equipment installed to supply electric energy to consumers. The power system is divided into three main pillars: generation, transmission, and distribution. The distribution system is where the voltage is stepped down to medium voltage (MV) level at 132 kV and below [86], [87].

3.2.1 Distribution systems

A typical distribution network consists of a step-down transformer at a supply point feeding a various number of circuits that may have different lengths that can vary from a few hundred meters to a number of kilometres. Throughout these circuits, a series of step down transformers are equipped, from which the final consumer is supplied [86], [87].

3.2.1.1 Distribution system configurations

Distribution systems have several types different in configurations, designs and lengths. However, most of these types share common characteristics. In which the main feeder known as the mains or mainline is the back-bone of the circuit, where it is a three-phase circuit out of the substation. One or more circuits branch from the mains, known as taps; lateral taps; branches; or branch lines to which distribution transformers are connected. Along with, laterals are usually connected to the main through a fuse. These laterals may be single-phase, two-phase, or three-phase depending on the nature of the load [89].

Distribution systems are classified into the following configurations in Figure 3.1 in which one or a combination of the following standard systems is applied.

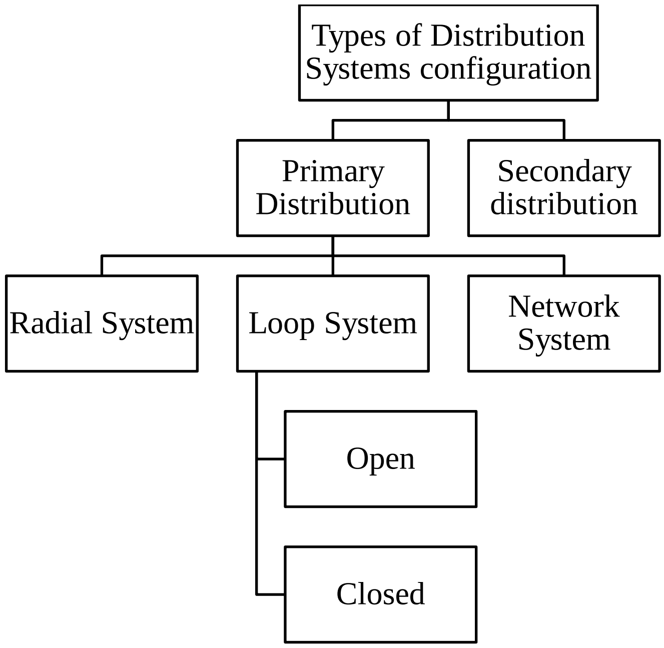

Figure 3.1 Distribution System Configuration

A. Radial system is considered to be the simplest, where the load is supplied through one radial feeder. However, in case of a fault occurs along the mains, or at the laterals on which the fuse fail to clear the line, the entire feeder will be de-energised. Therefore, all consumers (load) connected to this feeder will suffer from supply interruption until the fault is cleared or the feeder is tied to an adjacent emergency feeder, if there is enough capacity to accommodate this extra load. This type is not reliable for sensitive loads such as hospital and military establishments, where are not capable of tolerating supply interruption [87], [90].
B. Loop system- this system employs two main feeders to supply the load. Hence, if a feeder fails to operate, the entire load of this feeder may supply from the second feeder, in which sufficient spare capacity is considered in the design and available. This system is more advanced than radial systems in regards to the supply interruption duration. This type of system may be operated with the loop as normally open or with the loop normally closed [90].

- Open – loop system where the load is supplied through one of two available feeders [87], that is, one side of the loop is connected to the supply through a disconnecting device that is intentionally left open, hence the second available feeder is also connected to the supply through a normally closed disconnecting device. Both feeders are tied together at their other ends through a switch or disconnecting device [90]. This system still is not reliable enough to provide continuous supply without interruption, since a fault could occur causing the disconnecting switches at both ends to open, leaving the entire feeder de-energized.
- Closed – loop system where the load is supplied through the two sides of the loop simultaneously [87], in which the arrangement of this configuration is typically identical to the open loop system, hence, the two disconnecting devices at both ends connected to the source are normally closed. This type requires a higher degree of accuracy in the protective devices selectivity and relay settings, which may be non-economical/not guaranteed to achieve.

C. Network system, refers to supplying the load by more than one radial feeder [87]. It is created by connecting together the mains in the radial systems to form a grid or mesh. The grid is connected to several power transformers supplied in turn from the sub-transmission and transmission lines at higher voltages [90].

In this thesis, network and radial systems are the systems of interest to investigate and study. This is due to the fact that in practical, these are the most common especially the distribution networks.

3.2.2 Integration of renewable energy generators into power systems

The conventional arrangement of power systems has always been set in a hierarchy assembly. From large centralised generation sourced from fossil fuels or nuclear power source, connected to extra high voltage transmission system down through the HV and LV systems to be distributed to consumers. Lately, renewable energy sources are taking over fossil fuels and nuclear power sources. Generators powered from renewable energy sources excluding large scale hydro and large off shore and onshore wind farms are typically much smaller than generators powered through fossil fuels and nuclear power. These small generators are not possible to be connected to the transmission system due to the cost of high voltage transformers and switchgear. Also, the geographical location of the generator is restricted by the geographical location of the resources, which may not be always near the transmission system. Moreover, integration refers to the physical connection of the generator to the network while maintaining secure and safe operation of the system. Along with The generator control is essential, so that the energy resource is optimally exploited. Therefore, small generators are ideally to be connected to the distributed networks. Such generation is known as distributed generation [30].

3.2.2.1 Interface of distributed generation with the distributed network

The point at which the distributed generation unit is connected to the distribution network is known as the point of common coupling. Every DG unit has its own type of interface with the network, which enables to accommodate the generated power according to the grid requirements. The interface technologies are broadly divided into direct machine coupling and power electronics coupling [94].

A. Direct machine coupling with the distributed network

The direct machine coupling with the grid entails a DG source that harvests mechanical power such as wind power. The selection of the type of the machine depends on the nature of the mechanical power generated/provided. For a constant mechanical power, resulting in constant rotating shaft speed, the synchronous machine is the appropriate type, whereas for variable mechanical power, the induction machine is more suitable. Though, permanent magnet synchronous machines are used for slow rotational speed turbines [94].

B. Power electronics coupling with the distributed network

The power electronics interface conditions the power supplied by the DG unit to meet the grid requirements and improves the performance of the DG source. Power electronics converters such as DC/AC converters convert direct current (DC) power to alternating current (AC) power in order to be compatible with the grid AC power. DC/AC converters interface are applied with the PV systems. Furthermore, power electronics interface could still be used with the direct coupling machines such as DFIG wind turbines to adjust and control of active and reactive power, which is known as partial power electronics coupling to the grid [94]. Table 3.1 presents the type of interface for different DG sources.

TABLE 3.1:TYPE OF INTERFACE FOR DIFFERENT DISTRIBUTED GENERATION SOURCES

Energy source type	Type of interface	
	Direct Machine coupling - Type of generator	Power Electronics
Wind Power (wind)	Synchronous generator Permanent magnet synchronous generator Induction generator Doubly fed induction generator	AC/AC
Large Hydro power (water)	Synchronous generator	-
Small Hydro power (rivers)	Permanent magnet synchronous generator	AC/AC
Photovoltaics (sun)	-	DC/AC
Solar thermal (sun)	Induction generator	-
Wave Power (oceans)	Linear synchronous generator	AC/AC
Geothermal Power (earth temperature)	Synchronous generator Induction generator	-
Fuel Cells (Hydrogen)	-	DC/AC
Biomass	Synchronous generator Induction generator	-
Microturbines (diesel or gas)	Synchronous generator Induction generator	-

3.2.2.2 Impact of type of interface on the distribution system

The interface type of the DG with the grid identifies its impact on the distribution system operation. Basically, there are various interfacing impacts on the distribution system such as [94]:

1. Determines the quality of the power generated by the DG source.
2. Identifies the DG efficiency
3. Controls the cost of DG installation

3.3 Overview of DG technologies

Some of the DG technologies and their main characteristic are as follows

3.3.1 Diesel generators

Diesel generators are considered the most established DG technology. It is very suitable for stand-alone applications. Their major advantage is that they can be started and shut down almost spontaneously making them a viable choice for back up applications [4].

3.3.2 Hydropower

Hydropower converts the flow of water and the change in water level into electrical energy. The hydroelectric power stations are usually located on or near a water source (such as rivers) [95]. Power is generated through the flow of water in a controlled manner tuning turbines that drives electrical generators. Hydropower stations are classified into large scale hydro and small scale hydro depending on generation capacity. Large scale hydro could be addressed as centralised power generation as it is usually located at remote areas and requires strong transmission systems, though small scale hydro could be classified as distributed generation [30]. Small hydropower plants require low construction period, employ well-developed technology with an overall efficiency of over 80%, low operation and maintenance costs due to automatic operating systems [94].

3.3.3 Fuel cells

A fuel cell converts chemical energy into electrical energy. A fuel cell consists of two electrodes (an anode and a cathode) and an electrolyte, retained in a matrix. Fuel cells utilize a variety of fuels such as natural gas, propane, landfill gas, diesel, naptha, methanol and hydrogen. Fuel cells are environmentally friendly and are 20% more efficient than other forms of energy conversion [86]. A single fuel cell generates output voltage less than 1v. Therefore, in order to generate higher voltages; fuel cells are assembled above each other and are connected in series forming a fuel cell system [96]. There are four types of fuel cells with different electrolytes and operating temperatures as follows [96]:

1. Proton exchange membrane fuel cell (PEMFC) operating at 80 °C
2. Phosphoric acid fuel cell (PAFC) operating at 200°C
3. Molten carbonate fuel cell (MCFC) operating at 650°C
4. Solid oxide fuel cell (SOFC) operating at 1,000°C

3.3.4 Solar energy

Solar energy is predicted to provide one-third of the world energy demand after 2060. Solar energy is divided into solar thermal and solar electricity. Solar thermal uses the sun as direct source of heat energy to supply hot water for domestic use and swimming pools. Solar electricity uses photovoltaic for supplying electricity [97].

3.3.5 Photovoltaic power generation system

The photovoltaic cell is the main building block of the PV power system, as it is a semiconductor device that transforms solar light into electrical energy. This phenomenon is called 'Photovoltaic Effect'. Typically, it is few inches in size and produces about 1 Watt of power. In order to generate high power, PV cells are grouped in series and parallel circuits to form a PV module. Hence, numbers of PV modules are electrically connected in a series-parallel configuration to generate the required current and voltage. The PV array output power is affected by the operating conditions and the site conditions such as geometric location, irradiance level, and ambient temperature [97]-[99].

Photovoltaic system is classified into stand-alone photovoltaic system and grid-connected photovoltaic system. Their implementation depends upon the load function and operation conditions. Grid-connected photovoltaic system operates in parallel with and interconnected with the utility grid. A fundamental PV power generation system is shown in Figure 3.2.

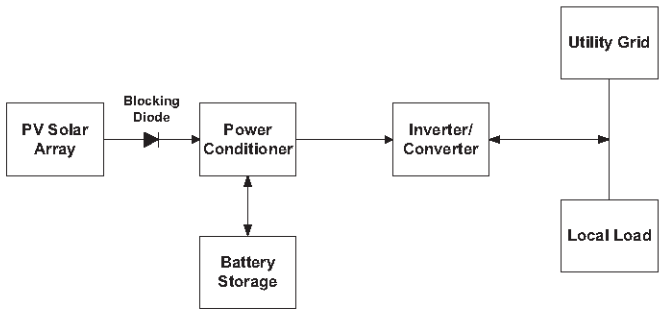

Figure 3.2 Block diagram of a fundamental photovoltaic power generation system [97]

The stand-alone PV system is capable to be designed and sized to provide electricity independently from the utility grid to a wide range of applications varying from wrist watches to spacecraft. Also, electric vehicles, street lights, and remote buildings are highly emerging applications for the use of stand-alone PV system [97], [99].

3.3.6 Wind energy

Wind Turbine Generators

The rapid pace of technology development for wind turbine generators (WTGs) is a robust area of research. WTGs developed from small machines with output power ratings of few kilowatts to numerous megawatts; and from machine with very limited speed control and basic capabilities to a sophisticated machine with variable speed control and advanced capabilities using latest power electronics technologies [100]. Modern wind turbines are classified according to the type of generator equipped and configuration. These generators are categorised according to speed control characteristics (either fixed or variable) and use of power electronics. These are: Type 1; Type 2; Type 3; Type 4; and Type 5.

3.3.6.1 Characteristics of different types of wind turbine generators

Type 1: Fixed Speed Conventional Induction Generator

This is a squirrel-cage induction generator (SCIG) and is connected to the grid via step-up transformer equipped with soft starter and switched capacitor banks [100], [101]. The maximum output power is generated at a fixed wind speed. The major disadvantage of the SCIG is that it requires a reactive power for its excitation field and huge starting current. Therefore discrete capacitor banks and a soft starter are equipped within the turbine to overcome these implications [100]. Any fluctuations in the wind speed are converted into fluctuations in the mechanical torque and then converted into fluctuations in the electrical power. In weak networks, these fluctuations result in voltage variations at the point of coupling. Consequently, the wind turbine consumes variable amount of reactive power from the grid causing line losses and voltage imbalance. It is more suitable to be connected to a stiff grid [101].

Type 2: Limited Variable Speed Wound Rotor Induction Generator with Variable Rotor Resistance

The WTG configuration is similar to that of Type I, where the induction generator is connected the grid through as step up transformer; capacitor bank; and start softer with regards to the machine stator circuit; with a variable resistor connected to the rotor circuit. The variable resistor is capable of controlling the rotor currents more rapidly so as to keep constant power even during gusting conditions, and enhancing the machine's dynamic response in case of grid disturbances [100], [101].

Type 3: Variable Speed Doubly-Fed Induction Generator with Partial-Scale Frequency Converter

This type of generator is also known as doubly fed asynchronous generators. The DFIG is a wound rotor induction generator. This machine has a unique characteristic in which both the stator circuit and the rotor circuit are connected to the grid (Figure 3.3), providing more operational and controllable features and more efficiency than other types of wind turbines. The stator circuit is connected directly to the grid through a step-up transformer, whereas the rotor circuit is connected to the grid through power electronics circuit via slip rings by a current regulated, voltage-source converter, and step up transformer. This power electronics circuit controls the rotor current magnitude and phase. It allows more variable operation speed range, both above and below synchronous speed ± 50%. The converters offer a wide range of output control that is only 30% of the rating of the machine. Active power is delivered to the grid through the stator circuit via the grid-connected invertor when the generator is running more than the synchronous speed. However, when the generator runs below the synchronous speed, active power flows form the grid, through both converters, and from rotor to stator. This in turn, offers the benefit of more speed range. Also, this adds to its flexible operation feature of active and reactive power control, while being able to run asynchronously [100], [102], [103], [2].

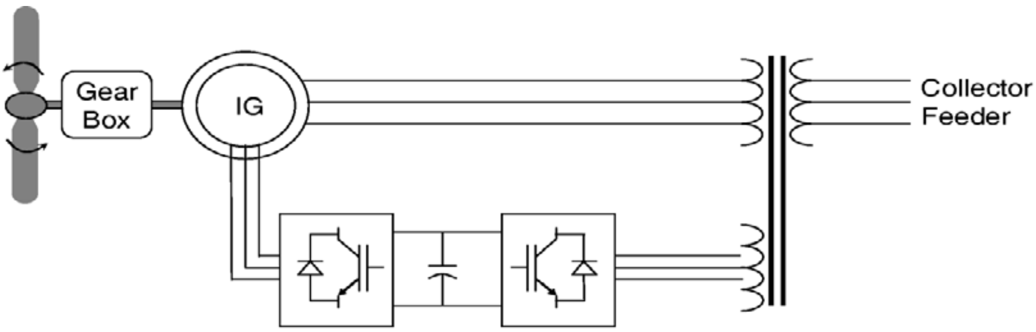

Figure 3.3 Schematic diagram of Type 3 WTG [100]

Type 4: Variable Speed with Full- Scale Frequency Converter

This type provides full variable speed wind turbine, in which is independent from the type of generator equipped. This type could accommodate different types of generators such as wound rotor synchronous machines; as permanent magnet synchronous machines, or as squirrel cage induction machines. The generator is connected to the grid via a full scale frequency converter. The full scale frequency converter enables control of the active and reactive power delivered by the generator to the grid and allows the generator to operate over a wide range of speeds. This type also offers flexible mechanical operation without affecting the electrical operation or efficiency, where the turbine could rotate at its optimal aerodynamic speed that in in return generates fluctuating AC power. Also, the gearbox may be excluded in some wind turbines configurations [100], [101], [104].

Type 5: Variable Speed Synchronous Generator

Type 5 turbines consist of a variable-speed drive connected to a speed/torque converter coupled with a synchronous generator of which is directly connected to the grid via a synchronizing circuit breaker. The speed/torque converter converts the variable speed of the rotor shaft into a constant output shaft speed. The synchronous generator operates at a fixed speed, equivalent to the grid frequency. This system configuration provides a synchronized and a generator protection system; along with the speed and torque control of speed/torque converter and the automatic voltage regulator (AVR), thus enhances the synchronous generator to be designed to the desired speed and voltage [100].

It can be concluded that Type 1 and Type 2 have no voltage control; reactive power compensators; and provide fixed and limited variable speed respectively. Types 1 and 2 are considered as “old fashioned” technologies. These types are unable to contribute in voltage control and therefore considered as not compliant with the grid codes. Consequently, their use in the industry has decreased and their study in research has been out of interest [104]. Though, Types 3, 4, and 5 offer wide range of variable speed; active and reactive power control; and voltage control. This is due to the presence of advanced power electronics in their configuration. Type 3 has taken over in research and industry due to the advantage of the DFIG that it offers which is the independent control of real and active power, while being able to run asynchronously [100], [101]. Also, Type 4 especially the permanent magnet synchronous generator technology started to gain focus on its research and production by large companies such as GE Energy and Vestas Wind Systems [101].

Despite the knowledge of the operating principles of these machines is known, the impact of these machines on the grid at the instance of grid disturbances such as short circuit is still uncertain, and requires more examination. This will facilitate the power system planning and protection design of introducing wind farms comprising these machines, into existing or during implementation of new grids [105] . Power system planning and protection highly depend on the type of wind turbine generator being connected. There various factors that may affect the fault current contribution of wind turbine generators such as: magnetic saturation; deep bar effects; and stator winding connection being wye or delta. Moreover, each of the wind turbine configurations behaves differently during faults. Furthermore, within these different types of wind turbines, manufacturers deploy variation in control, which in turn has an influence on the fault current contribution [106]. The presence of power electronics converters in Type 3 and 4 generators makes the short circuit behaviour more complicated than the Thevenin equivalent representation of synchronous generators [102].

3.4 Short circuit and short circuit currents

Short circuit is a significant parameter in the electrical power systems planning, design and operation. It is also known as faults. Short circuit is a failure in the network which interferes with the normal flow of current. The most common reasons for faults occurrence in power systems are lightning strikes; overhead lines breaking; damage of cables as a result of earth construction works; and internal faults (such as ageing of insulation materials). This ensures that short-circuits cannot be avoided despite cautious planning and design, appropriate regular maintenance and thorough/disciplined operation of the system. Faults often result in the conductors being effectively shorted together or shorted to ground. This leads to the flow of very large current which is called short circuit current, which may cause severe damage to the installed electrical equipment [30], [107].

Effect of short circuit current occurrence on the power system may be [108]:

1) The system components carrying the short circuit current will be subjected to high thermal and mechanical stresses that may not be capable to withstand these abnormal stresses and will be damaged.
2) At fault location, arcing and burning may happen destroying the adjacent components, and may cause an arc-flash burn hazard to personnel working on the equipment.
3) Short-circuit current may flow from the various rotating machines in the electrical power system to the fault location.
4) voltage drop is in proportion to the magnitude of the short-circuit currents flowing through the system elements, in particular at the fault location where the maximum voltage drop happens, however, all other sections of the power system may be subject to a voltage drop to some extent.

Therefore, short circuit currents have a significant impact on the design and operation of equipment of power system.

The short-circuit current is the maximum value of short circuit current that may occur in the system at given location with no fault impacts such as fault arc impedances (that reduce the fault current). The size and capacity of the power sources (such as generators) supplying the system have a direct impact on the short-circuit current. Generally, the greater the capacity of the power sources supplying the system, the larger the short-circuit current [108]. The main factors that identify the magnitude and duration of the short-circuit currents are:

1) The type of fault
2) contribution of fault current sources available
3) The impedances between the sources and the fault location.

3.4.1 Types of fault

The types of fault that may occur in a power system are classified into symmetrical and unsymmetrical faults, also described as balanced and unbalanced faults. Symmetrical faults are faults involving the three-phases. Though, the unsymmetrical faults are faults involving some unbalance as: Line to ground faults, Line-to-Line to ground faults, and Line-to-Line faults.

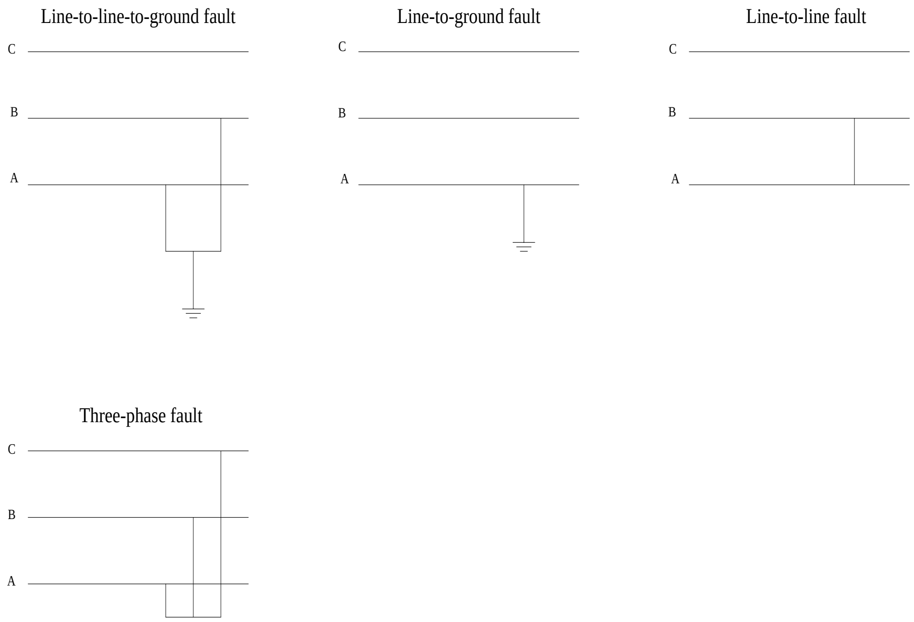

Figure 3.8 Schematic diagrams for type of faults

3.4.1.1 Short circuit level (fault level)

In addition to fault current I_f (in kA), fault MVA is frequently used as a rating and is often referred as the fault level. The fault level is expressed as follows [86]:

$$\text{MVA fault level} = \sqrt{3}V_L I_f \tag{3.1}$$

where, the V_L is the nominal line voltage of the faulted section in kV.

3.4.1.2 Basics of short circuit current calculations

The calculation of the precise magnitude of a short-circuit current at a given time after the occurrence of a fault is considerably complex computation. Simplified methods have been developed that provide conservative calculated short circuit currents that could be compared with the tested short circuit current ratings of protective devices [108].

In this section, a simplified short circuit calculation is presented to provide a basic understanding to further advanced procedures. In order to calculate the short circuit current magnitude at any point of time, an R-L circuit with an ideal sinusoidal voltage source and a switch as shown in Figure 3.9 is considered. The fault is initiated by closure of the switch.

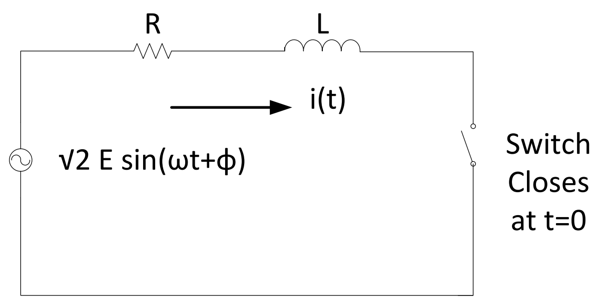

Figure 3.9 R-L circuit model for short circuit current calculation

Assumptions considered are:

1) All machines internal voltages are constant
2) Machines reactances and resistances are constant
3) Saturation effects are ignored
4) Load currents (pre-fault currents) are neglected

The rms value for short circuit current (I) is calculated by this formula [108]:

$$I = \frac{E}{Z} \tag{3.2}$$

where

E rms voltage

Z Is the Thevenin equivalent system impedance from the fault point back to and including the source or sources of short-circuit currents for the distribution system

Though in practice, the short circuit currents magnitudes vary with time. There are two main factors necessary to consider during the calculations of short circuit currents that varies with time [109]:

1) The presence of the DC component
2) The behaviour of rotating machines under short circuit conditions

The rotating machines including synchronous and induction motors, generators, and utility ties are the primary sources of short-circuit currents. All these rotating machines have machine currents that decay considerably with time due to reduction of flux in the machine during a short circuit. During the occurrence of a fault, synchronous and induction motors will perform as generators and will supply current to the fault depending on the amount of stored electrical energy [108].

Consequently, fault levels will vary considerably during a fault, taking into account the rapid drop of the current due to the armature reaction of the synchronous machines and the fact that fault clearance is not instantaneous [109]. The characteristics, locations, and sizes of the fault current sources connected to the distribution system when a fault occurs have an extensive impact on the initial magnitude and the wave shape of the fault current [108]. Therefore, short circuit currents have to be calculated prudently in order to obtain the accurate value for the relevant applications [109].

The calculation of the short circuit current as a function of time involves expansion of Equation (3.2) through the solution of the following differential equation for current i [108]:

$$\mathrm{Ri} + \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} = \sqrt{2}\,\mathrm{E}\sin(\omega\mathrm{t} + \varphi) \tag{3.3}$$

where

E	is the rms magnitude of the sinusoidal voltage source
i	Is the instantaneous current in the circuit at any time after the switch is closed
R	Is the circuit resistance in ohms
L	Is the circuit inductance in Henries
t	Is time in seconds
φ	Is the angle of the applied voltage in radians when the fault occurs
ω	Is the 2πf where f is the system frequency in hertz (Hz)

The solution to Equation 2.3 is where the instantaneous current solution is derived:

$$i = -\frac{\sqrt{2}E}{Z}\sin(\alpha - \varphi)e^{-\frac{\omega t R}{X}} + \frac{\sqrt{2}E}{Z}\sin(\omega t + \alpha - \varphi) \tag{3.4}$$

$$i = -i_{dc}\sin(\alpha - \varphi)e^{-\frac{\omega t R}{X}} + \sqrt{2}\; I_{ac,rms}\sin(\omega t + \alpha - \varphi) \tag{3.5}$$

where

$$\varphi = \tan^{-1}\left(\frac{\omega L}{R}\right) = \tan^{-1}\left(\frac{X}{R}\right) \tag{3.6}$$

$$X = \omega L \tag{3.7}$$

$$Z = \sqrt{R^2 + X^2} \tag{3.8}$$

In Equation 3.4, there are two distinct components of short circuit currents drawn: a) decaying dc component at exponential rate, b) ac component or steady state component.

The presence of the dc component depends on the time on the voltage sinusoidal waveform at which the fault occurs. The dc component adds a further increase on the fault current magnitude during the first few cycles. The dc component disappears eventually with time, in which it decays to zero in one to 30 cycles. The rate of decay depends on the X/R ratio, the higher the X/R ratio, the slower is the decay [108]. Remarkably, the magnitude and duration of the fault current depends on the X/R ratio of the circuit impedance and the phase angle α of the voltage at instance of fault. Also, the difference between the initial fault magnitude and the final steady state fault current magnitude depends on these same parameters [108].

3.4.1.3 Short circuit currents calculations

The calculation of currents that flow when different types of fault occur is a fundamental task carried out at the design of power systems networks [86]. The magnitudes of the fault currents provide the power system engineer the protection current settings to be used and the circuit breakers ratings [86]. Basically, for simple systems up to 6-8 buses, calculations could be performed manually, however, for complex networks with several numbers of buses and significant amount of components, it is more reliable and viable that fault currents are obtained using computer programs [110]. Moreover, these digital calculations provide the advantage of advanced manipulations through considering different study cases scenarios such as applying faults at various points in the network under study. Along with, the capability of modelling the machines in terms of their varying mechanical and electrical parameters in order to study their behaviour during short circuit conditions offers an extraordinary potential [110].

3.4.1.4 Aim and objectives of short circuit studies

1) To determine maximum and minimum three-phase short circuit currents [86]
2) To determine the unsymmetrical fault current (single -line to ground; line-line to ground; line to line faults) [86]
3) To design the fault protection scheme, in order to select the circuit breakers, other switching or protecting devices, and switchgear components ratings and locations. As it should withstand the fault current for short periods and disconnect the faulted system quickly [111]
4) To determine the voltages and the transient performance of the networks under various fault conditions. This is because faults cause drop in voltage, unbalance and loss of stability [111]
5) To select system layout and design [111]

Calculation techniques

The calculation of short circuit currents which are expected to flow in the system under study requires identifying an equivalent circuit for each system element in order to adequately represent its performance under short circuit conditions. The short circuit currents calculations enquire the solving of complex differential equations; hence the use of simplifying techniques is a necessity to ease the calculations, while at the same time obtain accurate results [108]. These techniques are well established, authorized, and recognised to be providing acceptable results for short circuit currents using system parameters and conditions. The most common standards referred to in short circuit analysis are ANSI/IEEE and IEC. These standards are presented in details in chapter 4.

3.5 Summary

In this chapter, an overview of distribution systems has been presented. The penetration of DG into distributed systems has several benefits and implications. Short circuit may influence the protection scheme coordination and reliability due to the reversible flow of power as a result DG integration. Though, short circuit is a fundamental feature that has various causes to occur and different types. It is necessary to obtain accurate short circuit currents during the short circuit studies to ensure reliable and valid selection of protective devices ratings and coordination. Therefore, short circuit analysis is essential for identifying the protective devices ratings and relays settings and coordination to maintain secure fault protection system.

Chapter Four

4 Short Circuit Calculations

4.1 Introduction

There are several authorised standards available to calculate the short circuit currents. These standards include IEC, ANSI, VDE, etc. In this thesis, IEC and ANSI are the standards selected to be used in the investigation. In this chapter, the conceptual techniques and detailed modelling of IEC and ANSI standards for short circuit calculations will be presented. This chapter consists of three main sections: first, short circuit calculation according to IEC standards will be presented; followed by the short circuit calculation according to ANSI standards in second section; and last, the differences in the calculation procedures between the two standards will be tabulated in the third section of this chapter.

4.2 Short circuit calculations according to IEC standards

The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The first edition issued for short circuit calculation was the IEC 909 Standard in 1988. This was a derivative work taken from the German Verband Deutscher Electrotechniker (VDE) Standard. In 2001, a renewed version IEC 60909 has been published and has been acknowledged as the accepted European standard for calculation of symmetrical and unsymmetrical faults [68]. IEC 60909-0 2016 is the most recent edition issued in 2016. This version cancels and replaces the 2001 edition. The major technical changes included with respect to the previous edition are: a) contribution of wind power station units to the short-circuit current; b) contribution of power station units with full size converters to the short-circuit current [112]. This standard applies to all voltages up to 550 kV three-phase systems operating at nominal frequency (50 or 60 Hz).

4.2.1 General characteristic: Definitions and assumptions

There are basic definitions and assumptions considered by the standard shall be demonstrated before discussing the short circuit current calculations.

4.2.1.1 IEC short circuit currents classification

The IEC standard considers four types of duties for the short circuit currents:

Initial symmetrical short circuit current $\left(I_k^{"}\right)$: rms value of the AC symmetrical component of a prospective short-circuit current applicable at the instant of short circuit if the impedance remains at zero-time value

Peak short circuit current (i_P): maximum possible instantaneous value of the prospective short circuit current

Symmetrical short circuit breaking current (I_b): rms value of an integral cycle of the symmetrical AC component of the prospective short circuit current at the instant of contact separation of the first pole to open of a switching device

Steady-state short-circuit current (I_k): rms value of the short-circuit current which remains after the decay of the transient phenomena

There are two different types of impedances considered in the standard: the short-circuit impedances at the short-circuit location F, and the short-circuit impedances of individual electrical equipment.

Basically, the IEC distinguishes between single-fed short circuit, multiple single-fed short circuits and multiple-fed short circuits. Also, this classification is known as non-meshed and meshed networks respectively. The calculation of peak short-circuit current (i_P) depends on the type of network especially in meshed networks, where specific methods shall be applied with adequate accuracy.

Also, IEC distinguishes between two fundamental faults which are ‘Far-from-generator’ and ‘Near-to generator’. In the former, the magnitude of the symmetrical AC component of the prospective short-circuit current remains essentially constant (i.e. have no AC component decay) as shown in Figure 4.1, whereas in the latter, the magnitude of the symmetrical AC component of the prospective short-circuit current decreases with time (i.e. have AC component decay) as shown in Figure 4.2.

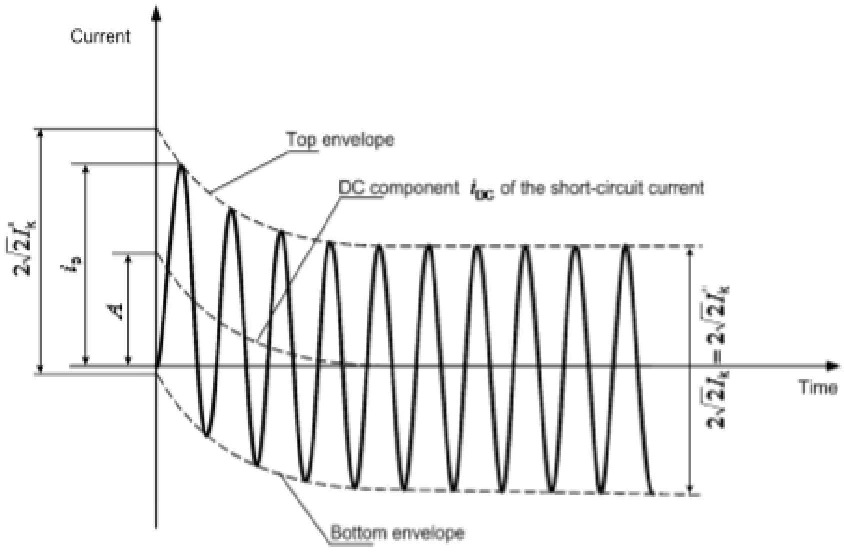

Figure 4.1 - Schematic diagram of short circuit current of a far-from-generator short circuit with constant AC component [112]

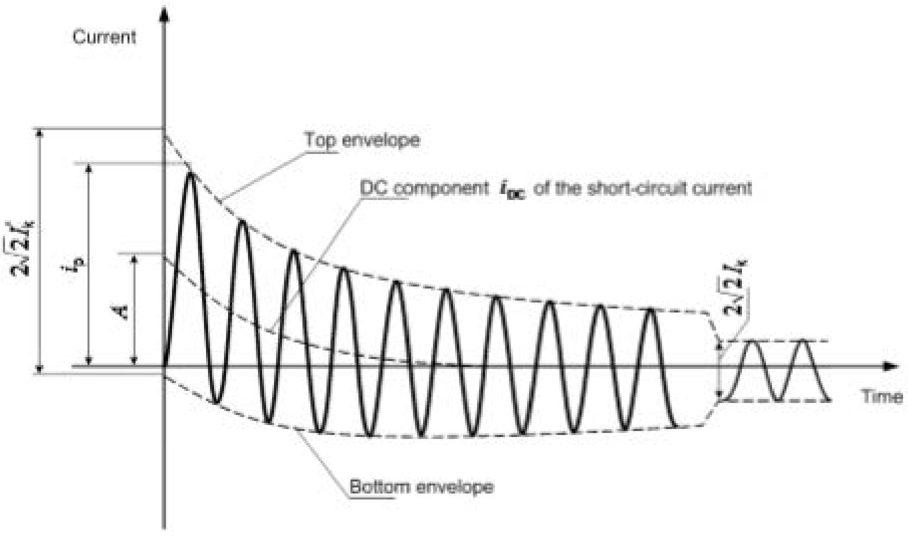

Figure 4.2- Schematic diagram of short circuit current of a near-to-generator short circuit with decaying AC component [112]

4.2.1.2 Equivalent voltage source

The IEC defines an equivalent voltage source as an ideal source applied at the short circuit location for calculating the short circuit current. This equivalent voltage source is the only active voltage of the system, where all other active voltages in the system are short-circuited. All network feeders, synchronous and asynchronous machines are replaced by their internal impedances. Moreover, IEC states that the operational data and the load of consumers, tap-changer position of transformers, and excitation of generators are not essential; hence, additional calculations about all the different possible load flows at the moment of short-circuit are superfluous [112]. This equivalent voltage source is derived as follows:

$$\text{Equivalent voltage source} = \frac{c.U_n}{\sqrt{3}} \tag{4.1}$$

where the c is the voltage factor (depends on system nominal voltage) in table 4.1; U_n is the system nominal voltage.

The voltage factor c considers the differences between the voltage at the short-circuit location and the internal voltage of system feeders, motors and generators due to voltage variations; transformer taps changing; loads and capacitances ignorance during calculations; and subtranasient behaviour of generators and motors. The assumption for considering a voltage factor will result in reliable short-circuit currents, that are higher than in the real power system, though, this will avoid an uneconomic high safety margin [107]. Table 4.1 introduces the voltage factor c values to be considered.

TABLE 4.1: VOLTAGE FACTOR C [112]

Nominal System Voltage U_n	Voltage factor c for the calculation of	
	Maximum short circuit currents c_{max}	Minimum short circuit currents c_{min}
Low voltage 100 V to 1 000 V voltage tolerance of ±6 % voltage tolerance of ±10 %	1.05 1.10	0.95 0.9
High voltage > 1 kV to 230 kV > 230kV	1.10	1.0

Remark: c_{max}Un should not exceed the highest voltage Um for equipment of power systems as per IEC 60909-0 2016 standard

4.2.1.3 Maximum and minimum short circuit currents

The IEC standard distinguishes between maximum short-circuit currents and minimum short-circuit currents, in which the former is responsible for the rating of equipment regarding mechanical and thermal stresses, whereas the latter has to be calculated for the selection of the system protection such as selection of fuses [112]. Table 4.2 provides an overview of the IEC standard classification for the short circuit currents and types of failures that have to be considered.

TABLE 4.2: IEC STANDARD CLASSIFICATION FOR THE SHORT CIRCUIT CURRENTS AND TYPES OF FAILURE [112]

Short circuit currents	Equipment	Relevant Currents		
		K3	K2	K1
Maximum currents Stress:				
Dynamic	Components of installations	i_p	i_p	-
Switching on	Switching devices	i_p	-	i_p
Switching off	Switching devices	I_b	-	I_b
Thermal	Components of installations, lines	I_{th}	-	I_{th}
Minimum currents				
Tripping of relays	Protection	-	I_k'', I_k	I_k'', I_k

I_{th}-Thermal equivalent short-circuit current; k1- Line-to-earth short circuit, line-to-neutral short circuit; k2- Line-to-line short circuit; k3-Three-phase short circuit

4.2.1.4 Calculation assumptions

The IEC standard takes the following assumptions for the calculation of maximum and minimum short-circuit currents [112]:

a) For the duration of the short circuit, there is no change neither in the type of short circuit nor the network involved, where a three-phase short-circuit remains three-phase and a line-to-earth short circuit remains line-to-earth during the time of short circuit.
b) The impedance of the transformers is referred to the tap-changer in main position.
c) Arc resistances are neglected.
d) Shunt admittances of non-rotating loads shall be neglected in the positive-, the negative- and the zero-sequence system.

e) Line capacitances shall be neglected in the positive- and negative-sequence system. Line capacitances in the zero-sequence system shall be taken into account in low-impedance earthed networks.

f) Magnetising admittances of transformers shall be neglected in the positive- and negative sequence system.

4.2.1.5 Calculation conditions

The IEC states that the following conditions shall be applied when calculating maximum and minimum short circuit currents [112].

Conditions for maximum short circuit currents calculations

a) Voltage factor C_{max} shall be applied in the absence of a national standard.

b) Select the system configuration and the maximum contribution from power station units and network feeders which lead to the maximum value of short-circuit current at the short circuit location

c) Impedance correction factors shall be introduced in the positive-, the negative- and the zero-sequence system with exception of the impedances between neutral point and earth.

d) When equivalent impedances Z_Q are used to represent external networks, the minimum equivalent short-circuit impedance shall be used which corresponds to the maximum short-circuit current contribution from the network feeders.

e) Motors shall be included

f) Resistance R_L of lines (overhead lines and cables) shall be introduced at a temperature of 20 °C.

Conditions for minimum short-circuit currents calculations

a) Voltage factor C_{min} shall be applied.

b) Choose the system configuration and the minimum contribution from power station units and network feeders which lead to a minimum value of short-circuit current at the short circuit location.

c) The impedance correction factors are equal to 1.

d) Contributions of wind power stations units shall be neglected.

e) Contributions of photovoltaic power station units shall be neglected.

f) Contributions of motors shall be neglected.

g) Resistances R_L of lines (overhead lines and cables, line conductors, and neutral conductors) shall be introduced at a higher temperature.

4.2.2 Calculation of initial short circuit current

4.2.2.1 Three-phase short circuit current ($\mathbf{I_k^{"}}$)

$$I_k^{"} = \frac{c\,U_n}{\sqrt{3}\,Z_k} = \frac{c\,U_n}{\sqrt{3}\sqrt{R_k^2 + X_k^2}} \tag{4.2}$$

where Z_k is the short-circuit impedance

The short-circuit impedance can be obtained by the network reduction or from the diagonal element of the nodal impedance matrix of the positive sequence system for the point where the short circuit.

4.2.2.2 Line-to-line short circuit ($\mathbf{I_{k2}^{"}}$)

$$I_{k2}^{"} = \frac{\sqrt{3}}{\left|\underline{Z}_{(1)} + \underline{Z}_{(2)}\right|}\frac{c\,U_n}{\sqrt{3}} \tag{4.3}$$

If $\underline{Z}_{(2)} = \underline{Z}_{(1)}$, then the formula becomes

$$I_{k2}^{"} = \frac{\sqrt{3}}{2} I_k^{"} \tag{4.4}$$

4.2.2.3 Line-to-line short circuit with earth connection

Initial symmetrical line two (L2) short circuit current with earth connection

$$I_{k2EL2}^{"} = \left|\frac{\sqrt{3}\left(\underline{Z}_0 - a\underline{Z}_{(2)}\right)}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}}\right|\frac{c\,U_n}{\sqrt{3}} \tag{4.5}$$

$$I_{k2EL3}^{"} = \left|\frac{\sqrt{3}\left(\underline{Z}_0 - a^2\underline{Z}_{(2)}\right)}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}}\right|\frac{c\,U_n}{\sqrt{3}} \tag{4.6}$$

$$I_{kE2E}^{"} = \left|\frac{3\underline{Z}_{(2)}}{\underline{Z}_{(1)}\underline{Z}_{(2)} + \underline{Z}_{(1)}\underline{Z}_{(0)} + \underline{Z}_{(2)}\underline{Z}_{(0)}}\right|\frac{c\,U_n}{\sqrt{3}} \tag{4.7}$$

4.2.2.4 Line-to-earth short circuit ($\mathbf{I_{k1}^{"}}$)

$$I_{k1}^{"} = \frac{3}{\left|\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)}\right|}\frac{c\,U_n}{\sqrt{3}} \tag{4.8}$$

4.2.2.5 Contribution of power stations with full size converter

If power stations with full size converter are to be considered then the maximum initial short circuit currents are to be calculated. The IEC adds the sum of the contributions of the wind power station units to the initial short circuit current, to the maximum initial symmetrical short-circuit current calculated without the contribution of the source currents of the power stations with full size converter.

Maximum initial Three-phase short circuit current ($\mathbf{I}^{"}_{\mathbf{kmax}}$)

$$I^{"}_{\mathrm{kmax}} = \frac{1}{Z_{\mathrm{k}}} \frac{c_{\mathrm{max}} U_{\mathrm{n}}}{\sqrt{3}} + \frac{1}{Z_{\mathrm{k}}} \sum_{j=1}^{n} Z_{ij} . I_{\mathrm{skPF}j} = I^{"}_{\mathrm{kmaxPFO}} + I^{"}_{\mathrm{kPF}} \tag{4.9}$$

where

I_{skPFj} is the rms value of the maximum source current (positive-sequence system) in case of three-phase short-circuit at the high-voltage side of the unit transformer, given by the manufacturer;

Z_{ii}, Z_{ij} are the absolute values of the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected;

$I^{"}_{\mathrm{kmaxPFO}}$ is the maximum initial symmetrical short-circuit current without the influence of power station units with full size converter;

$I^{"}_{\mathrm{kPF}}$ is the sum of the contributions of power station units with full size converter to the initial short-circuit current.

Maximum initial Line-to-line short circuit ($\mathbf{I}^{"}_{\mathbf{k2max}}$)

$$\begin{aligned} I^{"}_{\mathrm{k2max}} &= \frac{\sqrt{3}}{\left|\underline{Z}_{(1)\mathrm{ii}} + \underline{Z}_{(2)\mathrm{ii}}\right|} \frac{c_{\mathrm{max}} U_{\mathrm{n}}}{\sqrt{3}} \\ &+ \frac{\sqrt{3}}{\left|\underline{Z}_{(1)\mathrm{ii}} + \underline{Z}_{(2)\mathrm{ii}}\right|} \sum_{\mathrm{j}=1}^{\mathrm{n}} Z_{(1)\mathrm{ij}} . I_{(1)\mathrm{sk2PFj}} \\ &= I^{"}_{\mathrm{k2maxPFO}} + I^{"}_{\mathrm{k2PF}} \end{aligned} \tag{4.10}$$

where

$I_{(1)sk2PFj}$ is the rms value of the maximum source current (positive-sequence system) in case of a line-to-line short circuit at the high-voltage side of the unit transformer, given by the manufacturer;

$\underline{Z}_{(1)ii} = \underline{Z}_{ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the positive sequence system, where *i* is the short-circuit node;

$\underline{Z}_{(2)ii}$ is the i^{th} diagonal element of the nodal impedance matrix of the negative sequence system including the impedances of the power station units with full size converter, where *i* is the short-circuit node;

$\underline{Z}_{(1)ij} = \underline{Z}_{ij}$ are the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected;

$I''_{k2maxPFO}$ is the maximum initial symmetrical short-circuit current calculated by the equivalent voltage source at the short-circuit location without influence of the source currents of the power station units with full size converter;

I''_{k2PF} is the sum of the contributions of power station units with full size converter to the initial short-circuit current.

Maximum initial Line-to-line short circuit with earth connection

$$I''_{k2EL2max} = \left| \frac{\sqrt{3}\left(\underline{Z}_{(0)ii} - a\underline{Z}_{(2)ii}\right)}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}} \right| \cdot \left(\frac{c_{max}\,U_n}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij} . I_{(1)sk2PFj} \right) = I''_{k2EL2maxPFO} + I''_{k2EL2PF} \quad (4.11)$$

$$I''_{k2EL3max} = \left|\frac{\sqrt{3}\left(\underline{Z}_{(0)ii} - a^2\underline{Z}_{(2)ii}\right)}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}}\right| \cdot \left(\frac{c_{max}\,U_n}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij}.\,I_{(1)sk2PFj}\right) = I''_{k2EL3maxPFO} + I''_{k2EL3PF} \tag{4.12}$$

$$I''_{kE2Emax} = \left|\frac{3\underline{Z}_{(2)ii}}{\underline{Z}_{(1)ii}\underline{Z}_{(2)ii} + \underline{Z}_{(1)ii}\underline{Z}_{(0)ii} + \underline{Z}_{(2)ii}\underline{Z}_{(0)ii}}\right| \cdot \left(\frac{c_{max}\,U_n}{\sqrt{3}} + \sum_{j=1}^{n} Z_{(1)ij}.\,I_{(1)sk2PFj}\right) = I''_{k2E2maxPFO} + I''_{kE2EPF} \tag{4.13}$$

where

$I_{(1)sk2PFj}$	is the rms value of the maximum source current (positive-sequence system) in case of a line-to-line short circuit at the high-voltage side of the unit transformer, given by the manufacturer;
$\underline{Z}_{(1)ii} = \underline{Z}_{ii}$	is the ith diagonal element of the nodal impedance matrix of the positive sequence system, where *i* is the short-circuit node;
$\underline{Z}_{(2)ii}$	is the ith diagonal element of the nodal impedance matrix of the negative sequence system including the impedances of the power station units with full size converter, where i is the short-circuit node;
$\underline{Z}_{(0)ii}$	is the ith diagonal element of the nodal impedance matrix of the zero-sequence system, where *i* is the short-circuit node;
$\underline{Z}_{(1)ij}=\underline{Z}_{ij}$	are the elements of the nodal impedance matrix of the positive-sequence system, where *i* is the short-circuit node and j are the nodes where power station units with full size converters are connected.

Maximum initial Line-to-earth short circuit

$$I''_{\mathrm{k1max}} = \frac{3}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii} + \underline{Z}_{(0)ii}\right|}\frac{c_{\mathrm{max}}U_{\mathrm{n}}}{\sqrt{3}} + \frac{3}{\left|\underline{Z}_{(1)ii} + \underline{Z}_{(2)ii} + \underline{Z}_{(0)ii}\right|}\sum_{j=1}^{n} Z_{(1)ij}.I_{(1)\mathrm{sk1PF}j} = I''_{\mathrm{k1maxPFO}} + I''_{\mathrm{k1PF}} \tag{4.14}$$

where

$I_{(1)\mathrm{sk1PFj}}$ is the rms value of the maximum source current (positive-sequence system) in case of a line-to-earth short circuit at the high-voltage side of the unit transformer, given by the manufacturer;

$\underline{Z}_{(1)\mathrm{ii}} = \underline{Z}_{\mathrm{ii}}$ is the i$^{\mathrm{th}}$ diagonal element of the nodal impedance matrix of the positive sequence system, where *i* is the short-circuit node;

$\underline{Z}_{(2)\mathrm{ii}}$ is the i$^{\mathrm{th}}$ diagonal element of the nodal impedance matrix of the negative sequence system including the impedances of the power station units with full size converter, where *i* is the short-circuit node;

$\underline{Z}_{(0)\mathrm{ii}}$ is the i$^{\mathrm{th}}$ diagonal element of the nodal impedance matrix of the zero-sequence system, where *i* is the short-circuit node;

$\underline{Z}_{(1)\mathrm{ij}}=\underline{Z}_{\mathrm{ij}}$ are the elements of the nodal impedance matrix of the positive-sequence system, where i is the short-circuit node and j are the nodes where power station units with full size converters are connected.

I''_{k1maxPFO} is the maximum initial symmetrical short-circuit current calculated by the equivalent voltage source at the short-circuit location without influence of the source currents of the power station units with full size converter;

I''_{k1PF} is the sum of the contributions of wind power station units with full size converter to the initial short-circuit current.

4.2.3 Calculation of peak short-circuit current

IEC 60909-0 2016 recommends that for identifying the peak short-circuit current, the initial symmetrical short-circuit current shall first be calculated considering that there are no fuses or current-limiting circuit-breakers to protect the substations, despite the fact that these protection equipment are existing. Afterwards, from the calculated initial symmetrical short-circuit current and characteristic curves of the fuses or current-limiting circuit-breakers, the peak short-circuit current (cut-off current) is determined [112].

4.2.3.1 Three-phase short circuit

For single-fed and multiple single-fed short circuits

$$i_p = \kappa\sqrt{2}\, I_k'' \tag{4.15}$$

where the factor κ can be obtained from the curves or calculated from the following expression

$$\kappa = 1.02 + 0.98e^{-3R/X} \tag{4.16}$$

For contribution of one power station unit with full size, the peak-short circuit current is calculated as follows:

$$i_p = \sqrt{2}\, I_{kPF}'' = \sqrt{2}\, I_{skPF} \tag{4.17}$$

The peak short circuit current i_p at the short-circuit location F that is considered fed from multiple single source, is the sum of the partial short-circuit currents.

$$i_p = \sum i_{pi} \tag{4.18}$$

For multiple-fed short circuit

$$i_p = \kappa\sqrt{2}\, I_{kmaxPFO}'' + \sqrt{2}\, I_{kPF}'' \tag{4.19}$$

where

$I_{kmaxPFO}''$ is the maximum initial three-phase short-circuit current without influence of power station units with full size converter calculated by Formula (4.2);

I''_{kPF} is the contribution of the power station units with full size converter calculated by Formula (4.9).

The κ factor is computed by the same formula (4.16), adopting one of the three following methods (A, B, and C) for identifying the R/X ratio. However, the IEC highly recommends method C.

Method A: Uniform R/X or X/R

The smallest ratio of R/X or the largest ratio of X/R of all branches of the network is considered. It is essential to select only the branches which carry partial short-circuit currents at the nominal voltage corresponding to the short-circuit location and branches with transformers feeding the voltage level of the short-circuit location. Any branch may be a series combination of several impedances [112].

Method B: Ratio R/X or X/R at the short-circuit location

For this method, the ratio $1.15\ R_k/X_k$ is used, where the R_k/X_k ratio is derived from the short-circuit impedance $\underline{Z}_k = R_k + jX_k$ as computed for the initial short-circuit calculation; and the 1.15 factor is a safety factor to cover an inaccuracies caused from the meshed network complex impedances reduction. In low voltage networks the value of $1.15\ R_k/X_k$ is limited to 1.8 and in high voltage networks to 2.0. It is not essential to use to 1.15 safety factor if the R/X ratio remains smaller than 0.3 in all branches which carry a short-circuit current [112].

Method C: Equivalent Frequency f_c

This method adopts the equivalent frequency approach. Equivalent impedance $Z_c = R_c + jX_c$ is calculated assuming a source of 20Hz for 50 Hz systems and 24 Hz systems to excite the network at the fault location. Then, the R/X ratio at the fault is determined as follow [112]:

$$\frac{R}{X} = \frac{R_c}{X_c} * \frac{f_c}{f} \tag{4.20}$$

where

$Z_c = R_c + jX_c$	is the equivalent impedance of the system as seen from the short-circuit location for the assumed frequency f_c;
R_c	is the real part of Z_c (R_c is generally not equal to the R at nominal frequency);
X_c	is the imaginary part of Z_c (X_c is generally not equal to the X at nominal frequency).

For a network with power station units with full size converter, the peak short-circuit current can be expressed as follows:

4.2.3.2 Line-to-line short circuit

$$i_{p2} = \kappa\sqrt{2}\, I''_{k2maxPFO} + \sqrt{2}\, I''_{k2PF} \tag{4.21}$$

where

$I''_{k2maxPFO}$	is the maximum initial line-to-line short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (4.10);
I''_{k2PF}	is the contribution of the power station units with full size converter calculated according to Formula (4.10).

4.2.3.3 Line-to-line short circuit with earth connection

$$i_{p2EL2} = \kappa\sqrt{2}\, I''_{k2EL2maxPFO} + \sqrt{2}\, I''_{k2EL2PF} \tag{4.22}$$

where

$I''_{k2EL2maxPFO}$	is the maximum initial line-to-line short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (4.11);
$I''_{k2EL2PF}$	is the contribution of the power station units with full size converter calculated according to Formula (4.11).

4.2.3.4 Line-to-earth short circuit

$$i_{p1} = \kappa\sqrt{2}\, I''_{k1maxPFO} + \sqrt{2}\, I''_{k1PF} \quad (4.23)$$

where

$I''_{k1maxPFO}$ is the maximum initial line-to-earth short-circuit current without influence of the source currents of power station units with full size converter calculated according to Formula (4.14);

I''_{k1PF} is the contribution of the power station units with full size converter calculated according to Formula (4.14).

4.2.4 Calculation of symmetrical breaking current ($\boldsymbol{I_b}$)

4.2.4.1 Three-phase symmetrical breaking current

In case of multiple fed sources, far from generator faults, the symmetrical breaking current I_b is assumed to be equal the maximum initial symmetrical current I''_{kmax}

$$I_b = I''_{kmax} \quad (4.24)$$

Similarly, the symmetrical breaking current of power station units with full size converter can be assumed to be equal the steady state short-circuit current (I_{kPFmax}), in which the I_{kPFmax} is provided by the manufacturer.

$$I_b = I_{kPFmax} \quad (4.25)$$

For multiple single fed short circuits, the I_b is computed by the summation of individual breaking currents contributions:

$$I_b = \sum_i I_{bi} \quad (4.26)$$

Symmetrical breaking currents of synchronous and asynchronous machines

In case of near-to generator, multiple fed short circuits, the symmetrical breaking currents of synchronous and asynchronous machines are respectively given by

$$I_b = \mu \, I''_{kmax} \tag{4.27}$$

$$I_b = \mu q \, I''_{kmax} \tag{4.28}$$

The factor μ depends on the minimum time delay t_{min} and is a function of the ratio I''_{kG}/I_{rG} for the synchronous machines, and I''_{kM}/I_{rM} for the asynchronous machines; where I_{rG} and I_{rM} are the rated currents of the synchronous and asynchronous machines respectively. Similarly, the factor q depends on the minimum time delay t_{min}, hence, is a function of the ratio P_{rM}/p, where the P_{rM} is the rated active power in MW and p is the number of pairs of poles of the asynchronous machine. Both factors have specific formulas and diagrams in the IEC standard.

4.2.4.2 For unbalanced short-circuits

The short-circuit breaking current is assumed to be equal to the maximum initial short-circuit currents:

$$I_{b2} = I''_{k2max} \tag{4.29}$$

4.2.4.3 Line-to-line short circuit with earth connection

$$I_{b2E} = I''_{k2Emax} \tag{4.30}$$

4.2.4.4 Line-to-earth short circuit

$$I_{b1} = I''_{k1max} \tag{4.31}$$

4.2.5 Calculation of steady state short-circuit current ($\mathbf{I_k}$)

4.2.5.1 Near-to-generator three-phase short circuits

Contribution of synchronous machines on I_k depends on the excitation system, the voltage regulator action, and saturation influences, along with the presence of an impedance between the terminals of the machine and the short-circuit location.

Maximum steady-state short circuit current of synchronous machines is calculated as follows:

$$I_{kmax} = \lambda_{max} I_{rG} \tag{4.32}$$

where λ_{max} is a factor that is determined graphically from graphs provided in the IEC standard.

4.2.5.2 Far from generator short circuit,

$$I_k = I_k'' \tag{4.33}$$

4.2.5.3 For unbalanced short-circuits

The steady-state short circuit current is assumed to be equal to the initial short-circuit currents:

$$I_{k2} = I_{k2}'' \tag{4.34}$$

4.2.5.4 Line-to-line short circuit with earth connection

$$I_{k2E} = I_{k2E}'' \tag{4.35}$$

4.2.5.5 Line-to-earth short circuit

$$I_{k1} = I_{k1}'' \tag{4.36}$$

4.3 Short circuit calculations according to ANSI/IEEE standards

The American National Standard Institute (ANSI) standard is a guideline for short circuit calculations for selection of equipment rating (circuit breakers) for electrical networks. This includes C37.010 for systems of nominal voltage above 1 kV, and C37.13 for systems below 1 kV [113], [114]. ANSI methods of short circuit calculations are commonly used all over North America and are widely accepted in many other countries worldwide. All equipment manufactured in the United States or exported to be used in the United States has been meeting or designed according to the ANSI standards requirements.

4.3.1 Basic assumptions considered are:

An equivalent voltage source at the fault location, which equals the prefault voltage at the location, replaces all external voltage sources and machine internal voltage sources [115].

All machines are represented by their internal impedances. Line capacitances and static loads are neglected. Transformer taps can be set at either the nominal position or at the tapped position [115]. For 3-phase fault, the fault is bolted, which in turn, arc resistances are not considered [115].

There are three different impedance networks created to calculate momentary, interrupting, and steady-state short circuit currents. These networks are: ½ cycle network (subtransient network), 1.5-4 cycle network (transient network), and 30 cycle network (steady-state network) respectively. The ½ cycle network is referred to as subtransient network due to the representation of all rotating machines are represented by their subtransient reactance. Similarly, this primarily reason applies for 1.5-4 cycle network and 30 cycle network respectively [115]. Table 4.3 represents the rotating machines reactances considered by the ANSI/IEEE standards for the three different cycle networks.

TABLE 4.3: CLASSIFICATION OF ROTATING MACHINES REACTANCES [115]

Source type	½ cycle network	1.5-4 cycle network	30 cycle network
Utility	X''	X''	X''
Turbo generator	X''_d	X''_d	X'_d
Hydro-generators			
With damper	X''_d	X''_d	X'_d
Without damper	$0.75\ X'_d$	$0.75\ X'_d$	X'_d
Condenser	X''_d	X''_d	-
Synchronous motor	X''_d	$1.5\ X''_d$	-
Induction Machines			
Above 1000HP, 1800r/min or less	X''_d	$1.5\ X''_d$	-
Above 250HP, 3600 r/min	X''_d	$1.5\ X''_d$	-
All other above 50 HP	$1.2\ X''_d$	$3.0\ X''_d$	-
Below 50 HP	$1.67\ X''_d$	-	-

X''_d is the positive sequence subtransient reactance of a synchronous machine or locked-rotor reactance of an induction machine ; X'_d is the positive sequence transient reactance of a synchronous machine

ANSI/IEEE Standards recommend the use of separate R and X networks to calculate R/X values. An R/X ratio is obtained for each individual faulted bus and short circuit current. This R/X ratio is then used to determine the multiplying factor to account for the system DC offset [115].

In the cases of calculating the asymmetrical value of momentary and interrupting short circuit currents, through using the ½ cycle and 1.5-4 cycle networks respectively, the symmetrical rms value of the momentary and interrupting short circuit currents are initially determined, and then these values are multiplied by the relevant multiplying factors [115].

4.3.2 Types of calculations

ANSI standard classifies three basic types of short circuit currents, in which these are associated with three different time periods.

4.3.2.1 Calculation of the "first cycle" current

This represent the maximum value of the short circuit current up to and including one cycle immediately after the occurrence of fault, before its AC and DC components decay towards the steady-state value [108], [115]. This type of short circuit current is relevant to and referred to as "momentary" or "closing and latching" duties. Moreover, ETAP has a different identification to this type of current which is referred to as "½ cycle". The ETAP performs 3-phase, line-to-ground, line-to-line, and line-to-line-to-ground fault studies to calculate the short circuit currents in their rms values at ½ cycle at the faulted buses. The values of short circuit currents computed by this method are applicable for several purposes such as sizing of fuses and low-voltage circuit breakers, and adjusting relay instantaneous settings.

The following procedure to calculate the momentary short circuit current [115]:

Calculates the symmetrical rms value of momentary short circuit current as provided

$$\mathrm{I_{mom,rms,symm}} = \frac{\mathrm{V_{pre-fault}}}{\sqrt{3}\,\mathrm{Z_{eq}}} \tag{4.37}$$

where the $\mathrm{Z_{eq}}$ is the equivalent impedance at the faulted bus from the ½ cycle network

Calculates the asymmetrical rms value of momentary short-circuit current as follows

$$I_{mom,rms,asymm} = MF_m I_{mom,rms,symm} \quad (4.38)$$

where MF_m is the momentary multiplying factor, given as

$$MF_m = \sqrt{1 + 2e^{-\frac{2\pi}{X/R}}} \quad (4.39)$$

Calculates the peak value of momentary short-circuit current as follows:

$$I_{mom,peak} = MF_p I_{mom,rms,symm} \quad (4.40)$$

where the MF_p is the peak multiplying factor, given as

$$MF_p = \sqrt{2}\,(1 + e^{-\frac{2\pi}{X/R}}) \quad (4.41)$$

It is to be noted that the generators and motors are represented by their positive, negative, and zero sequence subtransient reactance.

4.3.2.2 Calculation of the interrupting current

This represents the breaking current for medium and high-voltage circuit breaker parting times, relevant for the time period ranging from 1.5 to 4 cycles. ETAP perform 3-phase, line-to-ground, line-to-line, and line-to-line-to-ground fault studies to calculate short circuit currents in their rms values between 1.5 to 4 cycles at faulted buses. Generators are modelled by their positive, negative, and zero sequence subtransient reactance, and motors are modelled by their positive, negative, and zero sequence transient reactance.

The following procedure to calculate the interrupting short circuit current:

Calculates the symmetrical rms value of the interrupting short circuit current as provided:

$$I_{int,rms,symm} = \frac{V_{pre-fault}}{\sqrt{3}\,Z_{eq}} \tag{4.42}$$

where the Z_{eq} is the equivalent impedance at the faulted bus from the 1.5-4 cycle network

Calculate the short circuit current contributions to the fault location from the surrounding buses.

The ANSI/IEEE standard distinguishes between generating sources contribution to short circuit currents depending on location, denoted as either remote or local sources.

Fault fed from remote sources

It is considered a remote source contribution to a short circuit current when the short circuit current is fed from generator through two or more transformations, or with a per unit reactance external to the generator that is equal to or exceed 1.5 times the generator per unit subtransient reactance on a common MVA base. Hence, the effect of ac decay is not considered [110].

The symmetrical value is corrected by the multiplying factor of MF_r, where the factor MF_r can be manipulated from standard figures available in ANSI/IEEE C37.010 for several typical contact parting times, though these figures only for half cycle tripping decay(low contact parting time). For higher contact parting time, the remote contributions multiplying factor is calculated as follows:

$$MF_r = \sqrt{1 + 2e^{-\frac{4\pi}{X/R}t}} \tag{4.43}$$

where t is the circuit breaker contact parting time in cycles

Fault fed from local sources

It is considered local source contribution, when the short circuit current is fed from generators through no more than one transformation, or with a per unit external reactance in series to the generator, which is less than 1.5 times the generator subtransient reactance. Thus, the effect of ac and dc decays is considered.

The symmetrical value is corrected by the factor of $\mathrm{MF_l}$. The determination of local contributions multiplying factor is similar to the $\mathrm{MF_r}$ obtained from curves available in ref. [108].

For a system with several short circuit sources, determine the total remote contributions and total local contribution, through the NACD ratio

No AC Decay (NACD) ratio

The NACD ratio is defined as “the remote contributions to the total contributions for the short circuit current at a given location” [115]

It is calculated in ETAP as follows:

$$\mathrm{NACD} = \frac{\mathrm{I_{remote}}}{\mathrm{I_{total}}} \tag{4.44}$$

where,

$$\mathrm{I_{total}} = \mathrm{I_{remote}} + \mathrm{I_{local}} \tag{4.45}$$

Calculate the actual multiplying factor ($\mathrm{AMF_i}$)

$$\mathrm{AMF_i} = \mathrm{MF_l} + \mathrm{NACD}(\mathrm{MF_r} - \mathrm{MF_l}) \tag{4.46}$$

Determine the adjusted rms interrupting short-circuit current using the following formula

$$\mathrm{I_{int,rms,adj}} = \mathrm{AMF_i I_{int,rms,symm}} \tag{4.47}$$

4.3.2.3 Calculation of the steady state short circuit currents

These represent the short circuit currents after 30 cycles and beyond from the moment of fault occurrence. These currents are also called time-delayed currents; this is relevant to the duration after the opening time of medium voltage circuit-breaker, despite the intentional time delay [108].

ETAP perform 3-phase, line-to-ground, line-to-line, and line-to-line-to-ground fault studies to calculate short circuit currents in their rms values at 30 cycles at faulted buses, which are considered the minimum short-circuit current values.

Generators are modelled by their positive, negative, and zero sequence reactance, and short circuit current contributions from induction machines, synchronous motors, and condensers are ignored [115].

4.4 ANSI/IEEE standard vs IEC standard

Basically, ANSI and IEC standards were developed to provide conservative results through detailed techniques for the short circuit current calculations for the determination of protection equipment ratings. Despite the same aims and objectives of the two standards, there are rarely common similarities between ANSI and IEC standards for the short circuit calculations. Both standards recognize the principal figure representing the short circuit current against the time, the rapid dc decay, and the ac component decay, though the AC and DC decays modellings are different. It is generally described that the IEC standard is a correction factors based calculation, whereas the ANSI standard is an impedance based calculation [113]. The IEC requires the calculation of the symmetrical initial current in order to calculate the other types of short circuit currents, and applies correction factors. However, ANSI is concerned with type of reactance considered for the calculation of each short circuit current. The main differences between the two counterparts methods are provided as follows in Table 4.4.

TABLE 4.4: COMPARISON BETWEEN IEC STANDARD AND ANSI STANDARD

Characteristic	IEC	ANSI
System Frequency	50 or 60 Hz	60 Hz
Voltage Source	Equivalent voltage source, function of the system nominal voltage multiplied by c factor, depending on the system voltage level	Rated system voltage
Network Configuration	Classified into meshed and non-meshed networks, where certain multiplying factors and X/R ratios are selected accordingly	Classified into three fault cycles networks to be selected depending on the purpose of the calculation: ½ network; 1.5-4cycle network; 30 cycle network
Equipment Impedances	the network equipment impedances (generators, transformers, and power station units) are multiplied by correction factors	The machines impedances are categorized into transient and subtransient.
Location of rotating machines	Near and far sources Location of the rotating equipment from the fault point is significant for the breaking and steady state short circuit currents calculations	Remote and local sources Location of the generator is considered only if there are two transformers between the fault location and the generator or if the transfer (in between the fault location and the generator) reactance is 1.5 times greater than the generator reactance. Otherwise, it is considered local.
SC Current calculation methodology	The contribution of sc currents from each source is calculated ; and then the superposition is applied to calculate the total sc current	Applies Thevinin method where the network impedance is reduced and finally calculates the sc current

4.5 Summary

In this chapter, the IEC and ANSI standards procedures for short circuit calculations have been presented. The main conceptual differences between IEC and ANSI have been described. Both procedures provide detailed modelling for the short circuit calculations, however, IEC requires more detailed power system data to be available than ANSI. The ANSI standard is concerned with the machines impedances, where multiplying factors are applied to ensure secure reliable results. The IEC standard is concerned with the initial short circuit current contribution of each source separately. Moreover, IEC distinguishes between the radial and loop network contribution, while ANSI does not consider this issue. IEC differentiates in the calculations between the sources location near or far from the short circuit point; however, ANSI only considers the generator to be remote or local depending on the transformation impedance value between the generator and the short circuit location.

Chapter Five

5 IEEE 13 Bus Distribution Test System

5.1 Introduction

In this chapter, the main objective is to analyse the simulated results for the ANSI and IEC calculations. The analysis aim is to assess the impact of DG type, location and penetration level on the short circuit current of the distribution system under study. The short circuit currents magnitudes of the system under study with no DG connected are considered as reference inorder to be able to assess the impact of DG integration. Moreover, a comparison between the IEC simulated results and ANSI simulated results will be presented inorder to ensure valid and reliable results. Also, it is necessary to distinguish the competence between the two methods for short circuit calculations.

This chapter is divided into seven main sections. First, section 5.1 is an introduction and outline to the chapter. Section 5.2 will provide the main characteristics for the system under study. Section 5.3 will illustrate the case studies examined. Section 5.4 will present the ANSI simulated results and comprehensive analysis to the results. Similarly, section 5.5 will present and provide detailed analysis to the IEC simulated results. Section 5.6 will compare between the IEC and ANSI simulated results. Last, section 5.7 will provide a conclusion and recommendations.

5.2 System under study

The distribution test system used in this study is the IEEE 13-bus. The single line diagram is shown in Figure 5.1. The system elements full data are provided in Appendix A. This system is described as small test feeder operating at 4.16 kV; however, it displays wide variety of components and characteristics that include:

1. Short and relatively highly loaded for a 4.16 kV feeder

2. One substation voltage regulator consisting of three single-phase units connected in wye

3. Overhead and underground lines with variety of phasing

4. Shunt capacitor banks

5. In-line transformer

6. Unbalanced spot and distributed loads [116]

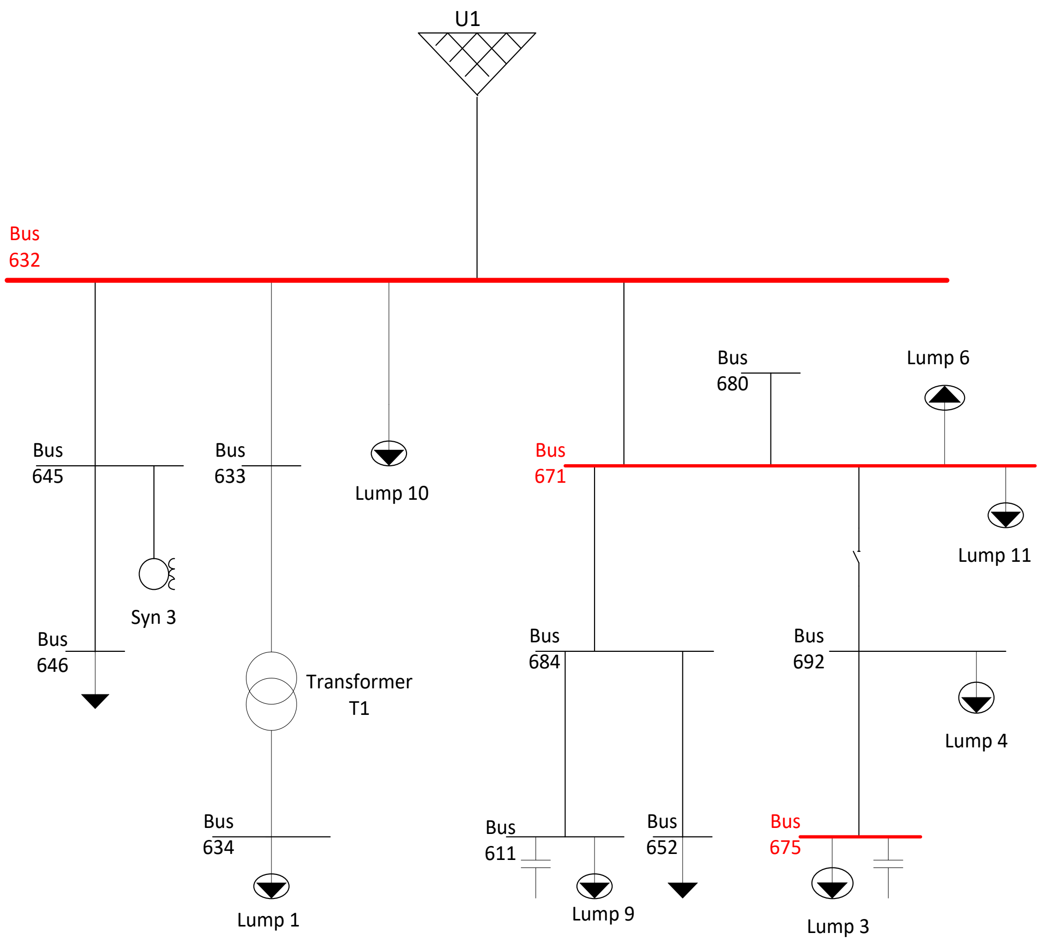

Figure 5.1 IEEE 13 Bus Distribution Test System Single Line Diagram

This system has been selected for initial investigation to examine the performance of a small scale (in terms of voltage and MW rating) unbalanced distribution system during short circuit when different types of DG are connected at various penetration levels up to 85% of the system rated generation. This is to determine and identify the implications in small system and obtain basic understanding. The model is implemented and modified in ETAP 12 software, where the short circuit analysis is performed for different four cases presented in section 5.3. The short circuit analysis is run twice to include the two different simulations which are: ANSI and IEC calculations methods. The IEEE 13-bus distribution test system original model is modified through connecting DG with various sizes and at different locations throughout the system under study. The DG units used are; Type 3 (DFIG) wind turbine generators (WTG), photovoltaics (PV), and diesel generators.

5.3 IEEE-13 bus distribution test system case studies

The study is divided into four main case studies to examine the impact of different DG types on different types of fault of distribution system under study. The four cases of different DG units connected to the system under study are:

Case 1: Wind

Case 2: PV

Case 3: Hybrid system (Wind and PV)

Case 4: Diesel Hybrid system (Diesel generator Wind, and PV)

For each case study, there are four different scenarios selected to study the impact of DG location on the short circuit level of the distribution system presented in Table 5.1.

TABLE 5.1: DIFFERENT SCENARIOS EXAMINED

Scenario	Condition
Scenario 1 (S1)	No DG
Scenario 2 (S2)	3 MW placed at Bus 632
Scenario 3 (S3)	3 MW at Bus 675
Scenario 4 (S4)	2x1.5 MW placed at buses 632 and 671

In cases 3 and 4 (where there are different types of DG units connected), the DG units ratings were equal. As in case 3, for S2 and S3, a 1.5 MW WTG and a 1.5 MW PV array were connected. The scenarios are varied to obtain valid and reliable results. The simulation involved examination of the occurrence of four types of fault which are 3-ph, LG, LL, and LLG at three different buses 632, 671, 675 respectively. The criterion for selection of buses where the fault may occur and DG location is based on the distance from the main utility grid and the concentration of loads. In which S2 represents the DG location near the utility grid. For the same DG capacity, S3 represents the DG location at the furthest bus from the utility grid. Though, S4 represents the distribution of the DG capacity between two buses away from the utility grid and in the middle of the system. The evaluation of the simulation results is based on comparing the short circuit current magnitudes at each scenario with the SCC in case of no DG connected (S1) to the system under study.

5.4 Simulated results for ANSI calculations

The study selected for the short circuit calculation is 1.5-4 cycles. This study performs 3-phase, line-to-ground, line-to-line, and line-to-line-to-ground fault studies per ANSI Standards. The study calculates short circuit currents in their rms values between 1.5 to 4 cycles at faulted buses. In this study, generators are represented by their positive, negative, and zero sequence subtransient reactance, and motors are modelled by their positive, negative, and zero sequence transient reactance [115]. The simulated results are presented in Tables 5.2 –5.5. The results are presented in this arrangement order to compare between the DG types, in regards their impact on the short circuit current, along with the influence of different DG location. Table 5.6 presents the impact of different penetration levels varied from 10% up to 85% for case 4 at S3.

5.4.1 Analysis of simulated results for ANSI calculations

Table 5.2 presents the simulated results for the short circuit current magnitudes of the system under study at no DG connected.

TABLE 5.2: ANSI SIMULATED RESULTS FOR SCENARIO 1 WITH NO DG INSTALLED (KA)

Bus		No DG			
ID	kV	3-Ph	LG	LL	LLG
632	4.16	11.276	8.463	9.766	10.631
671	4.16	6.453	4.536	5.588	5.903
675	4.16	5.771	4.181	4.998	5.277

From Table 5.2, it is observed that the results for 3-ph fault case are the highest values in comparison to the other types of faults examined. Therefore, this could be considered as the most severe case in which could be selected to illustrate the short circuit current characteristics of the system with no DG connected. Hence, it is crucial to analyse the main short circuit contributors to this system, especially on the same buses where the DG is anticipated to be connected in further studies in this thesis.

TABLE 5.3: ANSI SIMULATED RESULTS FOR SCENARIO 2

Bus		Wind				PV				Hybrid				Diesel Hybrid			
ID	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
632	4.16	13.318	9.337	11.967	12.844	11.494	8.534	9.954	10.685	12.392	8.948	10.950	11.760	12.793	10.673	11.249	12.267
671	4.16	6.922	4.717	6.083	6.398	6.510	4.554	5.638	5.921	6.720	4.640	5.868	6.170	6.809	4.889	5.934	6.254
675	4.16	6.143	4.333	5.389	5.657	5.807	4.193	5.029	5.298	5.979	4.267	5.216	5.479	6.054	4.476	5.271	5.564

TABLE 5.4: ANSI SIMULATED RESULTS FOR SCENARIO 3

Bus		Wind				PV				Hybrid				Diesel Hybrid			
ID	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
632	4.16	12.577	9.010	11.103	11.936	11.435	8.514	9.903	10.670	12.028	8.787	10.545	11.360	12.283	9.491	10.730	11.713
671	4.16	8.423	5.203	7.681	7.954	6.644	4.599	5.754	6.089	7.516	4.922	6.712	6.956	7.923	6.657	7.017	7.652
675	4.16	7.813	4.910	7.190	7.482	6.014	4.268	5.209	5.571	6.886	4.606	6.178	6.409	7.286	6.405	6.478	7.034

TABLE 5.5: ANSI SIMULATED RESULTS FOR SCENARIO 4

Bus		Wind				PV				Hybrid				Diesel Hybrid			
ID	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
632	4.16	13.030	9.217	11.639	12.502	11.464	8.524	9.928	10.675	12.361	8.939	10.923	11.748	12.342	10.121	10.893	11.812
671	4.16	7.731	5.001	6.962	7.268	6.579	4.576	5.697	5.991	6.783	4.659	5.923	6.178	7.220	5.855	6.403	6.823
675	4.16	6.768	4.569	6.062	6.303	5.847	4.208	5.063	5.370	6.079	4.300	5.303	5.578	6.365	5.283	5.626	6.012

TABLE 5.6: ANSI SIMULATED RESULTS FOR SCENARIO 3 AT DIFFERENT PENETRATION LEVELS AND DIESEL HYBRID MIX LOCATED AT BUS 675

Bus		Wind				PV				Hybrid				Diesel Hybrid			
ID	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
632	4.16	12.283	9.491	10.730	11.713	11.714	9.034	10.225	11.132	11.589	8.886	10.095	10.989	11.400	8.650	9.891	10.771
671	4.16	7.923	6.657	7.017	7.652	7.049	5.616	6.221	6.645	6.872	5.309	6.034	6.419	6.615	4.867	5.753	6.098
675	4.16	7.286	6.405	6.478	7.034	6.384	5.286	5.650	6.083	6.201	4.966	5.456	5.838	5.936	4.512	5.166	5.479

Table 5.7 presents the contribution of equipment installed in the system to 3-ph short circuit currents when a fault occurs at 632, 675, and 671 respectively.

TABLE 5.7: THREE-PHASE SHORT CIRCUIT CURRENT MAGNITUDES (KA) AND PERCENTAGE OF THE TOTAL SHORT CIRCUIT CURRENT

Faulted Bus	632		675		671	
Total SCC (kA)	11.276		5.771		6.453	
	SCC (kA)	%	SCC (kA)	%	SCC (kA)	%
Utility Grid U1	9.864	87.5	4.385	76.0	4.957	76.8
Line 5	1.247	11.1	4.467	77.4	5.049	78.2
Lump 1	1.047	9.3	0.466	8.1	0.526	8.2
Lump 6	0.695	6.2	0.7	12.1	0.791	12.3
Lump 3	0.497	4.4	0.572	9.9	0.565	8.8
Cable 606_500	0.497	4.4	5.213	90.3	0.565	8.8
switch	0.497	4.4	5.213	90.3	0.565	8.8
Line 2	0.121	1.1	0.054	0.9	0.061	1.0
Transformer T1	0.121	1.1	0.054	0.9	0.061	1.0
Lump 10	0.063	0.6	0.028	0.5	0.032	0.5
Lump 11	0.056	0.5	0.056	1.0	0.063	1.0

The contribution of other loads in the system is not included in the results in Table 5.7. This is due to the ANSI standard assumption in which load currents could be neglected as they are much smaller than the fault currents. Therefore, it can be concluded that static loads have no significant contribution to the short circuit current.

From the short circuit analysis performed, it was concluded that the utility grid has significantly contributed to the short circuit current at the three different faulted buses 632,675, and 671 respectively for all type of faults examined. Whereas for 3-ph fault at faulted bus 632, the total simulated symmetrical short circuit current is 11.276 kA, of which the utility grid (U1) contributed 9.864 kA. Thus, is approximately 87% of the total 3-ph short circuit current at bus 632.

The five motors (Lump 1, Lump 3, Lump 6, Lump 10, and lump 11) connected to the system have contributed to total short circuit currents at the faulted buses 632,675, and 671 respectively for all types of fault. The location of motors in regards to the fault location has varied the SCC results considerably. From table 5.25, it is observed for Lumps 3 and 6, which are connected directly to the buses 675 and 671 respectively, that their contributions to SCC to these buses when a fault occurs are higher than their contribution on SCC at faulted bus 632. This could be due to the series impedances considered of the line 5 and the cable 606_500 connected between bus 632 and lumps 3 and 6. It should be not that the line and cable resistances are proportional of the conductor length (i.e. 2000 ft. for Line 5).

From Tables 5.3 – 5.5

The simulated results show that the maximum short circuit current magnitudes occurred in the following descending order at faulted buses 632, 671, and 675 respectively. It can be observed that the SCCs at faulted bus 632 is approximately double the SCCs at faulted buses 671 and 675. In addition, the short circuit current magnitudes for the four types of faults tested decremented order in which the 3-ph fault current values are the highest; LL-G; LL; and the lowest are the LG fault current magnitudes, respectively.

5.4.1.1 Impact of DG type on short circuit current

For the three scenarios examined S2, S3, and S4, it is noticed that the short circuit currents magnitudes were the highest in case of WTGs are connected to the distribution network. The WTG impact on short circuit current magnitudes is the highest for all types of fault studied and all faulted buses examined 632, 675, and 671 respectively. The diesel hybrid followed the WTGs in the significant impact on SCC, then the hybrid. Conversely, the impact of PV on short circuit current is observed to be the least, for all types of fault and faulted buses tested.

Further analysis in case 3 for 3-ph fault simulation results has been performed to ensure reliable assessment. The contribution of each DG type separately on the fault current of the IEEE 13-bus distributed test system is considered. Simulated results from the short circuit study were taken and the percentage of DG contribution of total fault current at its allocated bus has been calculated, presented in Tables 5.8 and 5.9.

TABLE 5.8: COMPARISON OF DG UNITS CONTRIBUTION ON THE SHORT CIRCUIT CURRENT LEVEL AT S2

Faulted Bus	%U1	%WTG	%PV	%Diesel Generator
632	77.1	5.5	0.2	6.7
671	67.7	4.9	0.1	5.9
675	67.0	4.8	0.1	5.8

TABLE 5.9: COMPARISON BETWEEN DG UNITS CONTRIBUTION ON THE SHORT CIRCUIT CURRENT AT S3

Faulted Bus	%U1	%WTG	%PV	%Diesel Generator
632	80.3	4.3	0.1	5.2
671	62.6	8.6	0.3	10.4
675	60.2	9.7	0.3	11.8

The utility grid contribution has the highest percentage of the total short circuit current, exceeding more than 50% in both scenarios S2 and S3 respectively, in comparison to the percentage contribution of the DG types connected. The highest percentage reached up to 80.3% in Scenario 3 at the occurrence of 3-ph fault at bus 632. Remarkably, it is almost double the percentage for the same conditions at scenario 2. The DFIG wind turbine contribution never exceeded the 10% in both scenarios. The PV contribution ranged from 0.1 – 0.3% in both scenarios 2 and 3. It is noticed that when the DG mix was located at the nearest bus to the grid (bus 632) the grid contribution was higher in Scenario 2 than scenario 3, for faults occurring at buses 671, and 675 [2].

For S2 and S3, it could be observed that the diesel generators connected contributed more that the WTG and PV. The induction and synchronous machines connected on a system remain to supply current to the fault during short circuit due to the limited amount of stored flux in the machine. However, the current decays significantly with time due to the reduction in this stored energized field [108]. The diesel generator connected the system under study adopts the synchronous machine characteristics and behaviour during short circuit, in which it maintains the stored flux for more cycles resulting in higher symmetrical SCC more than the induction machines. Moreover, the WTG installed in the system under study is DFIG that is equipped with power electronics which controls SCC.

5.4.1.2 Impact of DG location on short circuit current

In this section, it is intended to compare between the short circuit current magnitudes in terms of the DG location impact. From Tables 5.3 – 5.5, it is noticed that for the four types of fault examined, the results reflected the same performance for the different types of DG integrated in respect to same location. The maximum SCC usually occurred at scenario S2 (in which the DG is located at bus 362) and the faulted bus 632. The minimum SCC usually occurred at scenario 3 (in which the DG is located at bus 675). It is noticed that scenario S4 is in the intermediate between S2 and S3. Furthermore, the results demonstrated that in the case of PV is integrated to the distribution network, the SCC magnitudes could be considered approximately equal in the three scenarios examined.

5.4.1.3 Worst case scenarios for ANSI calculations

From Tables 5.2 – 5.5, the overall worst 10 cases occurred at the system under study have been selected for 3-ph and LL-G faults, and presented in Figures 5.2 and 5.3. The LL-G fault currents are the highest of the faulted line currents examined. Hence, the LL-G fault current has been presented to represent the worst case scenario of the faulted line currents. It is noticed that all of the worst case scenarios have occurred at bus 632 for the two types of fault respectively.

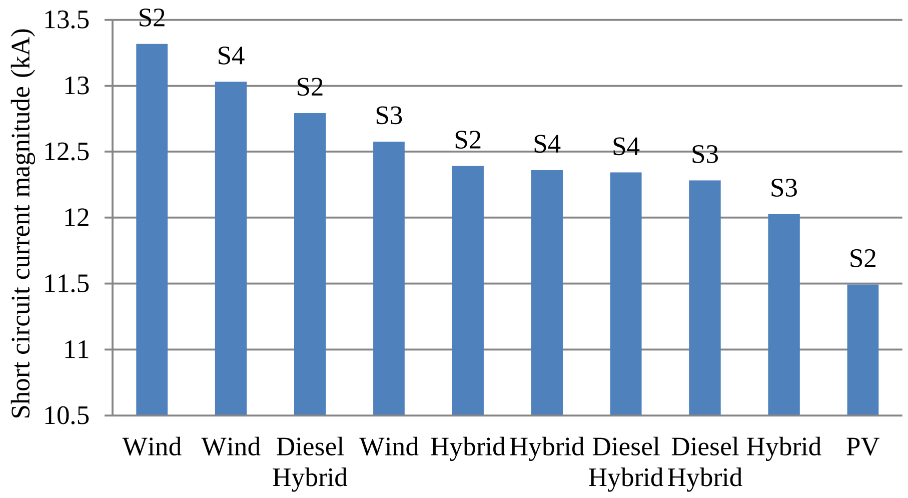

Figure 5.1. The worst cases during 3-ph fault for ANSI calculations

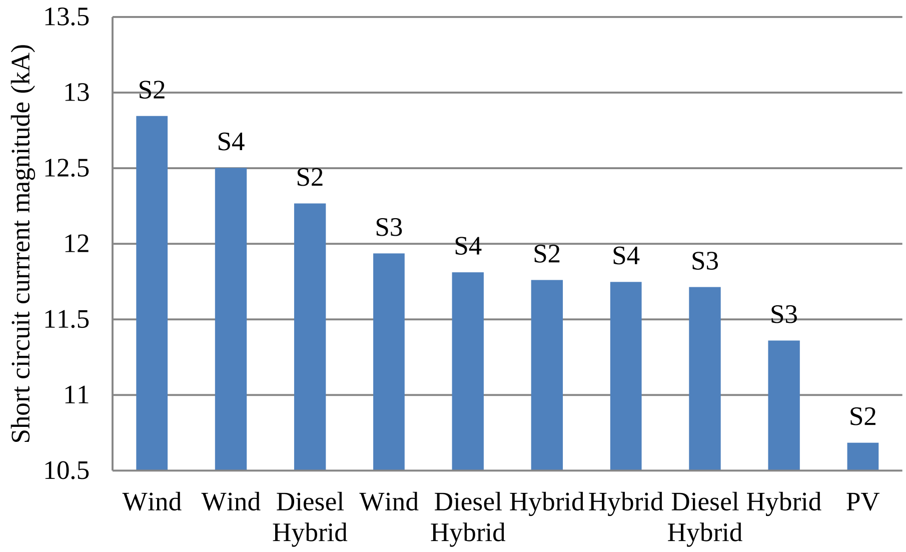

Figure 5.2. The worst cases during LL-G fault for ANSI calculations

From Figures 5.2 and 5.3, it is observed that the worst case for both fault types is at the case of wind at scenario two (S2). The least DG impact is the PV at scenario two (S2). In comparing the scenarios that reflect the impact of DG location on the system short circuit level, it is noticed that scenario 2 represented the worst location a DG could be located for all types of DG used and DG mix applied in this study. Wind is the worst DG type regardless of the three scenarios S2, S3, and S4 that have been tested respectively. Similarly, the DG mixes are among the critical cases for the three scenarios.

5.4.1.4 Lowest case scenarios for ANSI calculations

From Tables 5.2 – 5.5, the least short circuit currents occurred during the 3-ph and LL-G faults inorder to be able to identify the most appropriate DG type and their suitable locations for the 13 bus distribution system studied in this thesis. These types of faults are selected based on the previous analysis discussed earlier, where the highest values of short circuit currents occurred. The results for the lowest short circuit currents during the 3-ph and LL-G faults are represented in Figure 5.4and 5.5.

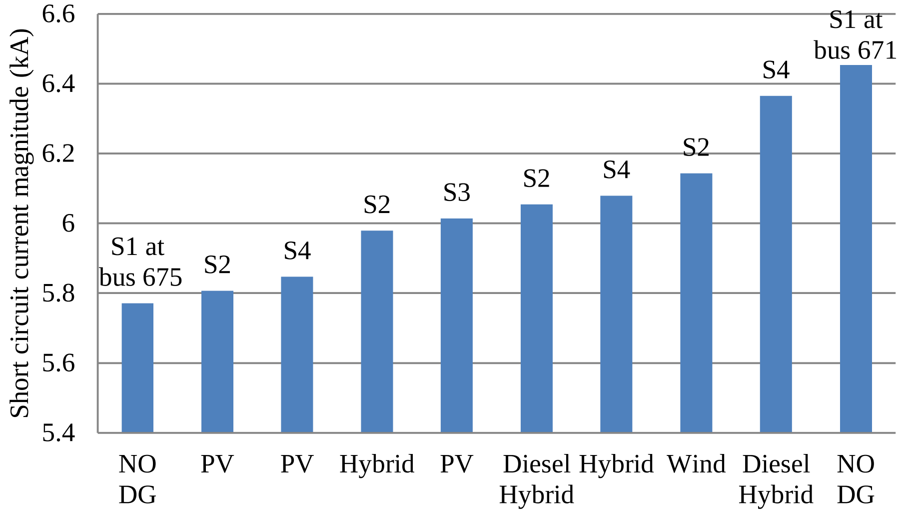

Figure 5.3 The minimum short circuit currents during 3-ph fault for ANSI calculations

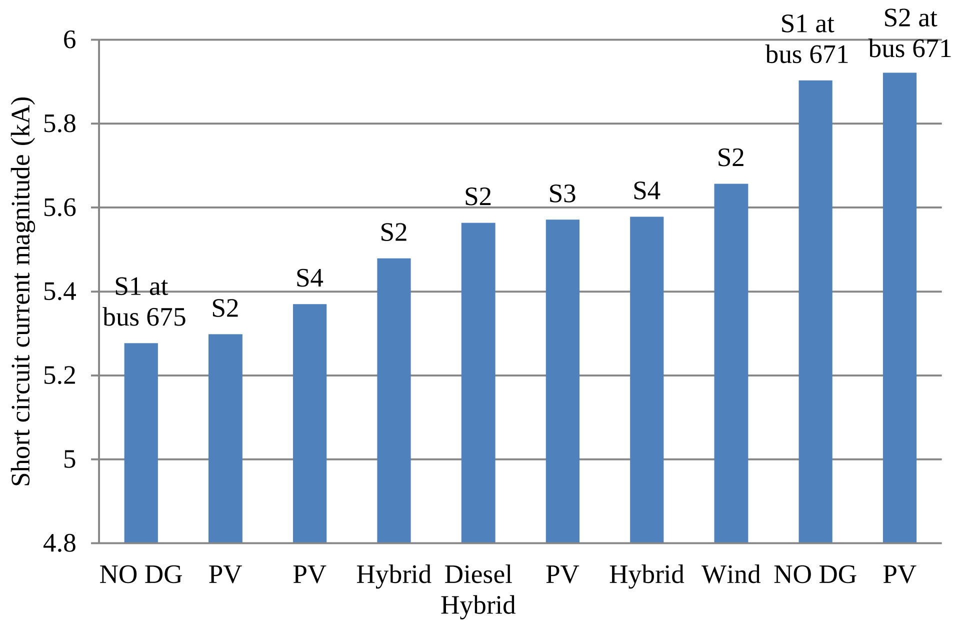

Figure 5.4 The minimum short circuit currents during LL-G fault for ANSI calculations

It is observed that the two figures are not identical in terms of the type of DG and scenarios sequence. The least SCC achieved when a fault occurred at buses 675 and 671 respectively. Both figures have the least SCC in case of no DG at scenario S1 when a fault occurred at bus 675. It is noticed that the PV for all scenarios studied during the fault occurrence at bus 675 is the most DG type sustained the system SCC to a minimum.

In Figures 5.4 and 5.5, it could be observed that the minimum short circuit currents were at the case where 3-ph and LL-G faults occurring at bus 675 with all types and

DG mix tested in scenario S2 (DG located at bus 632). In Figure 5.5, this figure shows that system SCC could be improved if the DG are located at certain locations.

5.4.1.5 Impact of DG penetration level

Figure 5.6 presents the impact of different penetration levels of diesel hybrid DG during the occurrence of 3-ph faults at buses 632,675, and 671 respectively.

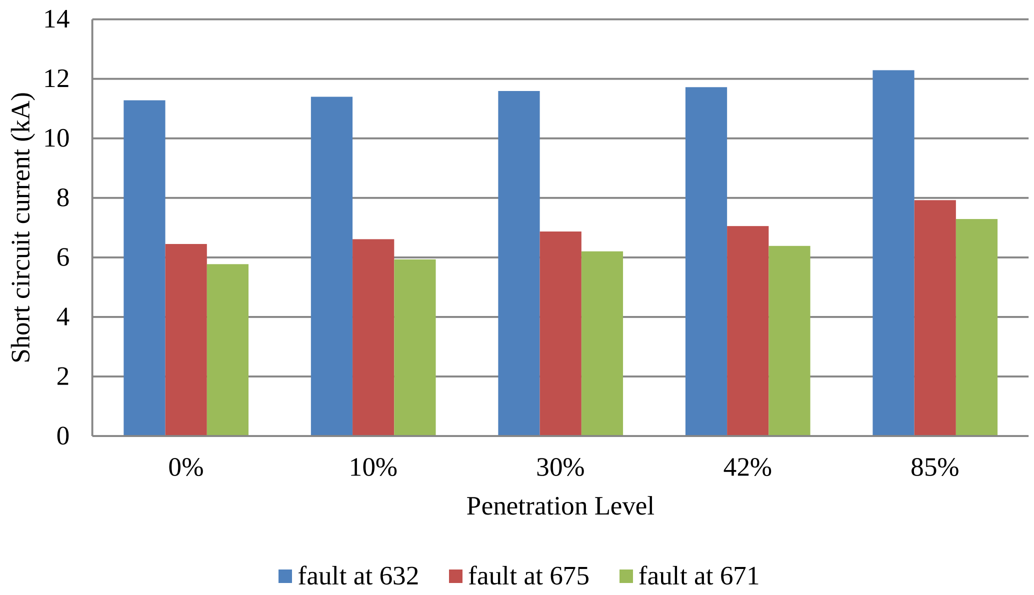

Figure 5.5 Penetration level vs 3-ph short circuit currents for diesel hybrid mix located at bus 675 for ANSI calculations

It is noticed that the short circuit currents are directly proportional to the penetration level, as the penetration level increases the short circuit currents increases. The maximum increase calculated between the 85% penetration level and the no DG level is found to be 8.9% higher at faulted bus 632. The difference between SCC during a fault at bus 632 and fault at buses 675 and 671 is observed to be about the double. The short circuit currents are the highest at faulted bus 632, followed by 671, and least at faulted bus 675.

5.5 Analysis of simulated results for IEC calculations

The simulated results for IEC standard are different than the ANSI standard results in regards to the different types of prospective short circuit current that should be calculated. These are: initial symmetrical current ($I_k^{''}$); peak short circuit current(i_p); symmetrical short-circuit breaking current (I_b); and steady-state short circuit current (I_k). The computation is set to calculate the maximum short circuit currents which determine the capacity or rating of electrical equipment (IEC). In this thesis, the main principal is to calculate the short circuit current to evaluate the system performance during short circuit with DG integration. The minimum short circuit currents are calculated for selection of fuses and for setting of protectives devices. Furthermore, The IEC condition for calculating the minimum short circuit currents is to neglect the contribution of wind power stations, PV units and motors, which is out of the scope of this study.

The LG, LL, LLG, & 3-Phase Faults (IEC 60909) study is selected in ETAP 12 for the short circuit calculation. This study performs line-to-ground, line-to-line, line-to-line-to-ground, and three-phase fault studies per IEC 60909 Standard. The study calculates initial symmetrical rms, peak and symmetrical breaking rms, and steady-state rms short-circuit currents at faulted buses. However, the symmetrical breaking rms current for the 3-ph fault is not considered by ETAP in this study. ETAP 12 models the generators by their positive, negative, and zero sequence reactance, while motors are modelled by their locked-rotor impedance [115]. The IEC standard considers an equivalent voltage source at the faulted bus for the initial symmetrical current calculation. The voltage factor *c* value varies depending on the system rated voltage. For the system under study (4.16 kV rated voltage), the *c* factor is selected to be 1.10 according to IEC-909606. According to IEC classification to types of circuits during short circuit, the system under study in this chapter could be considered as multiple fed short-circuit.

The simulated results for the system at no DG connected are presented in Table 5.10. For the same system with different types of DG connected (Wind, PV, Hybrid, and diesel hybrid respectively) considering different scenarios, these simulated results are presented in Tables 5.11 – 5.22.

TABLE 5.10: IEC SIMULATED RESULTS FOR SCENARIO 1- NO DG

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	12.291	24.162	9.864	8.984	17.662	8.984	8.984	10.644	20.925	10.644	10.644	11.536	22.679	11.536	11.536
671	4.16	7.714	15.914	5.237	5.139	10.602	5.139	5.139	6.680	13.782	6.680	6.680	7.026	14.495	7.026	7.026
675	4.16	6.906	13.562	4.733	4.751	9.330	4.751	4.751	5.981	11.745	5.981	5.981	6.284	12.341	6.284	6.284

TABLE 5.11: IEC SIMULATED RESULTS FOR SCENARIO 2 - WIND

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	15.729	32.707	9.864	10.067	20.934	10.067	10.067	13.614	28.308	13.614	13.614	14.602	30.362	14.602	14.602
671	4.16	8.514	17.902	5.237	5.364	11.278	5.364	5.364	7.372	15.500	7.372	7.372	7.731	16.256	7.731	7.731
675	4.16	7.526	14.884	4.733	4.937	9.765	4.937	4.937	6.516	12.888	6.516	6.516	6.817	13.483	6.817	6.817

TABLE 5.12: IEC SIMULATED RESULTS FOR SCENARIO 3 - WIND

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	14.053	27.816	9.864	9.569	18.941	9.569	9.569	12.167	24.083	12.167	12.167	13.059	25.849	13.059	13.059
671	4.16	10.899	23.043	5.237	5.906	12.486	5.906	5.906	9.432	19.940	9.432	9.432	9.775	20.6667	9.775	9.775
675	4.16	10.347	22.123	4.733	5.610	11.995	5.610	5.610	8.952	19.141	8.952	8.952	9.324	19.936	9.324	9.324

TABLE 5.13: IEC SIMULATED RESULTS FOR SCENARIO 4 - WIND

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	15.068	30.666	9.864	9.876	20.099	9.876	9.876	13.040	26.538	13.040	13.040	13.987	28.465	13.987	13.987
671	4.16	9.881	21.140	5.237	5.695	12.183	5.695	5.695	8.550	18.291	8.550	8.550	8.918	19.079	8.918	8.918
675	4.16	8.542	16.902	4.733	5.207	10.303	5.207	5.207	7.392	14.626	7.392	7.392	7.676	15.188	7.676	7.676

TABLE 5.14: IEC SIMULATED RESULTS FOR SCENARIO 2 - PV

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	12.526	24.349	10.120	9.056	17.603	9.056	9.056	10.848	21.087	10.848	10.848	11.597	22.542	11.597	11.597
671	4.16	7.778	15.970	5.315	5.157	10.588	5.157	5.157	6.736	13.831	6.736	6.736	7.047	14.468	7.047	7.047
675	4.16	6.944	13.578	4.788	4.763	9.313	4.763	4.763	6.014	11.759	6.014	6.014	6.288	12.295	6.288	6.288

TABLE 5.15: IEC SIMULATED RESULTS FOR SCENARIO 3 - PV

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	12.429	24.246	10.151	9.025	17.606	9.025	9.025	10.764	20.998	10.764	10.764	11.563	22.556	11.563	11.563
671	4.16	7.906	16.025	5.500	5.194	10.529	5.194	5.194	6.846	13.878	6.846	6.846	7.165	14.523	7.165	7.165
675	4.16	7.162	13.784	5.031	4.832	9.300	4.832	4.832	6.202	11.937	6.202	6.202	6.560	12.624	6.560	6.560

TABLE 5.16: IEC SIMULATED RESULTS FOR SCENARIO 4 - PV

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	12.480	24.299	10.127	9.041	17.604	9.041	9.041	10.808	21.044	10.808	10.808	11.579	22.545	11.579	11.579
671	4.16	7.848	16.006	5.400	5.177	10.558	5.177	5.177	6.797	13.862	6.797	6.797	7.074	14.427	7.074	7.074
675	4.16	6.981	13.572	4.847	4.775	9.282	4.775	4.775	6.046	11.753	6.046	6.046	6.344	12.333	6.344	6.344

TABLE 5.17: IEC SIMULATED RESULTS FOR SCENARIO 2 - HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	14.118	28.395	9.987	9.586	19.280	9.586	9.586	12.221	24.578	12.221	12.221	13.091	26.329	13.091	13.091
671	4.16	8.167	16.987	5.274	5.268	10.958	5.268	5.268	7.071	14.708	7.071	7.071	7.410	15.412	7.410	7.410
675	4.16	7.253	14.273	4.759	4.857	9.558	4.857	4.857	6.280	12.358	6.280	6.280	6.570	12.929	6.570	6.570

TABLE 5.18: IEC SIMULATED RESULTS FOR SCENARIO 3 - HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	13.322	26.248	9.995	9.333	18.388	9.333	9.333	11.535	22.725	11.535	11.535	12.395	24.420	12.395	12.395
671	4.16	9.413	19.583	5.358	5.585	11.618	5.585	5.585	8.147	16.948	8.147	8.147	8.438	17.555	8.438	8.438
675	4.16	8.733	17.801	4.872	5.254	10.709	5.254	5.254	7.557	15.403	7.557	7.557	7.833	15.966	7.833	7.833

TABLE 5.19: IEC SIMULATED RESULTS FOR SCENARIO 4 - HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	14.078	28.357	9.995	9.576	19.288	9.576	9.576	12.185	24.545	12.185	12.185	13.077	26.341	13.077	13.077
671	4.16	8.240	17.026	5.358	5.287	10.925	5.287	5.287	7.135	14.742	7.135	7.135	7.423	15.338	7.423	7.423
675	4.16	7.291	14.264	4.816	4.868	9.525	4.868	4.868	6.313	12.351	6.313	6.313	6.582	12.878	6.582	6.582

TABLE 5.20: IEC SIMULATED RESULTS FOR SCENARIO 2 – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	14.424	29.365	10.237	11.578	23.569	11.578	11.578	12.512	25.472	12.512	12.512	13.553	27.591	13.553	13.553
671	4.16	8.236	17.207	5.501	5.584	11.667	5.584	5.584	7.137	14.911	7.137	7.137	7.484	15.636	7.484	7.484
675	4.16	7.309	14.425	4.948	5.121	10.105	5.121	5.121	6.333	12.498	6.333	6.333	6.648	13.12	6.648	6.648

TABLE 5.21: IEC SIMULATED RESULTS FOR SCENARIO 3 – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	13.478	26.655	10.751	10.108	19.99	10.108	10.108	11.681	23.101	11.681	11.681	12.692	25.1	12.692	12.692
671	4.16	9.709	20.412	6.201	7.639	16.06	7.628	7.639	8.424	17.711	8.424	8.424	9.108	19.149	9.108	9.108
675	4.16	9.038	18.773	5.111	7.414	15.399	7.385	7.414	7.848	16.301	7.848	7.848	8.558	17.777	8.558	8.558

TABLE 5.22: IEC SIMULATED RESULTS FOR SCENARIO 4 – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	14.039	28.225	10.825	10.947	22.009	10.947	10.947	12.107	24.34	12.107	12.107	13.137	26.41	13.137	13.137
671	4.16	9.06	19.136	5.863	6.766	14.289	6.766	6.766	7.806	16.487	7.806	7.806	8.294	17.517	8.294	8.294
675	4.16	7.926	15.656	5.239	6.052	11.953	6.052	6.052	6.834	13.498	6.834	6.834	7.297	14.413	7.297	7.297

TABLE 5.23: IEC SIMULATED RESULTS FOR SCENARIO 3 AT 10% PENETRATION LEVEL – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	12.444	24.476	9.970	9.152	18.001	9.152	9.152	10.772	21.187	10.772	10.772	11.680	22.974	11.680	11.680
671	4.16	7.941	16.409	5.345	5.444	11.249	5.444	5.444	6.870	14.195	6.870	6.870	7.244	14.970	7.244	7.244
675	4.16	7.142	14.098	4.774	5.058	9.986	5.058	5.058	6.177	12.194	6.177	6.177	6.494	12.821	6.494	6.494

TABLE 5.24: IEC SIMULATED RESULTS FOR SCENARIO 3 AT 30% PENETRATION LEVEL – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I''_k	i_p	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k	I''_k	i_p	I_b	I_k
632	4.16	12.756	25.142	10.194	9.467	18.660	9.467	9.467	11.033	21.747	11.033	11.033	11.979	23.611	11.979	11.979
671	4.16	8.430	17.522	5.578	6.075	12.627	6.075	6.075	7.279	15.129	7.279	7.279	7.731	16.069	7.731	7.731
675	4.16	7.653	15.336	4.864	5.709	11.439	5.709	5.709	6.605	13.236	6.605	6.605	7.025	14.077	7.025	7.025

TABLE 5.25: IEC SIMULATED RESULTS FOR SCENARIO 3 AT 50% PENETRATION LEVEL – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	12.937	25.529	10.327	9.636	19.015	9.636	9.636	11.185	22.073	11.185	11.185	12.153	23.982	12.153	12.153
671	4.16	8.730	18.209	5.722	6.449	13.450	6.449	6.449	7.530	15.705	7.530	7.530	8.038	16.765	8.038	8.038
675	4.16	7.972	16.122	4.918	6.102	12.342	6.102	6.102	6.871	13.897	6.871	6.871	7.367	14.900	7.367	7.367

TABLE 5.26: IEC SIMULATED RESULTS FOR SCENARIO 3 AT 85% PENETRATION LEVEL – DIESEL HYBRID

Bus		3-Ph			LG				LL				LLG			
ID	kV	I_k''	i_p	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k	I_k''	i_p	I_b	I_k
632	4.16	13.478	26.655	10.751	10.108	19.99	10.108	10.108	11.681	23.101	11.681	11.681	12.692	25.1	12.692	12.692
671	4.16	9.709	20.412	6.201	7.639	16.06	7.628	7.639	8.424	17.711	8.424	8.424	9.108	19.149	9.108	9.108
675	4.16	9.038	18.773	5.111	7.414	15.399	7.385	7.414	7.848	16.301	7.848	7.848	8.558	17.777	8.558	8.558

5.5.1 Analysis of simulated results for IEC calculations

Referring to Tables 5.10-5.22, it is possible to notice the following:

For unbalanced faults (LG, LL, and LL-G):

- The symmetrical short circuit breaking current (I_b) is equal to the initial symmetrical current ($I_k^{"}$). This is according to the IEC assumption considered for the I_b calculation. In which I_b is assumed to be equal to $I_k^{"}$ for the all types of unbalaced faults. However, this assumption should be only applied if the generator is far away from the fault
- The steady-state short circuit current (I_k) is equal to the initial symmetrical current ($I_k^{"}$). This is according on the IEC rule for the clculation of I_k, which is based on the assumption that the flux decay in the generator is neglected.

For 3-ph, LL, and LL-G faults, the highest initial symmetrical current ($I_k^{"}$) occurred in the case of wind at S2 at faulted bus 632. As the peak short circuit current (i_p) depends on the$I_k^{"}$, the highest i_p is for case of wind at S2 at faulted bus 632.

For LG fault, the case of diesel hybrid at S2 is found to be the highest values for $I_k^{"}$. Simultaneously, the maximum i_p is found to be for the same case study.

Consequently, as the steady state short circuit currents are equal to the initial symmetrical currents $I_k^{"}$ for unbalanced faults, therefore, the highest I_k is found to be in case of wind at S2 at faulted bus 632. Hence, for the 3-ph fault, the highest I_k is observed to occur at case of diesel hybrid at S4 at faulted bus 632.

The main short circuit contributors to this system, especially on the same buses where the DG will be connected to in further studies in this thesis are presented in Table 5-27. This table 5-27 provides the 3-ph initial symmetrical short circuit currents when a fault occurs at 632, 675, and 671 respectively

TABLE 5.27: THREE-PHASE INITIAL SYMMETRICAL SHORT CIRCUIT CURRENT MAGNITUDES (KA) AND PERCENTAGE OF THE TOTAL SHORT CIRCUIT CURRENT

Faulted Bus	632		675		671	
Total SCC (kA)	12.291		6.906		7.714	
	SCC (kA)	%	SCC (kA)	%	SCC (kA)	%
Utility Grid U1	9.864	80.3	4.505	65.2	5.116	66.3
Line 5	1.954	15.9	4.732	68.5	5.374	69.7
Lump 1	3.416	27.8	1.560	22.6	1.772	23.0
Lump 6	1.091	8.9	1.162	16.8	1.320	17.1
Lump 3	0.775	6.3	0.954	13.8	0.938	12.2
Cable 606_500	0.775	6.3	5.971	86.5	0.938	12.2
switch	0.775	6.3	5.971	86.5	0.938	12.2
Line 2	0.394	3.2	0.180	2.6	0.204	2.6
Transformer T1	0.394	3.2	0.180	2.6	0.204	2.6
Lump 10	0.106	0.9	0.048	0.7	0.055	0.7
Lump 11	0.088	0.7	0.093	1.3	0.106	1.4

According to the IEC standard, non-rotating loads are disregarded for the short circuit current calculations. Therefore, it could be observed that the contribution of other non-rotating loads in the system is not included in the results in Table 5.27.

From Table 5.27, during a 3-ph fault at bus 632, the total initial symmetrical short circuit current ($\mathbf{I_k''}$) is found to be 12.291 kA, of which the utility grid (U1) contributed 9.864 kA. Thus, is approximately 80% of the total 3-ph initial symmetrical current at bus 632.

The five motors (Lump 1, Lump 3, Lump 6, Lump 10, and lump 11) connected to the system have contributed to total short circuit currents at the faulted buses 632,675, and 671 respectively. The location of motors in regards to the fault location has varied the SCC results relatively. From Table 5.27, it could be said that due to the series impedances of the transmission lines, cables, and transformers in between the fault and the motors, this could still have limited influence on the short circuit current.

5.5.1.1 Impact of DG type on short circuit current

Similarly to the ANSI analysis in 5.4.1, the contribution of each DG type distinctly is considered of the total SCC at each faulted bus for the IEC method. Simulated results from the short circuit study were taken and the percentage of each type of DG used of the total SCC at its allocated bus has been calculated, and presented in Tables 5.28 and 5.29.

TABLE 5.28: COMPARISON OF DG UNITS CONTRIBUTION ON THE SHORT CIRCUIT CURRENT LEVEL AT S2

Faulted Bus	%U1	%WTG	%PV	%Diesel Generator
632	68.4	8.1	1.6	6.5
671	56.5	6.7	1.3	5.4
675	55.6	6.6	1.3	5.3

TABLE 5.29: COMPARISON BETWEEN DG UNITS CONTRIBUTION ON THE SHORT CIRCUIT CURRENT AT S3

Faulted Bus	%U1	%WTG	%PV	%Diesel Generator
632	73.2	5.9	1.2	4.8
671	52.7	11.4	2.2	9.2
675	49.8	12.9	2.5	10.4

From Tables 5.28 and 5.29, it is found that:

- U1 contributes approximately about 50% and more of the total SCC at faulted bus for S2 and S3
- WTG percentage of the total SCC at different faulted bus for S2 and S3 is more than the diesel generator and PV percentages.
- Comparing the DG contribution between S2 and S3

Fault at bus 632: contribution of DG on SCC is lower at S3 than S2

Fault at bus 671: contribution of DG on SCC is higher at S3 than S2

Fault at bus 675: contribution of DG on SCC is higher at S2 than S3

5.5.1.2 Impact of DG location on short circuit current

From Table 5.11 – 5.22, it can be noticed that for the four types of fault examined, the highest SCCs usually occurred at scenario S2 (in which the DG is located at bus 362) and the faulted bus 632 for the four case studies examined. The minimum SCC usually occurred at scenario 3 (in which the DG is located at bus 675), while scenario S4 is in the intermediate between S2 and S3.

5.5.1.3 Worst case scenarios for IEC calculations

From Tables 5.10 – 5.22, the overall worst 10 cases occurred at the system under study have been selected for 3-ph and LL-G faults, and presented in Figures 5.7 and 5.8 for the IEC simulated results. The LL-G fault currents are the highest of the faulted line currents examined. Hence, the LL-G fault current has been presented to represent the worst case scenario of the faulted line currents. It is noticed that all of the worst case scenarios have occurred at bus 632 for the two types of fault respectively.

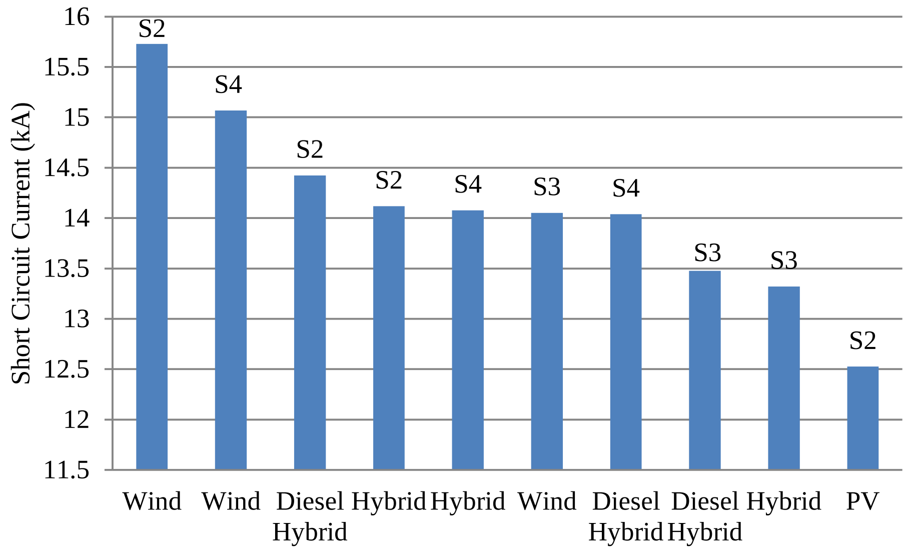

Figure 5.6 The worst cases during 3-ph fault for IEC calculations

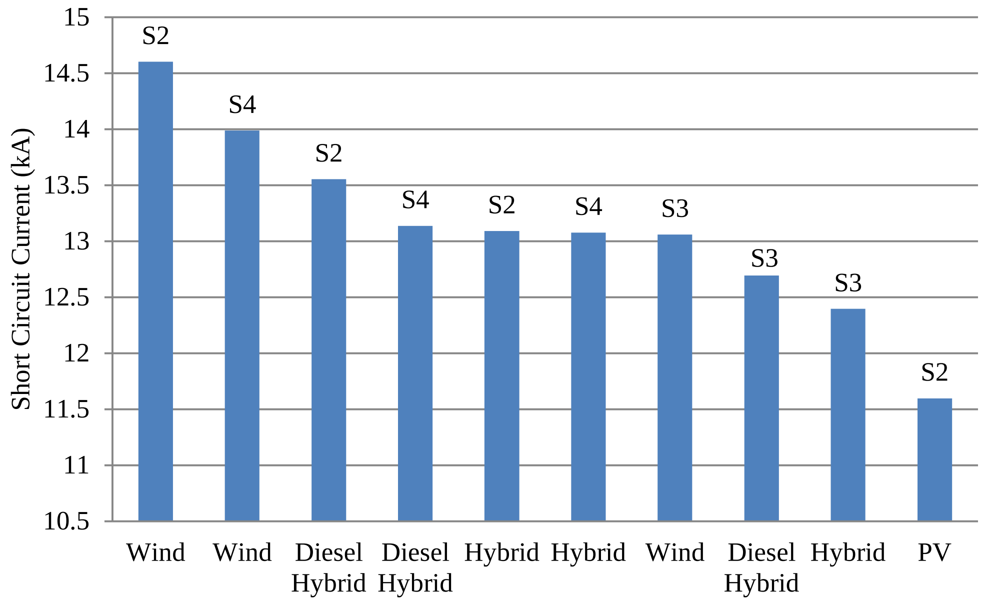

Figure 5.7 The worst cases during LL-G fault for IEC calculations

From figures 5.7 and 5.8, it is observed that the worst case for both fault types is at the case of wind at scenario two (S2). The least DG impact is the PV at scenario two (S2). In comparing the scenarios that reflect the impact of DG location on the system short circuit level, it is noticed that scenario 2 represented the worst location a DG could be located for all types of DG used and DG mix applied in this study. In case of wind only, it is found that this is the worst DG type regardless of the three scenarios S2, S3, S4 that have been tested respectively. Similarly, the DG mix is among the critical cases for the three scenarios.

5.5.1.4 Lowest case scenarios for IEC calculations

The results for the lowest short circuit currents during the 3-ph and LL-G faults are represented in Figures 5.9 and 5.10.

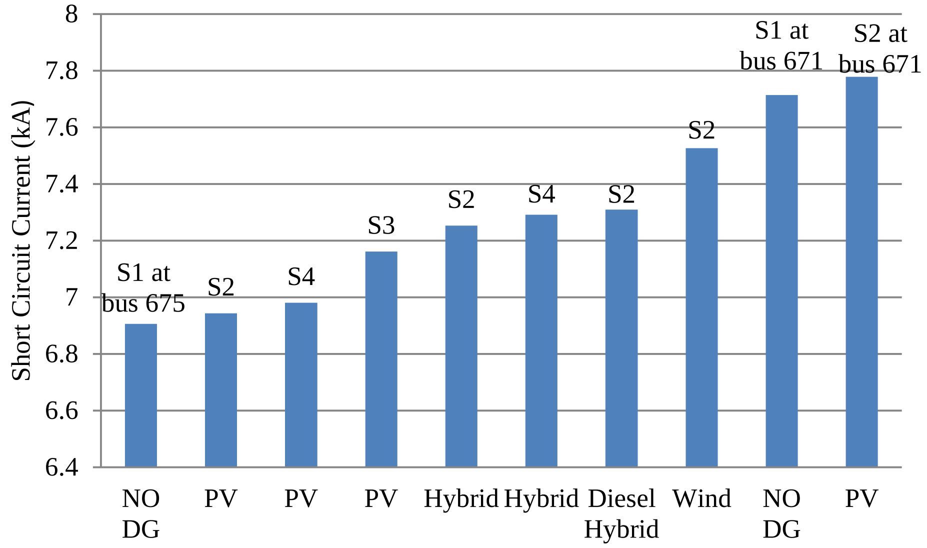

Figure 5.8 The minimum short circuit currents during 3-ph fault for IEC calculations

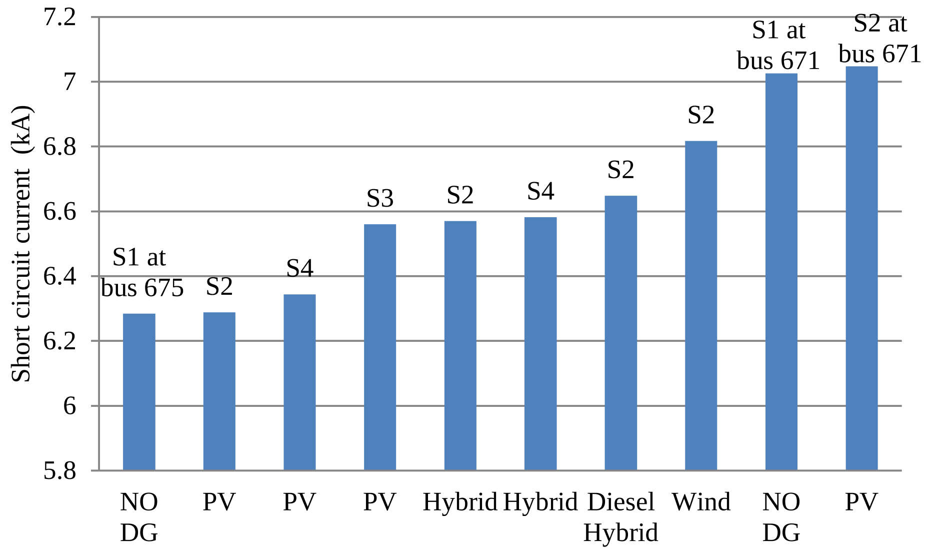

Figure 5.9 The minimum short circuit currents during LL-G fault for IEC calculations

From Figures 5.9 and 5.10, it could be noticed that the least SCC achieved when a fault occurred at buses 675 and 671 respectively. Both figures have the least SCC in case of no DG at scenario S1 when a fault occurred at bus 675. The PV for scenarios S2, S3, and S4 at faulted bus 675 is the most DG type maintained lowest.

5.5.1.5 Impact of DG penetration level

Figure 5.11 presents the impact of different penetration levels of diesel hybrid DG during the occurrence of 3-ph faults at buses 632, 675, and 671 respectively.

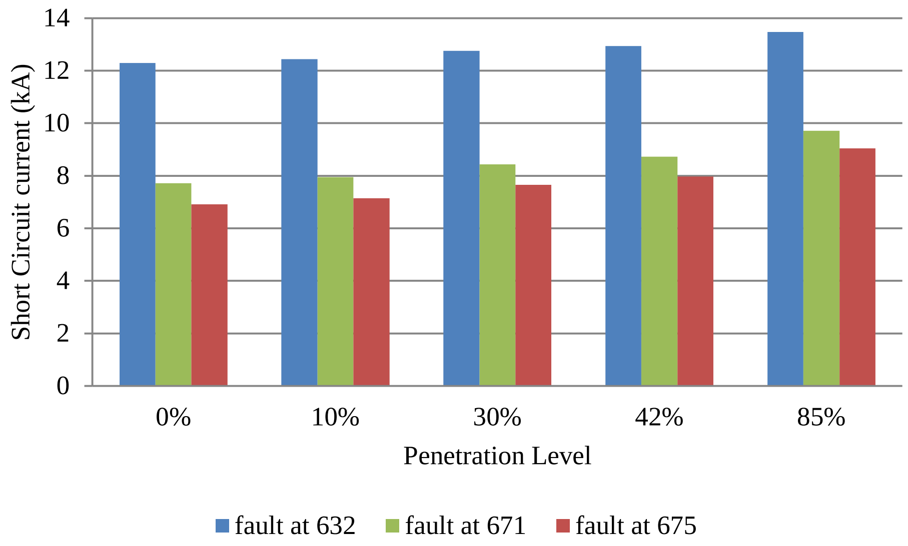

Figure 5.10 Penetration level vs 3-ph short circuit currents for diesel hybrid mix located at bus 675 for IEC calculation

From Figure 5.11, it could be noticed that as the penetration level increases the SCC increases. The maximum increase calculated between the 85% penetration level and the no DG level is found to be approximately 9.7 % higher at faulted bus 632. The difference between SCC during a fault at bus 632 and faulted bus 675 is noticed to be around the double. The short circuit currents are the highest at faulted bus 632, followed by 671, and least at faulted bus 675.

5.6 Comparison between ANSI and IEC simulated results

- It is noticed that the initial symmetrical IEC currents are found to be higher than the symmetrical ANSI currents. This behaviour can be attributed to the following factors considered by the IEC for the initial symmetrical currents calculation:
  - Higher voltage factor *c* adopted in the equivalent voltage source
  - Subtransient impedances considered for all rotating loads in the system.
  - Use of impedance correction factors
- Referring to Tables 5.8 and 5.28, the following comments are:
  - Contribution of U1 of the total SCC at faulted buses 632,675, and 671 is higher in ANSI more than IEC
  - Contribution of diesel generator of the total SCC at faulted buses 632,675, and 671 is higher in ANSI more than IEC
  - Contribution of WTG of the total SCC at faulted buses 632,675, and 671 is higher in IEC more than ANSI
  - Contribution of PV WTG of the total SCC at faulted buses 632,675, and 671 is higher in IEC more than ANSI
  - From ANSI results, the diesel generator contribution is higher than the WTG. Though, in IEC it less than the WTG contribution
- In comparing between the IEC Figures 5.7-5.10 and ANSI Figures 5.2-5.5
  - For 3-ph and LL-G short circuit currents 10 worst cases

  In IEC, the order for the 10 worst cases is found not to be the same order as in ANSI

  - For 3-ph and LL-G short circuit currents 10 least cases

  In IEC, the order for the 10 minimum cases is found not to be the same sequence as in ANSI

- Comparing between Figure 5.6 and 5.11
  The simulated results at faulted bus 671 are found to be higher in IEC more than in ANSI, which led to alter the impact of DG on faulted buses. The results at faulted bus 671 are higher than the results at faulted bus 675 for IEC

5.7 Summary

In this chapter the modified IEEE 13 bus test distribution system has been modelled in ETAP 12 to examine the impact of different types of DG (wind, PV, hybrid, and diesel hybrid) on the short circuit level. In addition to the impact of DG location and various penetration levels for diesel hybrid integration into the system studied. The short circuit analysis performed using the ANSI and IEC methods for the calculation of SCC at selected bus at occurrence of 3-ph, L-G, LL, LL-G faults.

The simulated results showed that the SCC for 3-ph fault is the highest in comparison to all types of fault tested for both calculation methods. This is due to the positive sequence impedances that are involved in the 3-ph fault calculation are higher than the negative and zero sequences. For the unbalanced faults, LL-G is found to be the highest for IEC and ANSI standards.

The DFIG WTG is found to have a significant impact on the calculated short circuit currents when connected as the only DG source or when integrated with different types of DG. Conversely, it could be said that the PV have a limited impact on the short circuit currents neither connected as only source nor with other types of DG.

In the system under study, the relation between the DG location and SCC is relatively crucial, especially when the DG is connected near the utility grid, where the maximum values of SCCs were obtained. Scenario S4 confirmed this remark that is found, in which the SCCs are independent from the DG type or capacity once it is connected adjacent to the utility grid. Thus is a result of the high contribution of the utility grid on the SCC at the bus where it is connected. Furthermore, the SCCs for S3 where lower than S2 and S3 results, as the DG is connected to the furthest bus from the utility grid.

The examination of the different penetration level (10%, 30%, 42%, and 85%) of the utility rating showed that there is a direct relation between the penetration level of

DG and the SCCs. With the incremental increase of DG capacity connected to the system under study, there was an incremental increase in the SCCs. However, this increase could be considered as a limited, since the maximum difference between the SCC at no DG connected and with 85% penetration of DG is found to be about 9% depending on method of short circuit current calculation.

In the comparison between ANSI and IEC simulated results for the same system and scenarios applied, it was found that the IEC method yielded to higher values to the SCCs more than the ANSI method. Thus as a result to the impedance correction factors and voltage factor c taken into account by the IEC method. Therefore, the analysis outcome for the system was not similar for the two methods. IEC results led to different critique than that reached from ANSI results.

Chapter Six

6 IEEE 30 Bus Distribution Test System

6.1 Introduction

In this chapter, the main objective is to analyse the simulated results for ANSI and IEC calculations for the IEEE 30 bus, in order to evaluate the impact of DG type, location and penetration level on the short circuit current. The short circuit currents magnitudes of the system under study with no DG connected are considered as reference in order to be able to assess the impact of DG integration. Moreover, a comparison between the IEC simulated results and ANSI simulated results will be presented in order to ensure valid and reliable results.

This chapter is divided into seven main sections. First, section 6.1 is an introduction and outline to the chapter. Section 6.2 will provide the main characteristics for the system under study. Section 6.3 will illustrate the case studies examined. Section 6.4 will present the ANSI simulated results and comprehensive analyses to the results. Similarly, section 6.5 will present and provide detailed analysis to the IEC simulated results. Section 6.6 will compare between IEC and ANSI simulated results. Last, section 6.7 will provide a conclusion and recommendations.

6.2 System under study

The distribution test system used in this study is the IEEE 30-bus, shown in Figure 6.1. The system elements full data are provided in Appendix B.

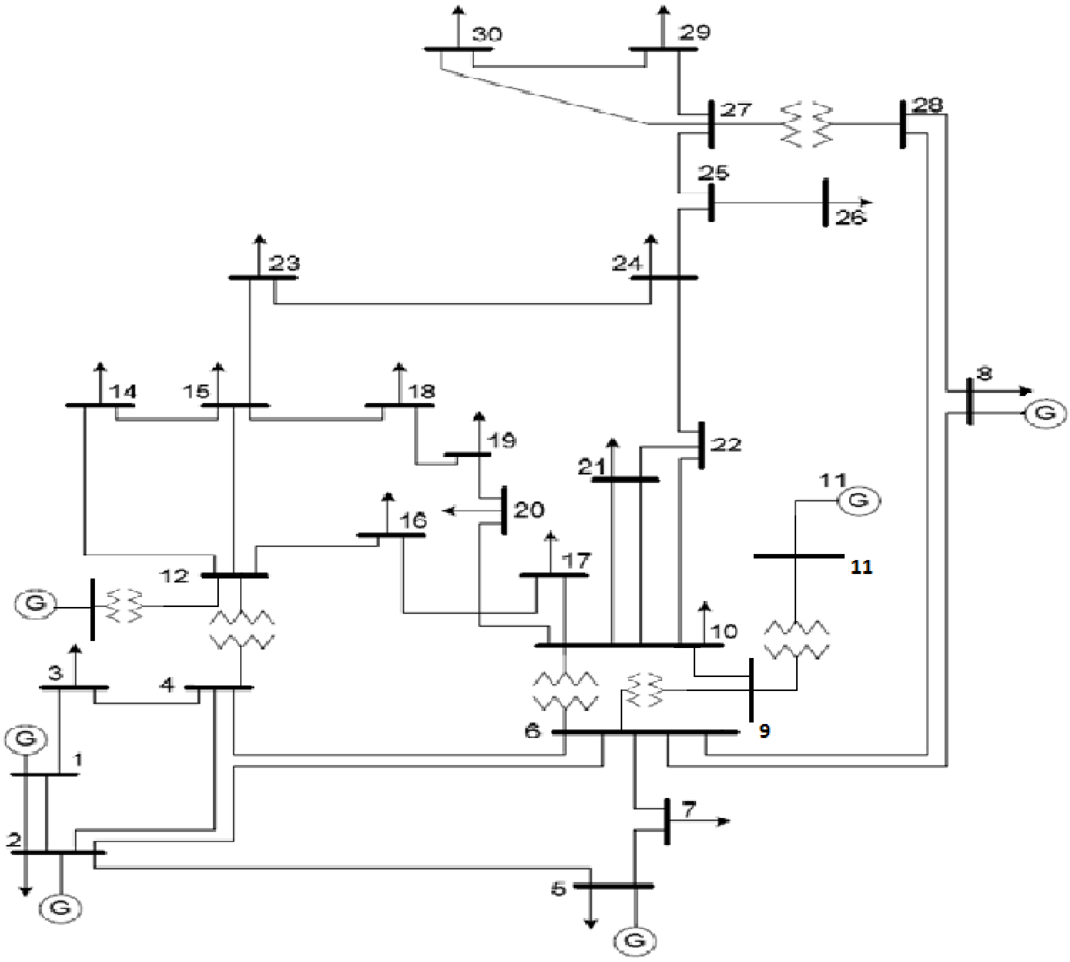

Figure 6.1 The IEEE30 bus system [12]

The model is implemented and modified in ETAP 14 software, where the short circuit analysis is performed for different six scenarios presented in section 6.3.

Initially, it was essential to ensure that the system is stable. Therefore, load flow analysis has been performed to obtain the magnitude and phase angle of voltage at each bus, and the real and reactive power flowing in each transmission line. Furthermore, in this system, the criteria to select the buses for DG installation is found to be different from the IEEE 13-bus distribution test system. For latter system, the distance from the main grid was considered as the reference on which the DG will be located. Whereas, the IEEE 30 bus system, there is no main grid to be taken as a reference. Therefore, the buses where the DG will be connected were selected based on their voltage profile at the base case (no DG installed) based on the Newton-Raphson (NR) load flow analysis. Results for load flow analysis are presented in Appendix C. It was found that the buses with lower voltage profile were: 7, 26, 29, and 30. Similar results were found in [117] after performing Newton-Raphson load flow analysis on the same system under study using MATLAB 7.0. Detailed load flow analysis is out of the scope of this research, however, it was crucial to be performed and considered to be aware with the system performance for coherent evaluation and assessment.

6.3 IEEE-30 bus distribution test system case studies

There are four cases of different DG units connected to the system under study as follows:

Case 1: Wind

Case 2: PV

Case 3: Hybrid system (Wind and PV)

Case 4: Diesel Hybrid system (Diesel generator Wind, and PV)

For each case study, there are six different scenarios selected to study the impact of DG location and capacity on the short circuit level of the distribution system presented in Table 6.1. The six scenarios for each case were repeated at different penetration levels: 10%; 30%, 42%; and 85% respectively.

TABLE 6.1: DIFFERENT SCENARIOS EXAMINED

Scenario	Condition
Scenario 1 (S1)	DG placed at Bus 7
Scenario 2 (S2)	DG placed at Bus 26
Scenario 3 (S3)	DG placed at Bus 29
Scenario 4 (S4)	DG placed at Bus 30
Scenario 5 (S5)	DG placed at Bus 7 and Bus 29
Scenario 6 (S6)	DG placed at Bus 26 and Bus 30

In cases 3 and 4 (where there are different types of DG units connected), the DG units ratings were equal. Similarly, DG capacities for S5 and S6 were divided equally.

6.3.1 Preliminary analysis for load flow studies

Load flow analysis has been performed after modifying the system model by including the DG at different scenarios with various penetration levels. Table 6.2 present a summary of load flow results obtained.

TABLE 6.2: SUMMARY OF LOAD FLOW ANALYSIS FOR MODIFIED IEEE 30 BUS TEST SYSTEM

Case ID	Load Flow Analysis (System Status)
No DG	Converged
10% Penetration Level	
Case 1: Wind Case 2: PV Case 3: Wind and PV Case 4: Wind, PV, and Diesel	Converged at all scenarios Converged at all scenarios Converged at all scenarios Converged at all scenarios
30% Penetration Level	
Case 1: Wind Case 2: PV Case 3: Wind and PV Case 4: Wind, PV, and Diesel	Converged at all scenarios Converged at all scenarios Converged at all scenarios Converged at all scenarios
42% Penetration Level	
Case 1: Wind Case 2: PV Case 3: Wind and PV Case 4: Wind, PV, and Diesel	Diverged at S2, S3, and S4 Diverged at S2, S3, and S4 Diverged at S2, S3, and S4 Converged at all scenarios
85% Penetration Level	
Case 1: Wind Case 2: PV Case 3: Wind and PV Case 4: Wind, PV, and Diesel	Converged at S1 only Converged at S1 only Converged at S1 only Converged at all scenarios

In the 42% penetration level of wind, the load flow failed to converge for S2, S3, and S4 respectively. However, the load flow converged for S1, S5, and S6 respectively. In comparing between S1, S2, S3, and S4 parameters, it could be found that these scenarios could be considered identical in terms of DG capacity, though different in terms of DG location. For S5 and S6, these scenarios are different from S1, S2, S3, and S4 in terms of DG capacity. In investigating the reason for system divergence in given scenarios, it has been observed that the bus voltages at buses 26, 29, and 30 for

S2, S3, and S4 respectively are the same and equal to 33 kV. However, the bus voltage at bus 7 for S1 is 132 kV. This raised the question, is there a direct relation between the bus voltage and the DG capacity. An initial justification has been considered that the bus with a lower voltage in the system under study is unable to accommodate DG with high penetration level of 42%. Whereas, the distribution network still could withstand the same DG capacity if it is distributed between the buses with same voltage 33 kV as in the S5 and S6, or if the DG located at a higher bus voltage 132kV as in S1. Though, a further scenario has been created to verify this preliminary assumption. The same DG capacity has been relocated to bus 28 (the selection criteria based on the same zone of diverged buses, but with higher bus voltage 132 kV). After performing load flow analysis, the system converged for the same DG capacity.

More load flow studies were simulated and yet failed to converge, despite the fact of taking into consideration different parameters such as: (Refer to EATP help load flow):

- Increasing number of iterations for Newton Raphson load flow analysis including 5, 50, and 99 iterations respectively. Though, five iterations are the maximum number of iterations recommended for NR by ETAP.
- Performing different load flow solution methods such as Adaptive Newton-Raphson, Fast-decoupled, and Accelerated Gauss-Seidel (GS).

The load flow solution methods are Newton-Raphson, Adaptive Newton-Raphson, Fast-decoupled, and Accelerated Gauss-Seidel. NR and GS are the most common used methods for load flow analysis. These methods tend to converge in the load flow studies for transmission systems more than distribution networks systems. This is due to the fact that distribution networks systems are considered to be “ill-conditioned power networks”. The following characteristics of distribution networks made these methods not suitable to be applied [118], [119]:

• Radial structure or weakly-meshed topologies

• High resistance to reactance (R/X)

In distribution networks R/X for transmission lines and cables are in range 0.5 to 7, more than in transmission networks, usually less than 0.5

• Type of Load

Load flow methods assume static load flow, where it is not the case for distribution networks; non-linear load models (such as rectifiers)

• Unbalanced distributed loads.

• Distributed generation

These characteristics, along with the large number of nodes and branches of distribution networks make the load flow solution methods inappropriate and not reliable for load flow studies of unbalanced distribution systems. Therefore unbalanced load flow studies and some distribution systems components shall be accurately modelled according to three phase basis. Moreover, there are a number of modified load flow solutions methods and algorithms especially designed for distribution networks presented in the literature [117].

6.3.2 Short circuit analysis

The short circuit analysis is run twice to include the two calculation methods: ANSI and IEC. The IEEE 30-bus system original model is modified through connecting DG with various capacities, penetration levels and at various locations. The DG units used are; Type 3 (DFIG) wind turbine generators (WTG), photovoltaics (PV), and diesel generators. The short circuit study included the four types of fault: 3-ph; LG; LL; and LLG at all the system buses respectively.

6.4 Simulated results for ANSI calculations

The study selected for the short circuit calculation is 1.5-4 cycles. This study performs 3-phase, line-to-ground, line-to-line, and line-to-line-to-ground fault studies per ANSI Standards. The study calculates short circuit currents in their rms values between 1.5 to 4 cycles at faulted buses. In this study, generators are represented by their positive, negative, and zero sequence subtransient reactance, and motors are modelled by their positive, negative, and zero sequence transient reactance [115] .

The simulated results are presented in Appendix D. The results are presented in this arrangement order to compare between the DG types, in regards their impact on the short circuit current, along with the influence of different DG location.

6.5 Analysis of simulated results for ANSI calculations

Table 6.3 presents the simulated results for the short circuit current magnitudes of the system under study at no DG connected.

TABLE 6.3: ANSI SIMULATED RESULTS AT NO DG INSTALLED (KA)

Bus		Type of Faults			
ID	kV	3-Ph	LG	LL	LLG
1	132	9.698	11.89	8.551	11.241
2	132	8.526	9.442	7.46	9.129
3	132	5.254	5.285	4.569	5.323
4	132	6.698	6.585	5.83	6.75
5	132	5.666	5.56	4.934	5.671
6	132	7.537	7.353	6.565	7.573
7	132	4.947	4.752	4.296	4.912
8	132	5.686	5.745	4.953	5.766
9	33	12.945	13.195	11.252	13.257
10	33	14.592	14.122	12.668	14.608
11	11	19.151	22.956	16.689	21.863
12	33	12.56	12.087	10.91	12.527
13	11	21.077	25.741	18.329	24.903
14	33	6.796	6.497	5.89	6.693
15	33	10.355	9.767	8.98	10.16
16	33	8.416	8.154	7.297	8.372
17	33	10.627	10.206	9.217	10.535
18	33	7.085	6.702	6.139	6.928
19	33	7.377	6.92	6.393	7.174
20	33	7.711	7.311	6.683	7.553
21	33	11.907	11.292	10.327	11.712
22	33	11.665	11.119	10.117	11.514
23	33	7.012	6.715	6.076	6.901
24	33	8.754	8.331	7.586	8.577
25	33	5.669	5.573	4.912	5.653
26	33	2.551	2.446	2.209	2.526
27	33	6.217	6.217	5.388	6.309
28	132	4.446	4.314	3.863	4.428
29	33	3.289	3.137	2.849	3.232
30	33	3.315	3.035	2.871	3.241

From Table 6.3, it is observed that for all types of fault examined, the highest SCCs occurred at buses 10, 11, and 13. These buses are the outcome of substations 132/33 kV. The decrease in voltage caused the SCC to increase. Also, the substation impedance contributes to the R/X ratio. There is no general pattern to types of fault as in the 13-bus distribution test system. Every bus has responded differently to the types of fault applied. This could be summarised as follows:

For buses 1, 2, 3, 11, and 13: the LG fault results were higher than LLG and 3-ph results. For buses 4, 5, 6, 10, and 12: the LLG fault results were higher than 3-ph and LG results. Whereas for Buses 8 and 9, the LLG fault results greater than LG and 3-ph faults values. However, for the rest of the buses starting from bus 14 to bus 30, the SCCs for the 3-ph fault were the highest; more than LLG and LG. it could be summarised as follows:

At Buses 1, 2, 3, 11, and 13	LG > LLG > 3-ph
At Buses 4, 5, 6, 10, and 12	LLG > 3-ph> LG
At Buses 8 and 9	LLG > LG > 3-ph
At Buses 14 - 30	3-ph > LLG >LG

6.5.1 Impact of DG penetration level on short circuit current

For every scenario, comparison between the four penetration levels (10%, 30%, 42%, and 85%) and the scenario of no DG is performed and presented in Figures 6.2-6.5. The comparison is performed on the buses that adopted the DG in each scenario, in order to examine the impact of DG penetration level on the short circuit current of the allocated buses.

6.5.1.1 Scenario One

A 3-ph fault at bus 7 is examined; the simulated results at bus 7 for different penetration levels and DG types are presented in Figure 6.2

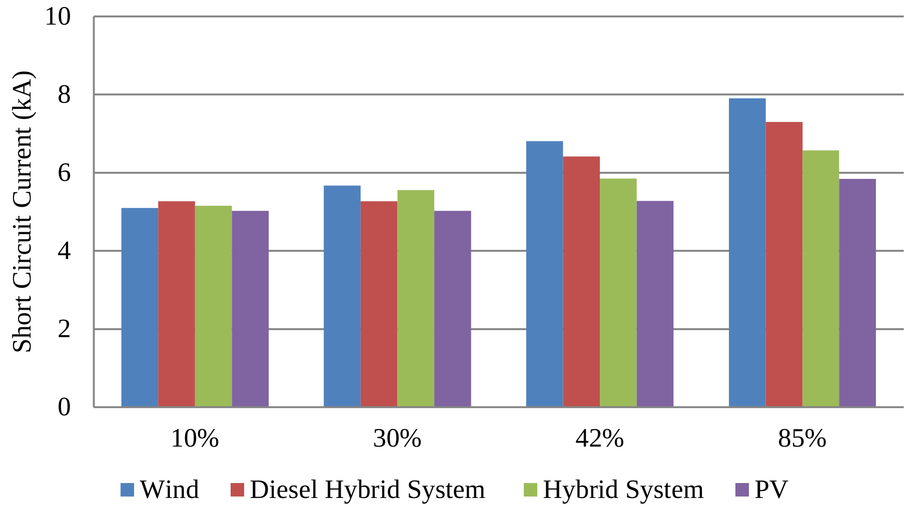

Figure 6.2 Short Circuit current versus different DG penetration level for Three-phase fault at bus 7

From Figure 6.2, it could be noticed that there is an increase in the SCCs with the increase of penetration level. The case of diesel hybrid system is noticed to be the highest case for the 10% penetration, with an increase of 0.326 kA (around 6%) from case of no DG. It could be observed that the case of wind is the highest type of DG in comparison to the other types and DG mix used for penetration levels 30%, 42%, and 85% respectively.

A LG fault at bus 7 is examined; the simulated results at bus 7 for different penetration levels and DG types are presented in Figure 6.3.

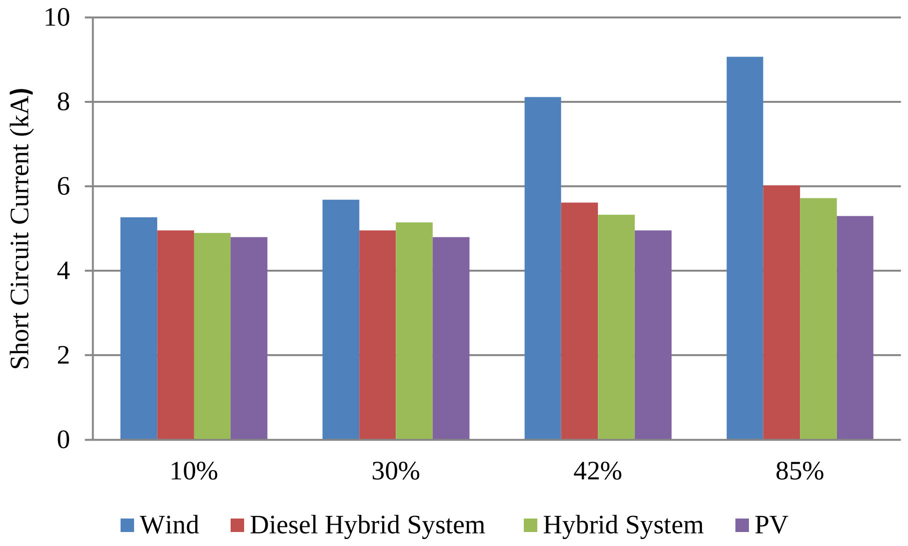

Figure 6.3 Short Circuit current versus different DG penetration level for LG fault at bus 7

From Figure 6.3, it could be observed that in case of wind for the 42% and 85% of penetration, the SCCs are higher in comparison to the other penetration levels and other DG types. The difference in case of no DG connected and 85% of wind is around 90% increase.

A LL fault at bus 7 is examined; the simulated results at bus 7 for different penetration levels and DG types are presented in Figure 6.4.

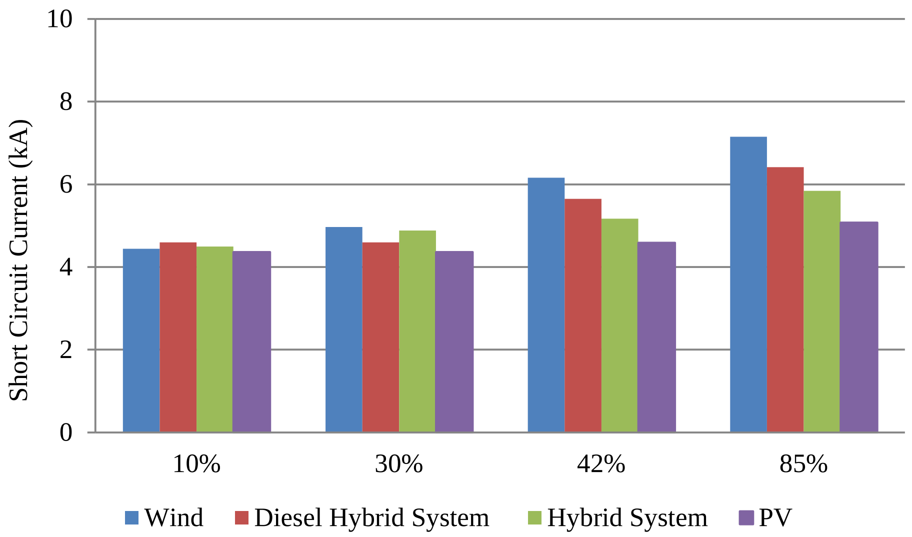

Figure 6.4 Short Circuit current versus different DG penetration level for LL fault at bus 7

A LLG fault at bus 7 is examined; the simulated results at bus 7 for different penetration levels and DG types are presented in Figure 6.5.

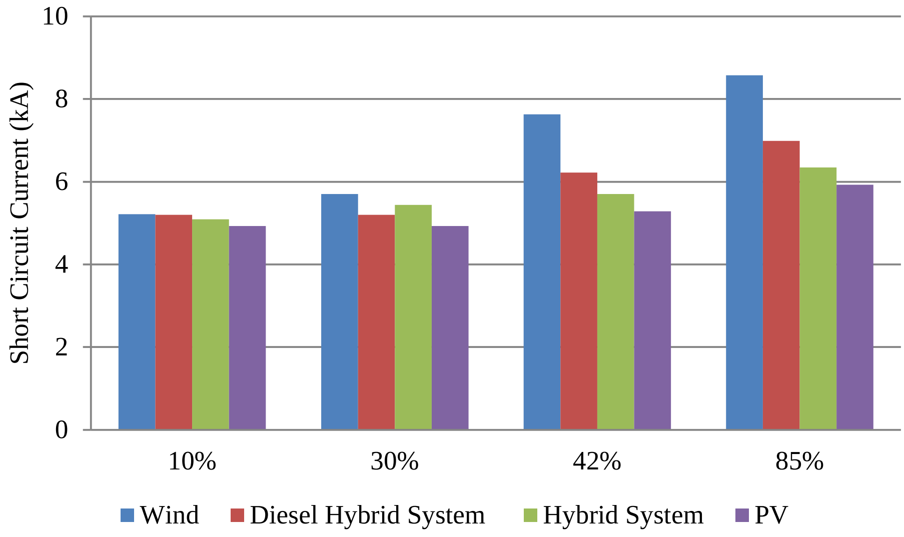

Figure 6.5 Short Circuit current versus different DG penetration level for LLG fault at bus 7

It could be concluded that for scenario one (S1), in instance of faults occurring at bus 7, the short circuit currents for every type of fault showed different outcomes. The LG fault yielded to a significant increase in case of wind at 42% and 85% of penetration, in comparison to the other types of DG used and penetrations 10% and 30%. For all types of fault, at 85% and 42% penetration, wind is the highest, followed by diesel hybrid, hybrid system, and PV is the lowest case. However, at 30% of DG penetration, hybrid system is higher than diesel hybrid system.

6.5.1.2 Scenario Two

A 3-ph fault at bus 26 is examined; the simulated results at bus 26 for different penetration levels and DG types are presented in Figure 6.6

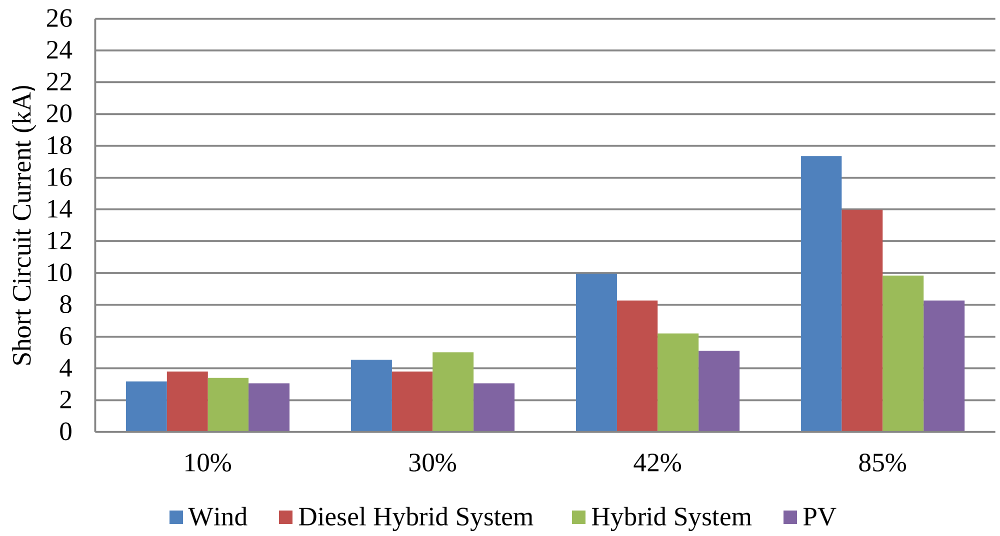

Figure 6.6 Short Circuit current versus different DG penetration level for Three-phase fault at bus 26

From Figure 6.6, it could be noticed that the increase in SCCs with the increase in penetration level started to double at 42% penetration level in particular in case of wind and diesel hybrid.

A LG fault at bus 26 is examined; the simulated results at bus 26 for different penetration levels and DG types are presented in Figure 6.7.

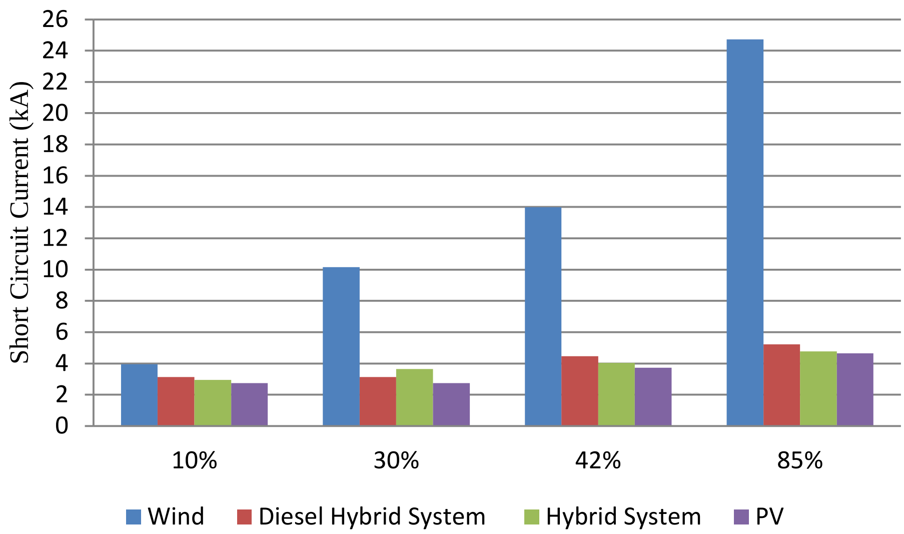

Figure 6.7 Short Circuit current versus different DG penetration level for LG fault at bus 26

From Figure 6.7, it could be observed that the SCCs incremented rapidly at 30% penetration level in case of wind where it exceeded the double in comparison to 10% penetration. Also, wind is much higher than other types of DG for 30%, 42% and 85% of penetration.

A LL fault at bus 26 is examined; the simulated results at bus 26 for different penetration levels and DG types are presented in Figure 6.8.

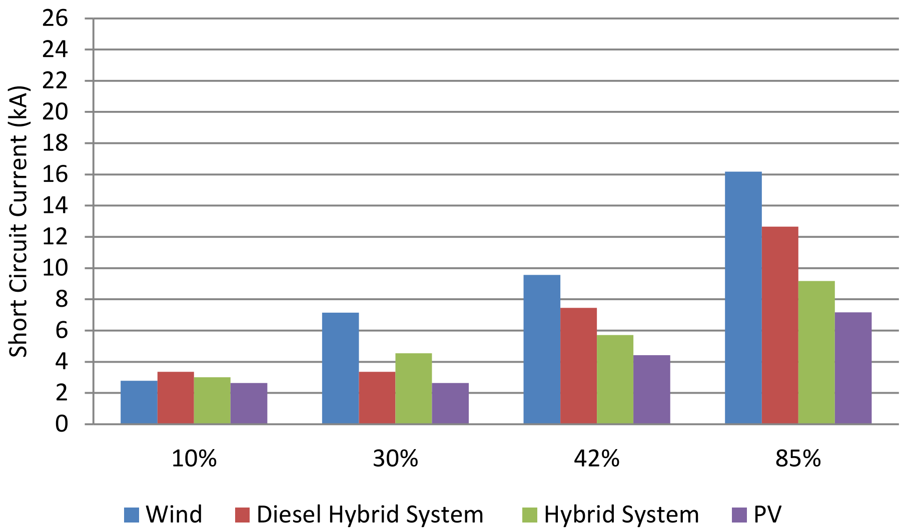

Figure 6.8 Short Circuit current versus different DG penetration level for LL fault at bus 26

A LLG fault at bus 26 is examined; the simulated results at bus 26 for different penetration levels and DG types are presented in Figure 6.9.

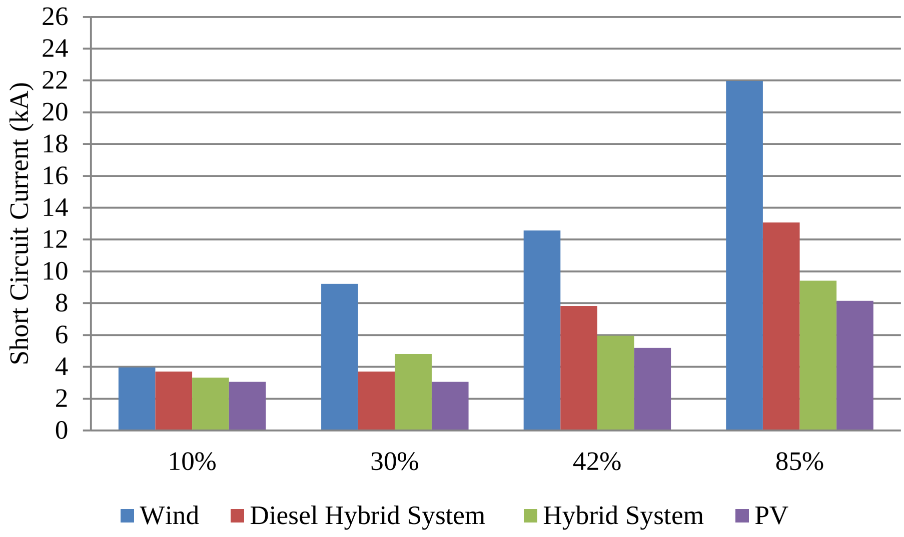

Figure 6.9 Short Circuit current versus different DG penetration level for LLG fault at bus 26

From Figures 6.6-6.9, for the four types of fault, it could be observed the following:

- 42% and 85% penetration levels: Wind impact on the SCCs is the highest, followed by diesel hybrid and hybrid, while the PV is the lowest impact.
- 30% penetration level: hybrid impact is higher than the diesel hybrid, though the wind and PV impacts are still similar to the 42% and 85% penetration levels.
- 10% penetration level: diesel hybrid influence on the SCCs is greater than wind, during the occurrence of 3-ph and LL faults.

6.5.1.3 Scenario Three

A 3-ph fault at bus 29 is examined; the simulated results at bus 29 for different penetration levels and DG types are presented in Figure 6.10

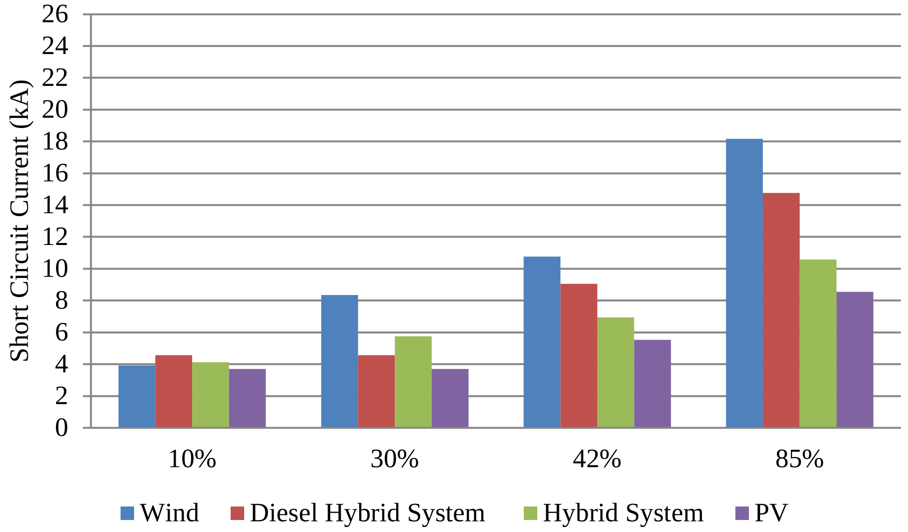

Figure 6.10 Short Circuit current versus different DG penetration level for Three-phase fault at bus 29

A LG fault at bus 29 is examined; the simulated results at bus 29 for different penetration levels and DG types are presented in Figure 6.11.

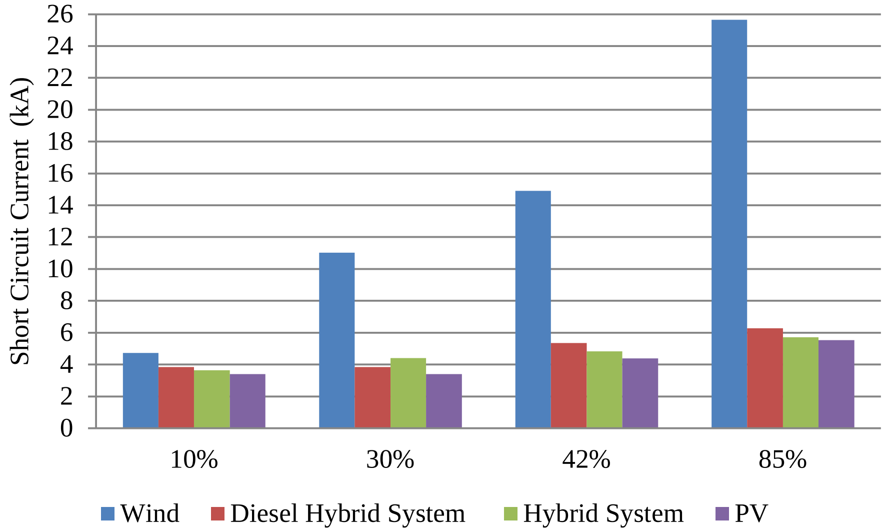

Figure 6.11 Short Circuit current versus different DG penetration level for LG fault at bus 29

A LL fault at bus 29 is examined; the simulated results at bus 29 for different penetration levels and DG types are presented in Figure 6.12.

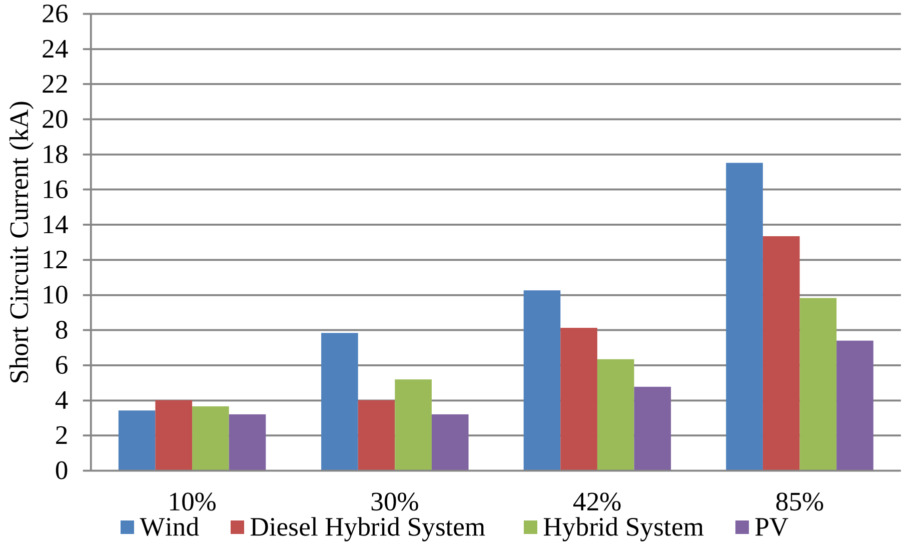

Figure 6.12 Short Circuit current versus different DG penetration level for LL fault at bus 29

A LLG fault at bus 29 is examined; the simulated results at bus 29 for different penetration levels and DG types are presented in Figure 6.13.

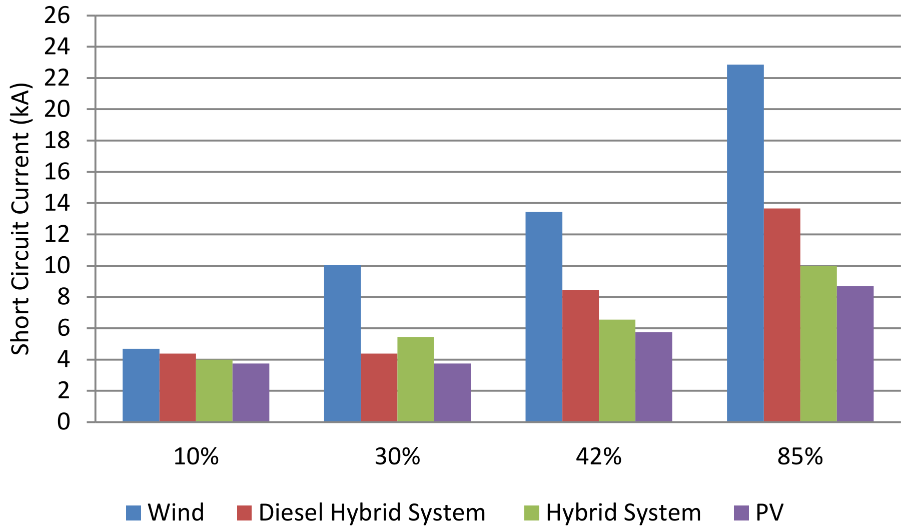

Figure 6.13 Short Circuit current versus different DG penetration level for LLG fault at bus 29

It is noticed that Scenario 3 is similar to scenario 2 in terms of consequence of different penetration levels and impact of DG types on the short circuit current.

6.5.1.4 Scenario Four

A 3-ph fault at bus 30 is examined; the simulated results at bus 30 for different penetration levels and DG types are presented in Figure 6.14.

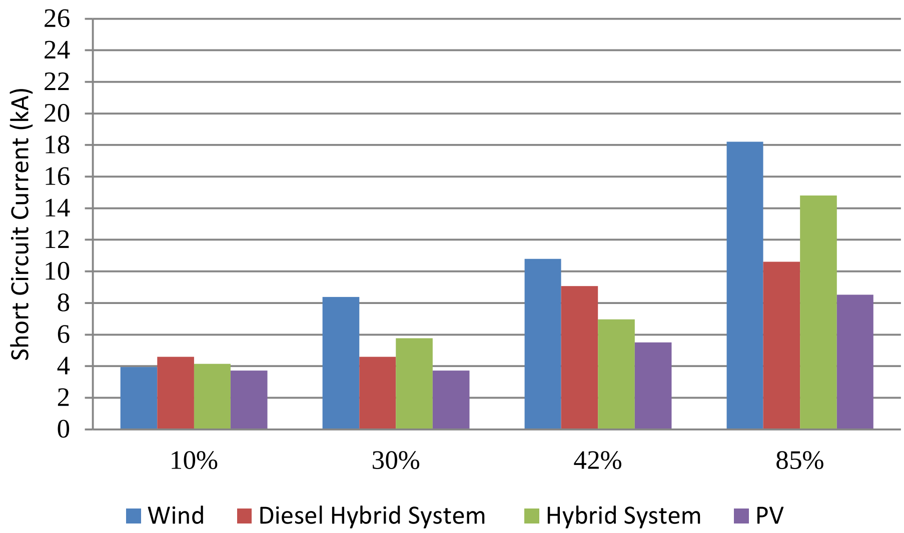

Figure 6.14 Short Circuit current versus different DG penetration level for Three-phase fault at bus 30

A LG fault at bus 30, the simulated results at bus 30 for different penetration levels and DG types are presented in Figure 6.15.

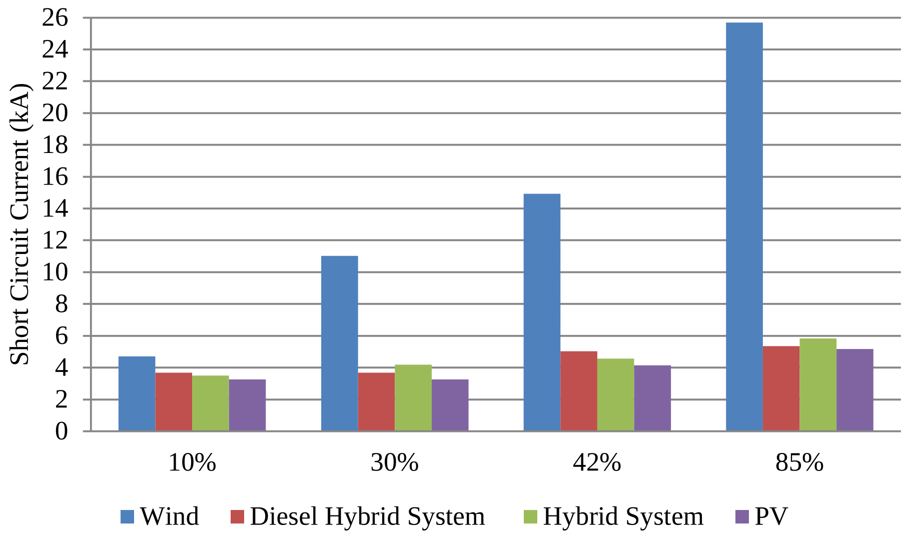

Figure 6.15 Short Circuit current versus different DG penetration level for LG fault at bus 30

A LL fault at bus 30 is examined; the simulated results at bus 30 for different penetration levels and DG types are presented in Figure 6.16.

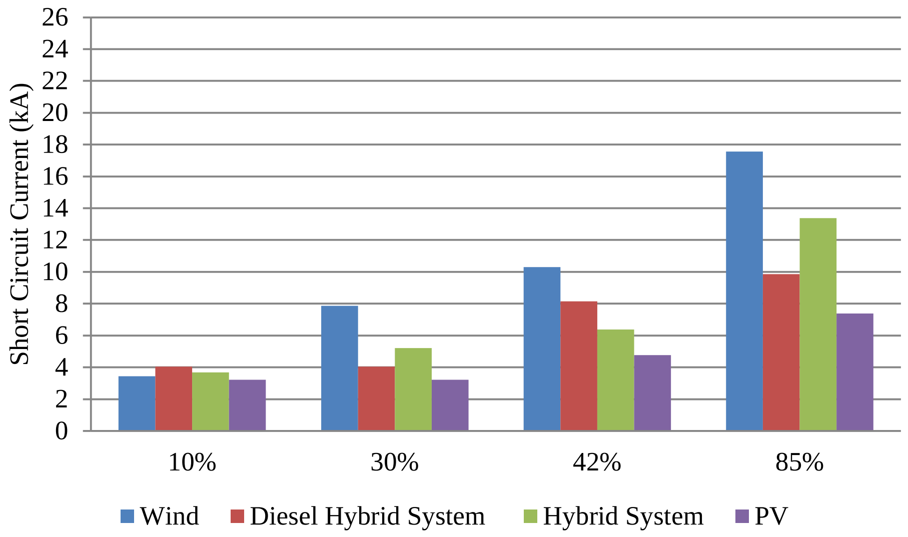

Figure 6.16 Short Circuit current versus different DG penetration level for LL fault at bus 30

A LLG fault at bus 30 is examined; the simulated results at bus 30 for different penetration levels and DG types are presented in Figure 6.17.

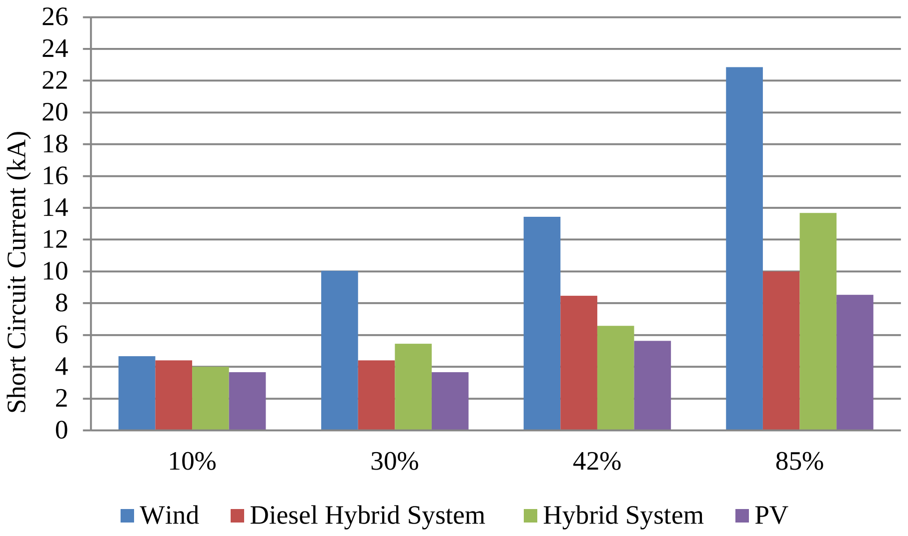

Figure 6.17 Short Circuit current versus different DG penetration level for LLG fault at bus 30

From Figures 6.14- 6.17, it could be noticed that for 85% penetration level, the hybrid system exceeded the diesel hybrid values. This did not occur for other scenarios.

6.5.1.5 Scenario Five

In this scenario, the DG capacity is divided over two buses. This is to examine the impact of DG capacity on the short circuit currents, and to identify the influence of dividing the capacity along the network. The results of the four types of fault simulated on bus 7 and 29 respectively are presented in Figures 6.18-6.21.

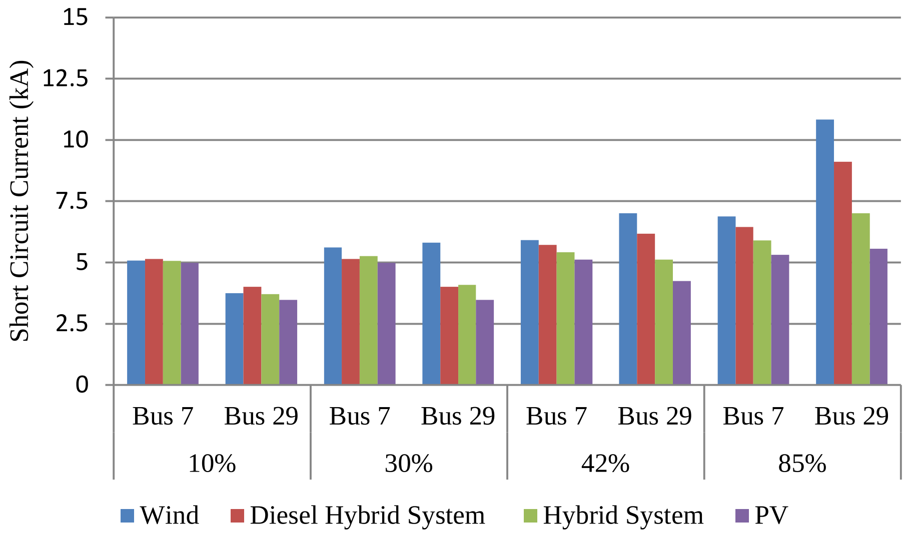

Figure 6.18 Short Circuit current versus different DG penetration level for Three-phase fault at buses 7 and 29

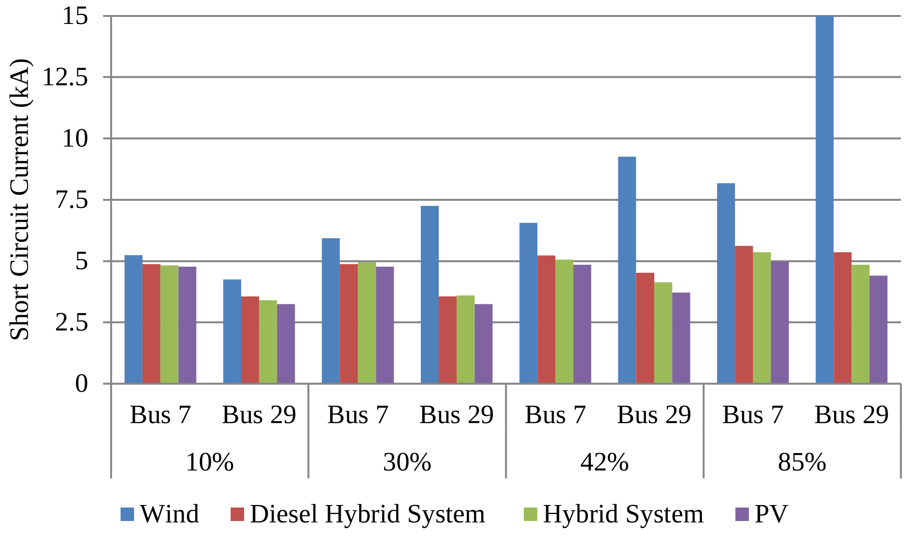

Figure 6.19 Short Circuit current versus different DG penetration level for LG fault at buses 7 and 29

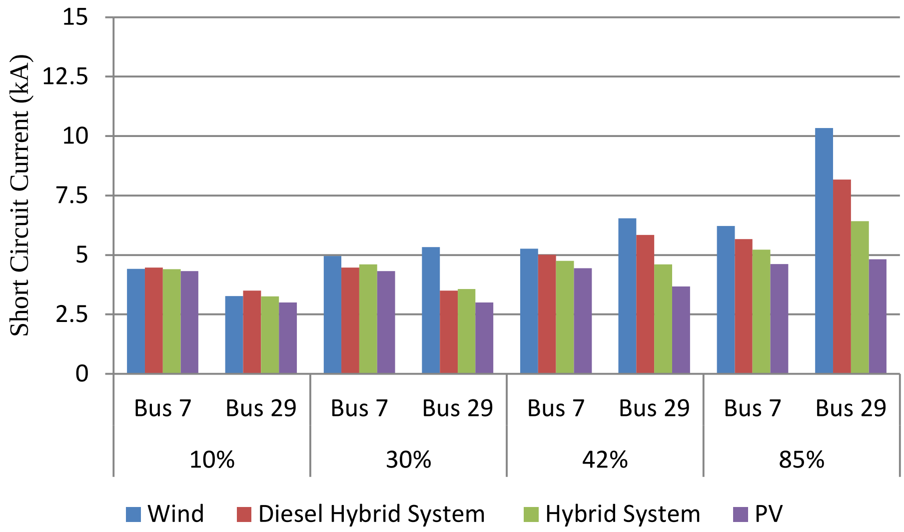

Figure 6.20 Short Circuit current versus different DG penetration level for LL fault at buses 7 and 29

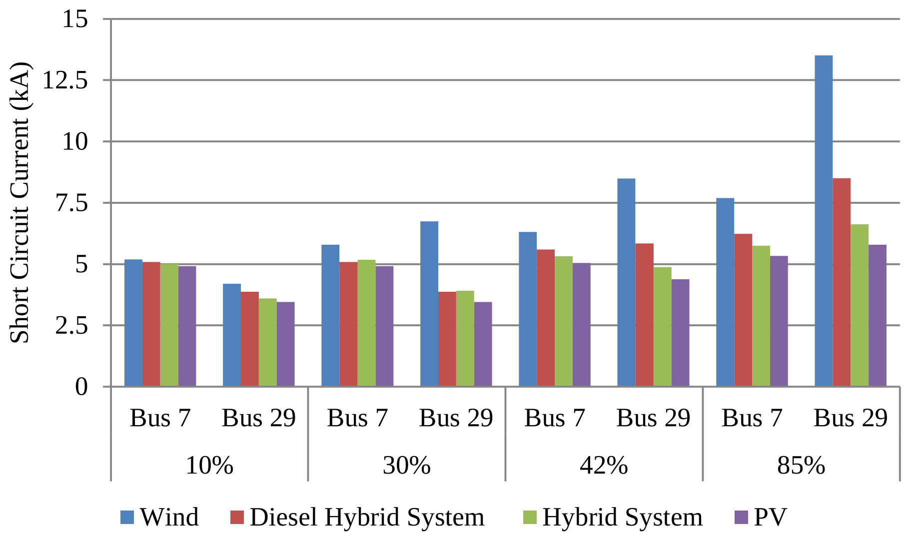

Figure 6.21 Short Circuit current versus different DG penetration level for LLG fault at buses 7 and 29

When comparing Figures 6.18-6.21 with Scenario 1 and scenario 3, it is observed that for bus 7 and 29, there was no change in the DG type performance. The sequence of DG types at each penetration level for the four types of fault applied is similar. Whereas, the impact of DG on SCC at bus 7 is very near to the results in S1. This is due to the existence of bus 7 in the transmission side of the network. However, for bus 29 the results indicated that with reducing the DG capacity, the SCCs are reduced.

6.5.1.6 Scenario Six

The aim of this scenario is similar to scenario 5, where the main objective is to examine the impact of DG capacity on the short circuit currents, and to identify the influence of dividing the capacity along the network. In this scenario the examined buses are 26 and 30. S5 and S6 are similar in capacities and different in location. The various scenarios would provide varied and reliable results.

The results of the four types of fault simulated on bus 26 and 30 respectively are presented in Figures 6.22- 6.25.

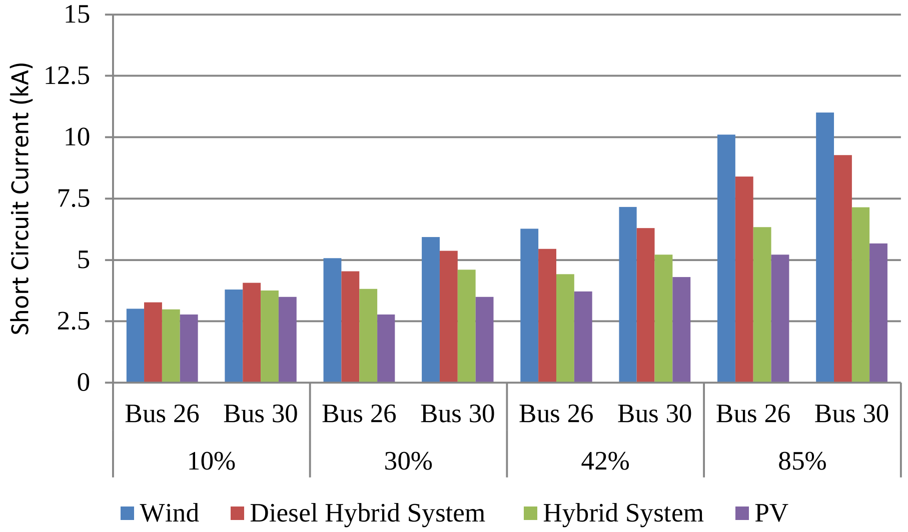

Figure 6.22 Short Circuit current versus different DG penetration level for Three-phase fault at buses 26 and 30

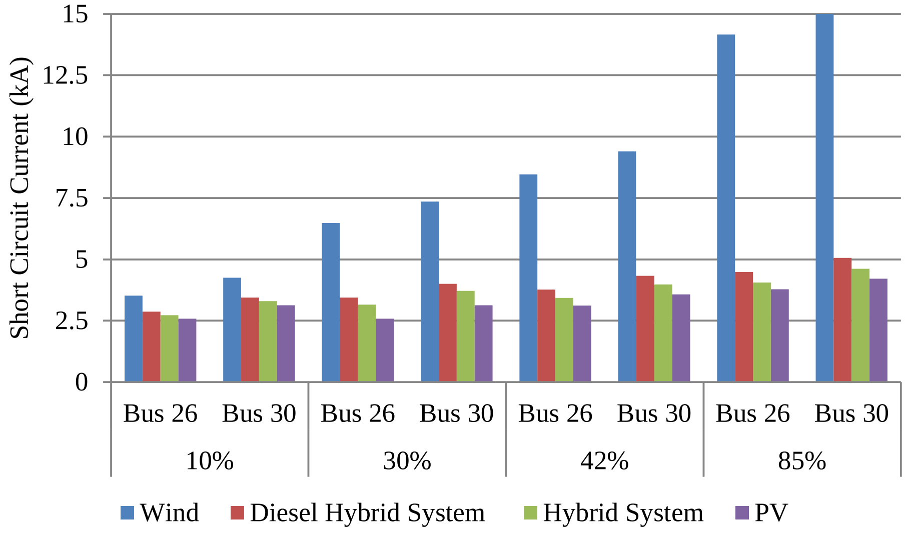

Figure 6.23 Short Circuit current versus different DG penetration level for LG fault at buses 26 and 30

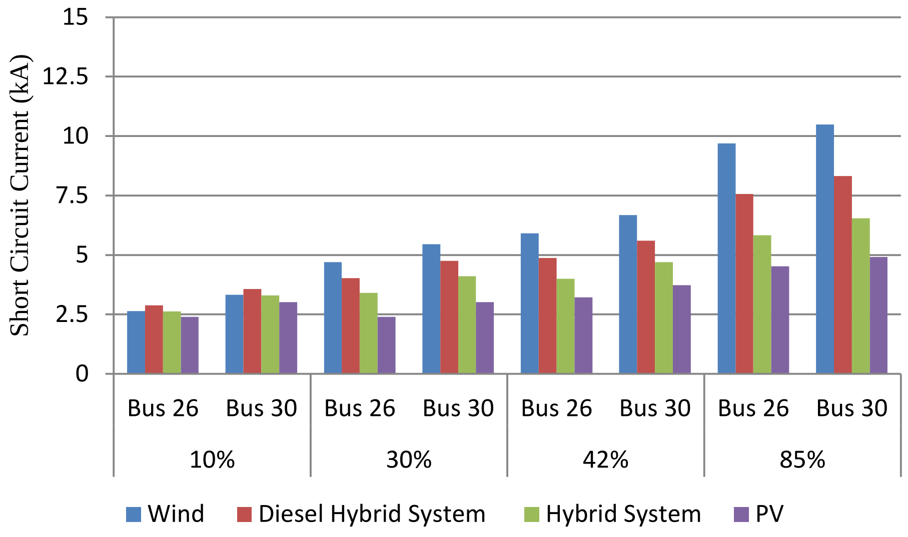

Figure 6.24 Short Circuit current versus different DG penetration level for LL fault at buses 26 and 30

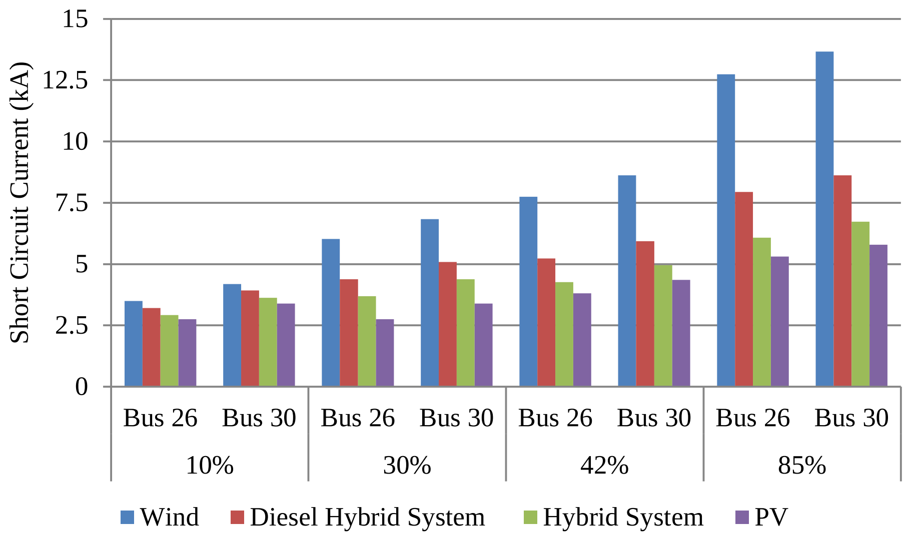

Figure 6.25 Short Circuit current versus different DG penetration level for LLG fault at buses 26 and 30

In comparing figures 6.22 – 6.25 with S2 and S4 figures, it is found that for penetration levels 10%, 30%, and 42%; the profile of DG types on the buses 26 and 30 is similar when these buses are accommodating the same DG type at increased capacity. Whereas for bus 30 at 85% penetration level, the diesel hybrid system increased the SCCs to exceed the hybrid system impact on SCCs, while in S4, the hybrid system was the dominant. Though, the short circuit currents for these buses in reduced, as a result of reducing the DG capacity.

6.5.2 Worst case scenarios

The worst 10 case scenarios are extracted and presented in Figure 6.26. It is found that the most severe scenarios that led to higher short circuit currents happened at 85% penetration level of wind.

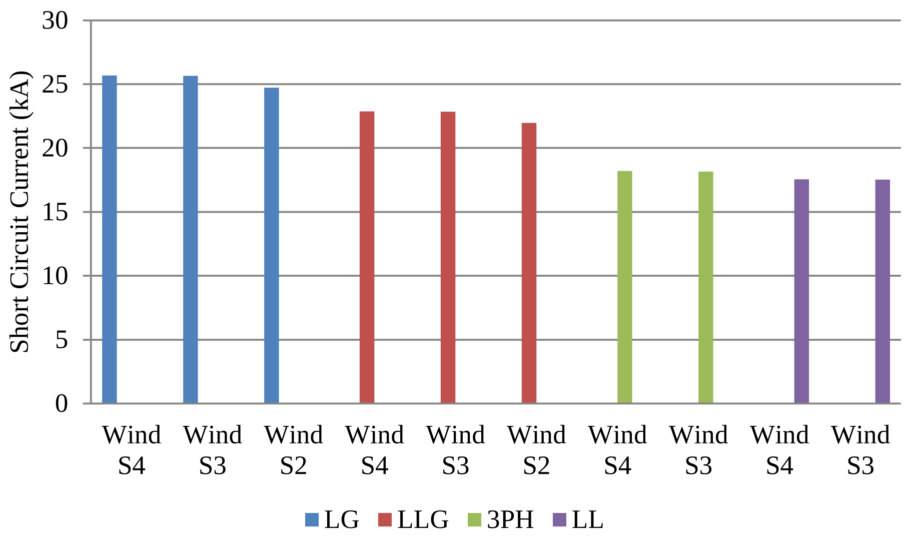

Figure 6.26 The worst cases for ANSI calculations

From Figure 6.26, it is noticed that S4 and S3 representing buses 30 and 29 respectively, are the most common buses affected when DG is installed during the occurrence of all types of fault. Furthermore, wind at bus 26 (S2) contributed effectively to the short circuit current on this bus for LG and LLG faults.

6.6 Analysis of simulated results for IEC calculations

As previously figured out in chapter five that the simulated results for IEC standard are different than the ANSI standard results due to the different types of prospective short circuit current determined (initial symmetrical current (I_k''); peak short circuit current (i_p); symmetrical short-circuit breaking current (I_b); and steady-state short circuit current (I_k).

Similarly to IEEE 13 bus distribution test system simulation, the computation is set to calculate the maximum short circuit currents which determine the capacity or rating of electrical equipment.

The LG, LL, LLG, and 3-Phase Faults (IEC 60909) study is selected in ETAP 14 for the short circuit calculation. This study performs line-to-ground, line-to-line, line-to-line-to-ground, and three-phase fault studies per IEC 60909 Standard. The study calculates initial symmetrical rms, peak and symmetrical breaking rms, and steady-state rms short-circuit currents at faulted buses. Detailed analyses have been provided in chapter five that differentiated between the different types of IEC simulated short circuit currents. In this chapter, the analyses are focused on the initial symmetrical current as it is found that the initial symmetrical current (I_k'') is the most SCC equivalent to ANSI symmetrical current, in order to be able to compare results. ETAP 14 models the generators by their positive, negative, and zero sequence reactance, while motors are modelled by their locked-rotor impedance [115]. The voltage factor *c* value varies depending on the system rated voltage. For the system under study, the *c* factor is selected to be 1.10 according to IEC-909606. The simulated results for the short circuit study are presented in Appendix D.

6.6.1 Worst case scenarios

From simulated results, it is found that the most severe scenarios that led to higher short circuit currents happened at 85% penetration level of wind. The worst 10 case scenarios are extracted and presented in Figure 6.27.

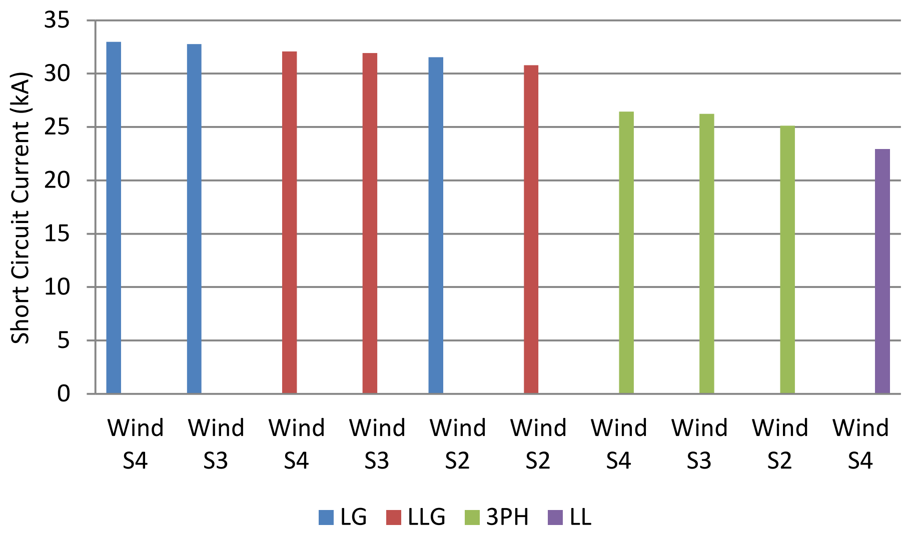

Figure 6.27 The worst cases for IEC calculations

From Figure 6.27, it is observed that scenario four (S4) in case of wind at bus 30 is the worst case scenario occurred in this study.

6.7 Differences between ANSI and IEC results

In this section the differences between ANSI and IEC results are calculated and presented in percentage in Tables 6.4 – 6.9.

TABLE 6.4: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 1

3-ph Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
Penetration Level	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	4.947	6.134	24.0	4.947	6.134	24.0	4.947	6.134	24.0	4.947	6.134	24.0
10%	5.101	6.325	24.0	5.273	6.546	24.1	5.156	6.427	24.7	5.022	6.215	23.8
30%	5.671	7.103	25.3	5.273	6.546	24.1	5.555	6.984	25.7	5.022	6.215	23.8
42%	6.809	9.041	32.8	6.417	7.999	24.7	5.85	7.416	26.8	5.277	6.487	22.9
85%	7.906	10.332	30.7	7.296	9.021	23.6	6.575	8.384	27.5	5.844	7.089	21.3

LG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	4.752	5.667	19.3	4.752	5.667	19.3	4.752	5.667	19.3	4.752	5.667	19.3
10%	5.267	6.331	20.2	4.959	5.897	18.9	4.892	5.83	19.2	4.798	5.712	19.0
30%	5.684	6.827	20.1	4.959	5.897	18.9	5.144	6.123	19.0	4.798	5.712	19.0
42%	8.113	10.093	24.4	5.612	6.625	18.1	5.327	6.338	19.0	4.956	5.869	18.4
85%	9.067	11.123	22.7	6.025	7.069	17.3	5.718	6.783	18.6	5.296	6.205	17.2

LL Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	4.296	5.322	23.9	4.296	5.322	23.9	4.296	5.322	23.9	4.296	5.322	23.9
10%	4.438	5.489	23.7	4.595	5.683	23.7	4.497	5.577	24.0	4.362	5.393	23.6
30%	4.97	6.161	24.0	4.595	5.683	23.7	4.879	6.058	24.2	4.362	5.393	23.6
42%	6.157	7.837	27.3	5.649	6.958	23.2	5.17	6.432	24.4	4.585	5.631	22.8
85%	7.147	8.955	25.3	6.415	7.853	22.4	5.842	7.27	24.4	5.078	6.154	21.2

LLG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	4.912	5.995	22.0	4.912	5.995	22.0	4.912	5.995	22.0	4.912	5.995	22.0
10%	5.217	6.372	22.1	5.203	6.351	22.1	5.094	6.235	22.4	4.926	6.009	22.0
30%	5.704	6.991	22.6	5.203	6.351	22.1	5.437	6.688	23.0	4.926	6.009	22.0
42%	7.633	9.863	29.2	6.222	7.602	22.2	5.702	7.044	23.5	5.287	6.386	20.8
85%	8.572	10.916	27.3	6.987	8.494	21.6	6.346	7.86	23.9	5.929	7.073	19.3

TAble 6.5: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 2

3-ph Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
Penetration Level	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	2.551	3.06	20.0	2.551	3.06	20.0	2.551	3.06	20.0	2.551	3.06	20.0
10%	3.174	3.841	21.0	3.803	4.632	21.8	3.391	4.232	24.8	3.052	3.596	17.8
30%	4.542	10.488	130.9	3.803	4.632	21.8	5.008	6.464	29.1	3.052	3.596	17.8
42%	9.952	14.193	42.6	8.267	10.257	24.1	6.196	8.192	32.2	5.099	5.8	13.7
85%	17.355	25.137	44.8	13.979	17.425	24.7	9.843	13.304	35.2	8.264	9.253	12.0

LG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	2.446	2.87	17.3	2.446	2.87	17.3	2.446	2.87	17.3	2.446	2.87	17.3
10%	3.942	4.69	19.0	3.136	3.659	16.7	2.95	3.472	17.7	2.743	3.172	15.6
30%	10.148	12.73	25.4	3.136	3.659	16.7	3.645	4.281	17.4	2.743	3.172	15.6
42%	13.985	17.74	26.9	4.47	5.158	15.4	4.024	4.722	17.3	3.731	4.208	12.8
85%	24.727	31.544	27.6	5.211	5.97	14.6	4.759	5.54	16.4	4.647	5.211	12.1

LL Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	2.209	2.65	20.0	2.209	2.65	20.0	2.209	2.65	20.0	2.209	2.65	20.0
10%	2.783	3.326	19.5	3.354	4.03	20.2	3.012	3.664	21.6	2.644	3.114	17.8
30%	7.136	9.077	27.2	3.354	4.03	20.2	4.544	5.596	23.2	2.644	3.114	17.8
42%	9.555	12.282	28.5	7.446	8.967	20.4	5.701	7.091	24.4	4.416	5.023	13.7
85%	16.187	21.751	34.4	12.66	15.253	20.5	9.178	11.515	25.5	7.158	8.014	12.0

LLG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	2.526	3.017	19.4	2.526	3.017	19.4	2.526	3.017	19.4	2.526	3.017	19.4
10%	3.959	4.753	20.1	3.705	4.449	20.1	3.311	4.035	21.9	3.062	3.56	16.3
30%	9.221	12.429	34.8	3.705	4.449	20.1	4.811	5.955	23.8	3.062	3.56	16.3
42%	12.572	17.374	38.2	7.835	9.452	20.6	5.956	7.451	25.1	5.19	5.863	13.0
85%	21.976	30.793	40.1	13.071	15.769	20.6	9.412	11.867	26.1	8.153	9.111	11.8

Table 6.6: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 3

3-ph Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
Penetration Level	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	3.289	4.08	24.0	3.289	4.08	24.0	3.289	4.08	24.0	3.289	4.08	24.0
10%	3.912	4.857	24.2	4.564	5.678	24.4	4.131	5.258	27.3	3.705	4.524	22.1
30%	8.342	11.57	38.7	4.564	5.678	24.4	5.745	7.493	30.4	3.705	4.524	22.1
42%	10.757	15.278	42.0	9.048	11.324	25.2	6.934	9.224	33.0	5.523	6.457	16.9
85%	18.166	26.227	44.4	14.768	18.5	25.3	10.581	14.34	35.5	8.55	9.727	13.8

LG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	3.137	3.799	21.1	3.137	3.799	21.1	3.137	3.799	21.1	3.137	3.799	21.1
10%	4.729	5.762	21.8	3.848	4.614	19.9	3.649	4.412	20.9	3.39	4.056	19.6
30%	11.025	13.881	25.9	3.848	4.614	19.9	4.396	5.295	20.5	3.39	4.056	19.6
42%	14.903	18.937	27.1	5.349	6.329	18.3	4.828	5.808	20.3	4.39	5.092	16.0
85%	25.661	32.757	27.7	6.283	7.391	17.6	5.717	6.832	19.5	5.531	6.341	14.6

LL Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	2.849	3.534	24.0	2.849	3.534	24.0	2.849	3.534	24.0	2.849	3.534	24.0
10%	3.423	4.207	22.9	4.015	4.935	22.9	3.656	4.553	24.5	3.21	3.919	22.1
30%	7.836	10.014	27.8	4.015	4.935	22.9	5.188	6.487	25.0	3.21	3.919	22.1
42%	10.261	13.222	28.9	8.124	9.891	21.8	6.349	7.986	25.8	4.784	5.593	16.9
85%	17.529	22.696	29.5	13.345	16.182	21.3	9.828	12.413	26.3	7.406	8.425	13.8

LLG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	3.232	3.976	23.0	3.232	3.976	23.0	3.232	3.976	23.0	3.232	3.976	23.0
10%	4.688	5.756	22.8	4.386	5.38	22.7	3.985	4.961	24.5	3.737	4.505	20.6
30%	10.047	13.513	34.5	4.386	5.38	22.7	5.436	6.828	25.6	3.737	4.505	20.6
42%	13.429	18.485	37.6	8.456	10.317	22.0	6.558	8.296	26.5	5.757	6.672	15.9
85%	22.848	31.918	39.7	13.662	16.599	21.5	9.967	12.656	27.0	8.706	9.886	13.6

TABLE 6.7: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 4

3-ph Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
Penetration Level	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	3.315	4.282	29.2	3.315	4.282	29.2	3.315	4.282	29.2	3.315	4.282	29.2
10%	3.937	5.056	28.4	4.593	5.885	28.1	4.155	5.459	31.4	3.716	4.697	26.4
30%	8.381	11.793	40.7	4.593	5.885	28.1	5.768	7.692	33.4	3.716	4.697	26.4
42%	10.797	15.504	43.6	9.081	11.539	27.1	6.957	9.424	35.5	5.503	6.55	19.0
85%	18.209	26.456	45.3	10.603	18.718	76.5	14.802	14.54	-1.8	8.514	9.765	14.7

LG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	3.035	3.751	23.6	3.035	3.751	23.6	3.035	3.751	23.6	3.035	3.751	23.6
10%	4.714	5.891	25.0	3.688	4.471	21.2	3.504	4.29	22.4	3.255	3.957	21.6
30%	11.033	14.051	27.4	3.688	4.471	21.2	4.179	5.058	21.0	3.255	3.957	21.6
42%	14.924	19.135	28.2	5.028	5.953	18.4	4.564	5.501	20.5	4.148	4.826	16.3
85%	25.687	32.965	28.3	5.344	6.849	28.2	5.838	6.373	9.2	5.162	5.901	14.3

LL Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	2.871	3.708	29.2	2.871	3.708	29.2	2.871	3.708	29.2	2.871	3.708	29.2
10%	3.444	4.378	27.1	4.04	5.115	26.6	3.678	4.727	28.5	3.219	4.068	26.4
30%	7.87	10.208	29.7	4.04	5.115	26.6	5.209	6.66	27.9	3.219	4.068	26.4
42%	10.296	13.417	30.3	8.152	10.076	23.6	6.37	8.159	28.1	4.767	5.674	19.0
85%	17.567	22.894	30.3	9.849	16.37	66.2	13.375	12.586	-5.9	7.375	8.458	14.7

LLG Fault	Wind			Diesel Hybrid System			Hybrid System			PV		
0%	3.241	4.147	28.0	3.241	4.147	28.0	3.241	4.147	28.0	3.241	4.147	28.0
10%	4.657	4.378	-6.0	4.399	5.553	26.2	3.997	5.131	28.4	3.658	4.522	23.6
30%	10.043	13.648	35.9	4.399	5.553	26.2	5.452	7.001	28.4	3.658	4.522	23.6
42%	13.435	18.637	38.7	8.477	10.495	23.8	6.578	8.473	28.8	5.626	6.591	17.2
85%	22.859	32.078	40.3	9.995	16.78	67.9	13.686	12.838	-6.2	8.536	9.733	14.0

TABLE 6.8: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 5

3-ph Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	7	4.947	6.134	24.0	4.947	6.134	24.0	4.947	6.134	24.0	4.947	6.134	24.0
	29	3.289	4.08	24.0	3.289	4.08	24.0	3.289	4.08	24.0	3.289	4.08	24.0
10%	7	5.076	6.295	24.0	5.139	6.373	24.0	5.058	6.288	24.3	4.982	6.171	23.9
	29	3.743	4.661	24.5	4.001	4.986	24.6	3.711	4.671	25.9	3.467	4.272	23.2
30%	7	5.609	7.099	26.6	5.139	6.373	24.0	5.264	6.57	24.8	4.982	6.171	23.9
	29	5.802	7.81	34.6	4.001	4.986	24.6	4.08	5.074	24.4	3.467	4.272	23.2
42%	7	5.914	7.677	29.8	5.715	7.096	24.2	5.423	6.799	25.4	5.114	6.308	23.3
	29	7.003	9.657	37.9	6.17	7.702	24.8	5.116	6.661	30.2	4.242	5.092	20.0
85%	7	6.875	8.997	30.9	6.448	8.003	24.1	5.905	7.471	26.5	5.316	6.518	22.6
	29	10.835	15.38	41.9	9.109	11.39	25.1	7.008	9.316	32.9	5.563	6.498	16.8

LG Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	7	4.752	5.667	19.3	4.752	5.667	19.3	4.752	5.667	19.3	4.752	5.667	19.3
	29	3.137	3.799	21.1	3.137	3.799	21.1	3.137	3.799	21.1	3.137	3.799	21.1
10%	7	5.249	6.311	20.2	4.876	5.802	19.0	4.828	5.753	19.2	4.773	5.687	19.1
	29	4.246	5.172	21.8	3.563	4.288	20.3	3.406	4.122	21.0	3.245	3.91	20.5
30%	7	5.939	7.184	21.0	4.876	5.802	19.0	4.961	5.907	19.1	4.773	5.687	19.1
	29	7.248	9.04	24.7	3.563	4.288	20.3	3.596	4.324	20.2	3.245	3.91	20.5
42%	7	6.564	8.075	23.0	5.224	6.187	18.4	5.065	6.028	19.0	4.854	5.765	18.8
	29	9.257	11.65	25.8	4.522	5.385	19.1	4.141	5	20.7	3.713	4.385	18.1
85%	7	8.173	10.06	23.0	5.624	6.627	17.8	5.356	6.365	18.8	4.98	5.886	18.2
	29	14.992	19.04	27.0	5.362	6.343	18.3	4.85	8.533	75.9	4.408	5.111	15.9

LL Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	7	4.296	5.322	23.9	4.296	5.322	23.9	4.296	5.322	23.9	4.296	5.322	23.9
	29	2.849	3.534	24.0	2.849	3.534	24.0	2.849	3.534	24.0	2.849	3.534	24.0
10%	7	4.416	5.462	23.7	4.473	5.532	23.7	4.404	5.456	23.9	4.327	5.355	23.8
	29	3.272	4.037	23.4	3.508	4.328	23.4	3.254	4.045	24.3	3.003	3.7	23.2
30%	7	4.952	6.157	24.3	4.473	5.532	23.7	4.599	5.7	23.9	4.327	5.355	23.8
	29	5.337	6.761	26.7	3.508	4.328	23.4	3.565	4.395	23.3	3.003	3.7	23.2
42%	7	5.261	6.657	26.5	5.003	6.166	23.2	4.756	5.898	24.0	4.442	5.475	23.3
	29	6.548	8.359	27.7	5.839	6.713	15.0	4.607	5.767	25.2	3.675	4.411	20.0
85%	7	6.216	7.798	25.5	5.67	6.962	22.8	5.219	6.48	24.2	4.619	5.658	22.5
	29	10.333	13.31	28.8	8.177	9.95	21.7	6.416	8.065	25.7	4.819	5.629	16.8

LLG Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	7	4.912	5.995	22.0	4.912	5.995	22.0	4.912	5.995	22.0	4.912	5.995	22.0
	29	3.232	3.976	23.0	3.232	3.976	23.0	3.232	3.976	23.0	3.232	3.976	23.0
10%	7	5.194	6.345	22.2	5.082	6.199	22.0	5.007	6.119	22.2	4.914	5.997	22.0
	29	4.197	5.163	23.0	3.879	4.769	22.9	3.602	4.463	23.9	3.451	4.199	21.7
30%	7	5.795	7.189	24.1	5.082	6.199	22.0	5.184	6.35	22.5	4.914	5.997	22.0
	29	6.747	8.836	31.0	3.879	4.769	22.9	3.91	4.792	22.6	3.451	4.199	21.7
42%	7	6.312	8.001	26.8	5.593	6.821	22.0	5.325	6.537	22.8	5.054	6.131	21.3
	29	8.492	11.37	33.9	5.839	7.146	22.4	4.879	6.13	25.6	4.382	5.193	18.5
85%	7	7.696	9.82	27.6	6.24	7.601	21.8	5.747	7.089	23.4	5.329	6.421	20.5
	29	13.509	18.59	37.6	8.509	10.38	21.9	6.626	8.377	26.4	5.797	6.713	15.8

TABLE 6.9: COMPARISON BETWEEN ANSI RESULTS AND IEC RESULTS FOR SCENARIO 6

3-ph Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	26	2.551	3.06	20.0	2.551	3.06	20.0	2.551	3.06	20.0	2.551	3.06	20.0
	30	3.315	4.282	29.2	3.315	4.282	29.2	3.315	4.282	29.2	3.315	4.282	29.2
10%	26	3.017	3.653	21.1	3.274	3.969	21.2	2.988	3.662	22.6	2.773	3.297	18.9
	30	3.798	4.888	28.7	4.074	5.233	28.4	3.762	4.898	30.2	3.49	4.46	27.8
30%	26	5.072	6.785	33.8	4.541	3.969	-12.6	3.817	4.793	25.6	2.773	3.297	18.9
	30	5.937	8.12	36.8	5.375	5.233	-2.6	4.606	6.05	31.4	3.49	4.46	27.8
42%	26	6.274	8.634	37.6	5.457	6.69	22.6	4.424	5.67	28.2	3.719	4.292	15.4
	30	7.154	9.982	39.5	6.303	8.004	27.0	5.22	6.937	32.9	4.302	5.278	22.7
85%	26	10.102	14.35	42.1	8.401	10.38	23.6	6.336	8.336	31.6	5.222	5.899	13.0
	30	11.002	15.717	42.9	9.267	11.717	26.4	7.144	9.62	34.7	5.671	6.694	18.0

LG Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	26	2.446	2.87	17.3	2.446	2.87	17.3	2.446	2.87	17.3	2.446	2.87	17.3
	30	3.035	3.751	23.6	3.035	3.751	23.6	3.035	3.751	23.6	3.035	3.751	23.6
10%	26	3.523	4.18	18.6	2.876	3.359	16.8	2.723	3.198	17.4	2.581	3.005	16.4
	30	4.257	5.298	24.5	3.449	4.202	21.8	3.296	4.047	22.8	3.131	3.838	22.6
30%	26	6.486	7.993	23.2	3.448	3.359	-2.6	3.159	3.709	17.4	2.581	3.005	16.4
	30	7.355	9.277	26.1	4.004	4.202	4.9	3.714	4.52	21.7	3.131	3.838	22.6
42%	26	8.459	10.558	24.8	3.773	4.374	15.9	3.43	4.031	17.5	3.113	3.544	13.8
	30	9.396	11.934	27.0	4.326	5.167	19.4	3.98	4.827	21.3	3.576	4.25	18.8
85%	26	14.162	17.91	26.5	4.492	5.176	15.2	4.06	4.753	17.1	3.78	4.248	12.4
	30	15.159	19.363	27.7	5.062	5.982	18.2	4.613	5.544	20.2	4.217	4.885	15.8

LL Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	26	2.209	2.65	20.0	2.209	2.65	20.0	2.209	2.65	20.0	2.209	2.65	20.0
	30	2.871	3.708	29.2	2.871	3.708	29.2	2.871	3.708	29.2	2.871	3.708	29.2
10%	26	2.645	3.164	19.6	2.878	3.448	19.8	2.627	3.171	20.7	2.402	2.855	18.9
	30	3.321	4.233	27.5	3.573	4.542	27.1	3.301	4.242	28.5	3.023	3.863	27.8
30%	26	4.702	5.873	24.9	4.028	3.448	-14.4	3.412	4.15	21.6	2.402	2.855	18.9
	30	5.458	7.03	28.8	4.752	4.542	-4.4	4.102	5.239	27.7	3.023	3.863	27.8
42%	26	5.912	7.472	26.4	4.872	5.838	19.8	4.003	4.909	22.6	3.221	3.717	15.4
	30	6.682	8.64	29.3	5.607	6.974	24.4	4.702	6.006	27.7	3.727	4.571	22.6
85%	26	9.692	12.418	28.1	7.564	9.075	20.0	5.828	7.216	23.8	4.523	5.109	13.0
	30	10.48	13.601	29.8	8.316	10.231	23.0	6.539	8.328	27.4	4.912	5.798	18.0

LLG Fault	Bus	Wind			Diesel Hybrid			Hybrid			PV		
Penetration Level	No	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%	ANSI	IEC	%
0%	26	2.526	3.017	19.4	2.526	3.017	19.4	2.526	3.017	19.4	2.526	3.017	19.4
	30	3.241	4.147	28.0	3.241	4.147	28.0	3.241	4.147	28.0	3.241	4.147	28.0
10%	26	3.499	4.191	19.8	3.206	3.84	19.8	2.924	3.531	20.8	2.757	3.229	17.1
	30	4.191	5.27	25.7	3.925	4.971	26.6	3.632	4.651	28.1	3.394	4.24	24.9
30%	26	6.02	7.832	30.1	4.377	3.84	-12.3	3.69	4.508	22.2	2.757	3.229	17.1
	30	6.839	9.047	32.3	5.09	4.971	-2.3	4.385	5.612	28.0	3.394	4.24	24.9
42%	26	7.747	10.353	33.6	5.228	6.278	20.1	4.269	5.264	23.3	3.806	4.34	14.0
	30	8.615	11.621	34.9	5.933	7.388	24.5	4.955	6.356	28.3	4.356	5.228	20.0
85%	26	12.744	17.543	37.7	7.942	9.551	20.3	6.074	7.569	24.6	5.313	5.965	12.3
	30	13.666	18.869	38.1	8.626	10.635	23.3	6.734	8.628	28.1	5.792	6.737	16.3

From Tables 6.4 – 6.9, it could be observed that the IEC simulated results are much higher than the ANSI simulated results in most of the examined scenarios, except in few instances. This occurred at 85% penetration level of hybrid in scenario S4 for 3-ph, LL and LLG fault. Also, IEC results were lower than ANSI results in scenarios S5 and S6 more frequently than in S1-S4.

6.8 Summary

This chapter main objective was to investigate the impact of four different cases of DG types on the short circuit current of the IEEE 30 bus system. Six different scenarios representing different locations on the system under study has been selected after conducting load flow analysis with no DG installed. The load flow analysis has been performed after DG penetration, and it showed that the system was unable to adopt the higher levels of penetration including 42% and 85%, especially for lower bus voltages.

It is could be concluded that the wind had the most significant impact on the short circuit currents in comparison to the other types of DG used, in particular during the occurrence of LG fault on buses 30, 29, and 26 respectively. The PV maintained the lowest impact on the SCCs through all the scenarios examined. The performance of diesel hybrid and hybrid system seemed to be fluctuating, varying the short circuit currents while varying the DG capacity, location and penetration level. The increase in penetration levels is found to have substantial influence on the short circuit currents with higher penetrations as 42% and 85%, as occurred in different scenarios examined. The 30% penetration level showed moderate results, though in case of wind in particular at the occurrence of LG and LLG faults, the results were exceptionally high in comparison to other types of DG used.

The IEC simulated results are found to be more than the ANSI results up to 68% approximately. This confirms that IEC method is much more conservative than ANSI method.

Chapter Seven

7 Conclusions and Future Work

The main aim of the current research was to investigate the impact of wind, PV, and their mix including diesel generators on the short circuit current in electrical distribution network using different calculation methods such as IEEE/ANSI and IEC.

This research motivation and drive have been presented in chapter one. The increased deployment of distributed generation to meet environmental targets, to ensure diversity of supply, and to meet increasing demand have created enormous technical challenges on the electrical power distribution systems that need to be addressed and tackled.

The introduction of distributed generation into the distribution networks has evolved their principal properties from being passive to being active, and the flow of power from unidirectional to being bi directional. Consequently, this caused some power systems operational issues to occur such as power quality, voltage control and network fault level. Chapter two presented a comprehensive review conducted on the various technical impacts of DG on distributed networks and the simulation studies performed in the existing literature examining the influence of DG on distribution systems parameters in particular short circuit level.

Furthermore, it identified the research gap that previous research have not addressed and investigated. Increased penetration level; diversified DG location; calculation of symmetrical and unsymmetrical faults using different methods were never proposed and implemented. This has led to the proposed main research objectives and contribution to investigate the impact of different types and mixes of DG including Wind, PV, and diesel generators on short circuit level on large distribution systems with considerable number of buses using different calculation methods.

Chapter three attempted to illustrate the relation between the distributed generation, its integration into distribution networks specifically, and the importance of short circuit studies. The penetration of DG (as renewable sources) into distributed systems is more practical and achievable than connection into transmission systems. Geographical locations of resources are more likely to be near the load; easily accessible and manageable operation and maintenance of generators; and high cost of high voltage transformers and switchgears is avoided; and high cost of high voltage transformers and switchgears is avoided.

Despite the several advantages that DG provides, its integration may have a significant impact on short circuit that as a consequence may affect the protection equipment, relay settings and coordination. As a consequence, the system reliability and robustness will be affected. Therefore, short circuit study is a fundamental examination that should be precisely considered.

In chapter four, the IEC and ANSI methods for short circuit calculations have been presented in details. Both methods require detailed modelling of system components for the short circuit calculations, hence, IEC requires more detailed data to be available than ANSI.

The IEC differentiates between the network types either radial or loop, and distinguishes whether or not the generator location is near or far from the short circuit point in short circuit currents calculations. Whereas, ANSI considers the generator location either to be remote or local depending on the transformation impedance value between the generator and the short circuit location.

In chapter five, the first objective of this thesis has been executed where the modified IEEE 13 bus distribution test system has been modelled in ETAP 12. The simulation included the short circuit analysis using the two standards ANSI/IEEE and IEC. The study considered the impact of different types of DG (wind, PV, hybrid, and diesel hybrid) and the impact of their location. Different penetration levels as 10%; 30%; 42%; and 85% of diesel hybrid integration into the system were examined.

The results of this investigation show that the 3-ph fault is the highest type of fault in comparison to all types of fault tested for both calculation methods IEC and ANSI. Surprisingly, the LL-G fault is found to be the highest unsymmetrical fault. This finding is contrary to previous studies which have suggested that LG is the common type of fault likely to occur and on this basis it is the most type of fault tested.

The investigation of impact of DG types on the short circuit current finds that wind has the most significant impact on the short circuit currents in particular when connected as the only DG source. Whereas, PV made no significant difference to short circuit current in all scenarios.

The results indicate that the short circuit currents are affected by the location of DG especially when the DG is connected near the utility grid, where the maximum values of SCCs were observed. These findings suggest that in general the optimal location for DG is as far as possible from the utility grid to minimize the impact of DG on short circuit current.

The examination of the different penetration levels shows that there is a direct relation between the penetration level of DG and the SCCs. The results show that as the penetration level increases the short circuit current increases.

The ANSI and IEC simulated results for the same system and scenarios applied are found to be not identical. The results for the IEC method are higher than the results for ANSI method. This finding is expected to be found due to the impedance correction factors and voltage factor c considered by the IEC method.

In chapter six, the main objective was to support the initial findings from the investigations applied in chapter five, however, on larger system as IEEE 30 bus system. Accordingly, more scenarios were examined representing different locations. In this system, there was no utility grid to set as a reference to decide the DG location. Therefore, the criteria came out after conducting load flow analysis with no DG installed. The load flow analysis has been performed after DG penetration, and it showed that the system was unable to adopt the higher levels of penetration including 42% and 85%, especially for lower bus voltages.

Similarly, the results show that the wind had the most significant impact on the short circuit currents in comparison to the other types of DG used and the PV had no recognised influence on the on the SCCs.

The IEC simulated results are found to be more than the ANSI results up to 68% approximately. This confirms that IEC method is much more conservative than ANSI method.

The most obvious finding to emerge from this study is that for the short circuit calculations using the IEC method leads to more conservative results than ANSI standard.

The second major finding was that all types of fault are crucial and there is no one type of fault more dominant or more common than the other, in which research has always focused only three phase and single line to ground faults. Though, full short circuit studies should be performed taking into consideration all types of fault for precise results and appropriate equipment sizing, reliable relay settings and coordination.

7.1 Future work

A number of proposed future works could be extended from this research such as performing the same study on systems with higher number of busses including the GB grid. The study on existing grid would add to current contributions and assures the research findings significance. Also, a methodology of allocating the DG technologies among the network with less impact is needed to be identified in order to set an appropriate guideline for distribution network operators to facilitate the design and implementation of DG integration. The impact of different short circuit calculations methods on the relay settings and coordination scheme of protection equipment in distributed networks is an opportunity for further studies to be carried out to ensure system protection and reliability. Furthermore, identifying the opportunities on to how to limit the impact of different DG technologies on the short circuit currents when will be located near utility grids. This is a crucial study that could be executed to limit the impact of DG on short circuit currents when connected to the nearest point to the grid, where in real situations could not be avoided. Meanwhile, higher penetration levels are uncertain and have negative impact on the power systems stability and short circuit currents. Therefore, a future prospective could be to identify the maximum permissible penetration level while maintaining system stability.

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Appendix A

IEEE 13 Bus Distribution Test System Data

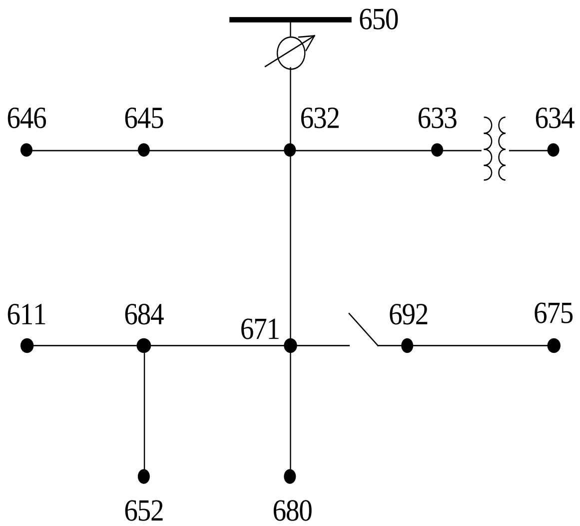

Figure A1 - One Line Diagram of IEEE-13 bus distribution test system

Table A1 - Underground Line Configuration Data

Configuration	Phasing	Cable	Neutral	Space ID
606	A B C N	250, 000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Table A2 - Overhead Line Configuration Data

Configuration	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556, 500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Table A3 - Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation	5,000	115 – D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Table A4 - Line Segment Data

Node A	Node B	Length(ft.)	Configuration
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Table A5 - Capacitor Data

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Table A6 - Regulator Data

Regulator ID	1		
Line Segment	650 – 632		
Location	650		
Phases	A-B-C		
Connection	3-Ph, LG		
Monitoring Phase	A-B-C		
Bandwidth	2.0 volts		
PT Ratio	20		
Primary CT Rating	700		
Compensator Settings	Ph-A	Ph-B	Ph-C
R-Setting	3	3	3
X-Setting	9	9	9
Voltage Level	122	122	122

Table A7 - Distribution Load Data

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
			kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Table A8 - Spot Load Data

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Appendix B

IEEE 30 – Bus Test Data

Table B10 - Load Demand

Bus	P in MW	Q in Mvar
2	21.7	12.7
3	2.4	1.2
4	7.6	1.6
5	94.2	19.0
7	22.8	10.9
8	30.0	30.0
10	5.8	2.0
12	11.2	7.5
14	6.2	1.6
15	8.2	2.5
16	3.5	1.8
17	9.0	5.8
18	3.2	0.9
19	9.5	3.4
20	2.2	0.7
21	17.5	11.2
23	3.2	1.6
24	8.7	6.7
26	3.5	2.3
29	2.4	0.9
30	10.6	1.9

Table B11 - Generator Controller Setting

Generator	Bus Type	Voltage per unit	Minimum MVAr	Maximum MVAr
1	Slack	1.05	N.A.	N.A.
2	PV	1.0338	-20.0	60.0
5	PV	1.0058	-15.0	62.5
8	PV	1.0230	-15.0	50.0
11	PV	1.0913	-10.0	40.0
13	PV	1.0883	-15.0	45.0

Table B12 - Transformer Data

Transformer No.	Between Buses	X per unit	Tap Setting
1	6 – 9	0.2080	1.0155
2	6 – 10	0.5560	0.9629
3	4 – 12	0.2560	1.0129
4	27 – 28	0.3960	0.9581
5	9 – 11	0.2080	0.0000
6	9 – 10	0.1100	0.0000
7	12 – 13	0.1400	0.0000

Table B13 - Line Data

Line No.	Between Buses	R per unit	X per unit	Susceptance per unit
1	1 – 2	0.0192	0.0575	0.0528
2	1 – 3	0.0452	0.1852	0.0408
3	2 – 4	0.0570	0.1737	0.0368
4	3 – 4	0.0132	0.0379	0.0084
5	2 – 5	0.0472	0.1983	0.0418
6	2 – 6	0.0581	0.1763	0.0374
7	4 – 6	0.0119	0.0414	0.0090
8	5 – 7	0.0460	0.1160	0.0204
9	6 – 7	0.0267	0.0820	0.0170
10	6 – 8	0.0120	0.0420	0.0090
11	6 – 9	0.0	0.2080	0.0
12	6 – 10	0.0	0.5560	0.0
13	9 – 11	0.0	0.2080	0.0
14	9 – 10	0.0	0.1100	0.0
15	4 – 12	0.0	0.2560	0.0
16	12 – 13	0.0	0.1400	0.0
17	12 – 14	0.1231	0.2559	0.0
18	12 – 15	0.0662	0.1304	0.0
19	12 – 16	0.0945	0.1987	0.0
20	14 – 15	0.2210	0.1997	0.0
21	16 – 17	0.0824	0.1932	0.0
22	15 – 18	0.1070	0.2185	0.0
23	18 – 19	0.0639	0.1292	0.0
24	19 – 20	0.0340	0.0680	0.0
25	10 – 20	0.0936	0.2090	0.0
26	10 – 17	0.0324	0.0845	0.0
27	10 – 21	0.0348	0.0749	0.0
28	10 – 22	0.0727	0.1499	0.0
29	21 – 22	0.0116	0.0236	0.0
30	15 – 23	0.1000	0.2020	0.0
31	22 – 24	0.1150	0.1790	0.0
32	23 – 24	0.1320	0.2700	0.0
33	24 – 25	0.1885	0.3292	0.0

34	25 – 26	0.2544	0.3800	0.0
35	25 – 27	0.1093	0.2087	0.0
36	27 – 28	0.0	0.3960	0.0
37	27 – 29	0.2198	0.4153	0.0
38	27 – 30	0.3202	0.6027	0.0
39	29 – 30	0.2399	0.4533	0.0
40	8 – 28	0.0636	0.2000	0.0428
41	6 – 28	0.0169	0.0599	0.0130

Table B14 - Shunt Capacitor Data

Bus No.	Susceptance per unit
10	0.19
24	0.04

Table B15 - Voltage Level of Each Buses

Bus No.	Voltage Magnitude in kV
1	132
2	132
3	132
4	132
5	132
6	132
7	132
8	132
9	132
10	33
11	18
12	33
13	18
14	33
15	33
16	33
17	33
18	33
19	33
20	33
21	33
22	33
23	33
24	33
25	33
26	33
27	33
28	33
29	33
30	33

Appendix C

Table C1 - Load Flow Simulation Results for IEEE 30 Bus test system with no DG connected.

Bus		Voltage		Load Flow				
ID	kV	%Magnitude	Angle	ID	MW	MVAr	Amp	%PF
Bus 1	132.0	106.0	0.0	Bus 2	173.2	-21.3	720.2	-99.2
				Bus 3	87.7	4.5	362.5	99.9
Bus 2	132.0	104.3	-5.4	Bus 1	-168.1	31.0	716.5	-98.3
				Bus 4	43.6	3.9	183.7	99.6
				Bus 5	82.4	1.8	345.5	100.0
				Bus 6	60.3	0.5	253.0	100.0
Bus 3	132.0	102.1	-7.5	Bus 1	-84.6	2.4	362.7	-100.0
				Bus 4	82.2	-3.6	352.6	-99.9
Bus 4	132.0	101.2	-9.3	Bus 2	-42.6	-4.7	185.3	99.4
				Bus 3	-81.4	5.2	352.4	-99.8
				Bus 6	72.2	-16.3	319.8	-97.5
				Bus 12	44.2	14.2	200.8	95.2
Bus 5	132.0	101.0	-14.2	Bus 2	-79.4	6.2	345.0	-99.7
				Bus 7	-14.8	11.7	81.5	-78.4
Bus 6	132.0	101.0	-11.1	Bus 2	-58.4	1.5	252.9	-100.0
				Bus 4	-71.5	17.6	318.9	-97.1
				Bus 7	38.1	-3.0	165.5	-99.7
				Bus 8	29.6	-8.1	132.7	-96.5
				Bus 28	18.7	0.0	80.8	100.0
				Bus 9	27.7	-8.2	125.1	-95.9
				Bus 10	15.8	0.2	68.6	100.0
Bus 7	132.0	100.2	-12.9	Bus 5	14.9	-13.3	87.3	-74.7
				Bus 6	-37.7	2.4	165.0	-99.8
Bus 8	132.0	101.0	-11.8	Bus 6	-29.5	7.5	131.7	-96.9
				Bus 28	-0.5	-0.4	2.9	80.1
Bus 9	33.0	105.1	-14.1	Bus 10	27.7	5.9	471.8	97.8
				Bus 6	-27.7	9.8	489.4	-94.3
				Bus 11	0.0	-15.7	261.8	0.0
Bus 10	33.0	104.5	-15.7	Bus 9	-27.7	-5.1	471.8	98.3
				Bus 17	5.3	4.4	115.9	76.9
				Bus 20	9.0	7.7	163.3	92.5
				Bus 21	15.8	10.0	312.9	84.4
				Bus 22	7.6	4.6	149.0	85.6
				Bus 6	-15.8	1.1	265.8	-99.7
Bus 11	11.0	108.2	-14.1	Bus 9	0.0	16.2	785.3	0.0
Bus 12	11.0	105.7	-14.9	Bus 14	7.9	2.4	136.0	95.6
				Bus 15	17.9	6.8	316.9	93.5
				Bus 16	7.3	3.4	132.2	90.8

				Bus 4	-44.2	-9.5	748.6	97.7
				Bus 13	0.0	-10.5	173.9	0.0
Bus 13	11.0	107.1	-14.9	Bus 12	0.0	10.6	521.7	0.0
Bus 14	33.0	104.2	-15.8	Bus 12	-7.8	-2.2	136.0	96.1
				Bus 15	1.6	0.6	28.7	92.6
Bus 15	33.0	103.8	-15.9	Bus 12	-17.7	-6.4	316.9	94.1
				Bus 14	-1.6	-0.6	28.7	92.6
				Bus 18	6.0	1.6	105.0	96.7
				Bus 23	5.0	2.9	98.2	86.6
Bus 16	33.0	104.4	-15.5	Bus 12	-7.2	-3.2	132.2	91.2
				Bus 17	3.7	1.4	66.5	93.2
Bus 17	33.0	104.0	-15.9	Bus 10	-5.3	-4.4	115.9	77.1
				Bus 16	-3.7	-1.4	66.5	93.4
Bus 18	33.0	102.8	-16.5	Bus 15	-6.0	-15.5	105.0	96.9
				Bus 19	2.8	0.6	48.5	97.6
Bus 19	33.0	102.6	-16.7	Bus 18	-2.8	-0.6	48.5	97.7
				Bus 20	-6.7	-2.8	124.2	92.4
Bus 20	33.0	103.0	-16.5	Bus 10	-8.9	-3.5	163.3	93.0
				Bus 19	6.7	2.8	124.2	92.2
Bus 21	33.0	103.3	-16.1	Bus 10	-15.7	-9.8	312.9	84.9
				Bus 22	-1.8	-1.2	39.3	78.8
Bus 22	33.0	103.3	-16.1	Bus 10	-7.6	-4.5	149.0	86.0
				Bus 21	1.8	1.4	39.3	78.8
				Bus 24	5.7	3.1	110.2	88.2
Bus 23	33.0	102.7	-16.3	Bus 15	-5.0	-2.8	98.2	86.9
				Bus 24	1.8	1.2	37.4	82.3
Bus 24	33.0	102.2	-16.5	Bus 22	-5.7	-3.0	110.2	88.5
				Bus 23	-1.8	-1.2	37.4	82.5
				Bus 25	-1.2	2.0	40.2	-51.3
Bus 25	33.0	101.7	-16.1	Bus 24	1.2	-2.0	40.2	-51.9
				Bus 26	3.5	2.4	73.3	83.2
				Bus 27	-4.8	-0.4	82.1	99.7
Bus 26	33.0	100.0	-16.5	Bus 25	-3.5	-2.3	73.3	83.6
Bus 27	33.0	102.3	-15.5	Bus 25	4.8	0.4	82.1	99.6
				Bus 29	6.2	1.7	109.6	96.6
				Bus 30	7.1	1.7	124.6	97.4
				Bus 28	-18.1	-3.7	315.5	97.9
Bus 28	132.0	100.7	-11.7	Bus 6	-18.6	-1.1	81.0	99.8
				Bus 8	0.5	-3.9	17.3	-13.7
				Bus 27	18.1	5.0	81.5	96.3
Bus 29	33.0	100.3	-16.8	Bus 27	-6.1	-1.5	109.6	97.1
				Bus 30	3.7	0.6	65.4	98.7
Bus 30	33.0	99.2	-17.7	Bus 27	-6.9	-1.4	124.6	98.1
				Bus 29	-3.7	-0.5	65.4	98.9

Appendix D

The IEEE 30 Bus system short circuit simulated results for ANSI and IEC calculations are presented in Tables D1 – D43.

Table D1: ANSI Simulated Results for Case 1 at 10% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.714	11.927	8.566	11.275	9.698	11.891	8.551	11.235	9.720	11.914	8.572	11.259	9.735	11.928	8.585	11.272
2	132	8.557	9.535	7.486	9.196	8.532	9.447	7.466	9.121	8.568	9.479	7.501	9.161	8.594	9.499	7.522	9.184
3	132	5.272	5.349	4.586	5.360	5.258	5.287	4.573	5.319	5.279	5.303	4.593	5.343	5.294	5.313	4.606	5.356
4	132	6.736	6.720	5.865	6.820	6.709	6.592	5.840	6.475	6.750	6.622	5.880	6.792	6.781	6.640	5.905	6.819
5	132	5.712	5.725	4.976	5.762	5.678	5.568	4.945	5.664	5.728	5.604	4.994	5.720	5.766	5.627	5.025	5.753
6	132	7.615	7.622	6.636	7.710	7.565	7.370	6.590	7.570	7.641	7.425	6.666	7.660	7.702	7.461	6.716	7.714
7	132	5.101	5.267	4.438	5.217	5.022	4.798	4.362	4.926	5.156	4.892	4.497	5.094	5.273	4.959	4.595	5.203
8	132	5.718	5.860	4.983	5.829	5.695	5.752	4.962	5.762	5.729	5.778	4.996	5.801	5.755	5.795	5.017	5.824
9	33	12.975	13.217	11.279	13.284	12.960	13.206	11.266	13.279	12.985	13.225	11.290	13.292	13.006	13.239	11.307	13.307
10	33	14.620	14.140	12.694	14.634	14.606	14.131	12.680	14.629	14.630	14.147	12.704	14.642	14.650	14.159	12.720	14.657
11	11	19.167	22.972	16.703	21.877	19.160	22.965	16.697	21.875	19.172	22.978	16.708	21.881	19.183	22.987	16.717	21.889
12	33	12.577	12.098	10.926	12.542	12.567	12.092	10.916	12.538	12.583	12.102	10.932	12.547	12.595	12.110	10.942	12.557
13	11	21.025	25.755	18.341	24.916	21.084	25.748	18.335	24.913	21.096	25.761	18.346	24.920	21.106	25.770	18.354	24.928
14	33	6.800	6.499	5.894	6.697	6.796	6.497	5.891	6.695	6.801	6.501	5.895	6.698	6.804	6.503	5.898	6.701
15	33	10.365	9.773	8.989	10.169	10.357	9.768	8.982	10.165	10.368	9.775	8.993	10.173	10.376	9.780	8.999	10.179
16	33	8.423	8.159	7.304	8.379	8.418	8.155	7.299	8.376	8.426	8.161	7.307	8.381	8.432	8.164	7.312	8.385
17	33	10.640	10.214	9.228	10.548	10.632	10.209	9.221	10.544	10.664	10.218	9.233	10.552	10.654	10.223	9.241	10.559
18	33	7.089	6.705	6.143	6.932	7.085	6.702	6.140	6.930	7.090	6.706	6.145	6.934	7.094	6.708	6.148	6.937
19	33	7.382	6.923	6.398	7.177	7.378	6.920	6.394	7.174	7.384	6.924	6.400	7.179	7.388	6.926	6.403	7.182
20	33	7.716	7.315	6.688	7.558	7.712	7.312	6.684	7.556	7.718	7.316	6.690	7.560	7.723	7.319	6.694	7.564
21	33	11.923	11.302	10.342	11.728	11.913	11.295	10.332	11.723	11.928	11.306	10.348	11.732	11.941	11.313	10.358	11.742
22	33	11.680	11.129	10.131	11.529	11.670	11.122	10.121	11.524	11.686	11.133	10.136	11.534	11.698	11.140	10.146	11.543
23	33	7.016	6.718	6.080	6.905	7.012	6.715	6.076	6.903	7.017	6.719	6.081	6.906	7.021	6.721	6.084	6.909
24	33	8.761	8.336	7.593	8.584	8.755	8.332	7.587	8.581	8.764	8.338	7.596	8.587	8.770	8.341	7.601	8.592
25	33	5.673	5.576	4.916	5.657	5.670	5.574	4.913	5.656	5.675	5.577	4.917	5.658	5.678	5.579	4.920	5.661
26	33	2.551	2.447	2.210	2.527	2.551	2.446	2.209	2.526	2.552	2.447	2.210	2.527	2.552	2.447	2.211	2.528
27	33	6.223	6.221	5.394	6.315	6.220	6.219	5.390	6.313	6.225	6.223	5.396	6.317	6.230	6.226	5.400	6.320
28	132	4.469	4.398	3.884	4.470	4.453	4.318	3.869	4.425	4.477	4.336	3.893	4.453	4.496	4.347	3.908	4.469
29	33	3.290	3.137	2.850	3.233	3.289	3.137	2.849	3.232	3.291	3.138	2.851	3.233	3.292	3.138	2.852	3.234
30	33	3.316	3.036	2.872	3.242	3.315	3.035	2.871	3.241	3.316	3.036	2.873	3.243	3.317	3.037	2.874	3.244

Table D2: ANSI Simulated Results for Case 1 at 30% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.779	11.993	8.625	11.333	9.698	11.891	8.551	11.235	9.758	11.955	8.609	11.288	9.735	11.928	8.585	11.272
2	132	8.673	9.634	7.594	9.298	8.532	9.447	7.466	9.121	8.640	9.542	7.569	9.216	8.594	9.499	7.522	9.184
3	132	5.341	5.397	4.649	5.419	5.258	5.287	4.573	5.319	5.322	5.334	4.634	5.375	5.294	5.313	4.606	5.356
4	132	6.875	6.816	5.992	6.945	6.709	6.592	5.840	6.745	6.839	6.683	5.965	6.863	6.781	6.640	5.905	6.819
5	132	5.882	5.843	5.133	5.913	5.678	5.568	4.945	5.664	5.837	5.679	5.097	5.805	5.766	5.627	5.025	5.753
6	132	7.891	7.815	6.891	7.965	7.565	7.370	6.590	7.570	7.825	7.548	6.840	7.810	7.702	7.461	6.716	7.714
7	132	5.671	5.684	4.970	5.704	5.022	4.798	4.362	4.926	5.555	5.144	4.879	5.437	5.273	4.959	4.595	5.203
8	132	5.835	5.946	5.091	5.935	5.695	5.752	4.962	5.762	5.805	5.833	5.068	5.862	5.755	5.795	5.017	5.824
9	33	13.071	13.286	11.367	13.357	12.960	13.206	11.266	13.279	13.053	13.275	11.353	13.352	13.006	13.239	11.307	13.307
10	33	14.713	14.200	12.778	14.706	14.606	14.131	12.680	14.629	14.694	14.191	12.764	14.700	14.650	14.159	12.720	14.657
11	11	19.216	23.021	16.748	21.916	19.160	22.965	16.697	21.875	19.208	23.014	16.742	21.913	19.183	22.987	16.717	21.889
12	33	12.634	12.134	10.977	12.588	12.567	12.092	10.916	12.538	12.621	12.128	10.968	12.583	12.595	12.110	10.942	12.557
13	11	21.136	25.802	18.382	24.954	21.084	25.748	18.335	24.913	21.127	25.794	18.376	24.950	21.106	25.770	18.354	24.928
14	33	6.814	6.509	5.907	6.710	6.796	6.497	5.891	6.695	6.810	6.506	5.904	6.707	6.804	6.503	5.898	6.701
15	33	10.399	9.794	9.021	10.199	10.357	9.768	8.982	10.165	10.390	9.789	9.013	10.194	10.376	9.780	8.999	10.179
16	33	8.449	8.176	7.328	8.400	8.418	8.155	7.299	8.376	8.443	8.172	7.323	8.397	8.432	8.164	7.312	8.385
17	33	10.684	10.243	9.269	10.583	10.632	10.209	9.221	10.544	10.674	10.237	9.261	10.579	10.654	10.223	9.241	10.559
18	33	7.105	6.715	6.158	6.946	7.085	6.702	6.140	6.930	7.100	6.712	6.154	6.944	7.094	6.708	6.148	6.937
19	33	7.400	6.934	6.414	7.192	7.378	6.920	6.394	7.174	7.395	6.931	6.410	7.188	7.388	6.926	6.403	7.182
20	33	7.737	7.328	6.707	7.576	7.712	7.312	6.684	7.556	7.731	7.325	6.702	7.573	7.723	7.319	6.694	7.564
21	33	11.979	11.337	10.392	11.772	11.913	11.295	10.332	11.723	11.965	11.330	10.382	11.767	11.941	11.313	10.358	11.742
22	33	11.734	11.163	10.180	11.573	11.670	11.122	10.121	11.524	11.721	11.156	10.170	11.567	11.698	11.140	10.146	11.543
23	33	7.032	6.728	6.094	6.919	7.012	6.715	6.076	6.903	7.027	6.725	6.091	6.916	7.021	6.721	6.084	6.909
24	33	8.789	8.353	7.618	8.608	8.755	8.332	7.587	8.581	8.781	8.349	7.612	8.604	8.770	8.341	7.601	8.592
25	33	5.688	5.586	4.929	5.669	5.670	5.574	4.913	5.656	5.684	5.584	4.926	5.667	5.678	5.579	4.920	5.661
26	33	2.554	2.448	2.212	2.529	2.551	2.446	2.209	2.526	2.553	2.448	2.211	2.528	2.552	2.447	2.211	2.528
27	33	6.244	6.236	5.413	6.331	6.220	6.219	5.390	6.313	6.240	6.234	5.410	6.330	6.230	6.226	5.400	6.320
28	132	4.553	4.454	3.960	4.545	4.453	4.318	3.869	4.425	4.531	4.372	3.944	4.496	4.496	4.347	3.908	4.469
29	33	3.295	3.141	2.855	3.237	3.289	3.137	2.849	3.232	3.294	3.140	2.854	3.236	3.292	3.138	2.852	3.234
30	33	3.320	3.038	2.876	3.246	3.315	3.035	2.871	3.241	3.319	3.038	2.875	3.245	3.317	3.037	2.874	3.244

Table D3: ANSI Simulated Results for Case 2 at 30% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.724	11.916	8.574	11.262	9.700	11.892	8.553	11.240	9.715	11.908	8.567	11.254	9.711	11.903	8.563	11.252
2	132	8.568	9.477	7.498	9.160	8.531	9.446	7.464	9.128	8.555	9.466	7.486	9.150	8.548	9.460	7.479	9.145
3	132	5.293	5.311	4.604	5.353	5.259	5.288	4.574	5.324	5.281	5.303	4.594	5.343	5.274	5.298	4.587	5.339
4	132	6.781	6.640	5.904	6.815	6.711	6.593	5.841	6.753	6.756	6.624	5.882	6.794	6.739	6.613	5.867	6.783
5	132	5.680	5.570	4.947	5.681	5.667	5.561	4.935	5.670	5.676	5.567	4.943	5.677	5.673	5.565	4.940	5.676
6	132	7.685	7.447	6.698	7.692	7.563	7.369	6.588	7.583	7.640	7.420	6.659	7.655	7.610	7.400	6.631	7.634
7	132	4.979	4.773	4.325	4.937	4.951	4.755	4.300	4.913	4.969	4.767	4.316	4.929	4.963	4.763	4.310	4.925
8	132	5.761	5.797	5.021	5.826	5.698	5.754	4.965	5.770	5.738	5.782	5.001	5.807	5.723	5.771	4.987	5.796
9	33	13.120	13.366	11.409	13.417	12.967	13.211	11.272	13.294	13.065	13.283	11.362	13.377	13.033	13.258	11.330	13.340
10	33	14.896	14.435	12.940	14.883	14.614	14.137	12.687	14.661	14.795	14.257	12.855	14.825	14.746	14.221	12.805	14.761
11	11	19.244	23.047	16.772	21.954	19.165	22.969	16.701	21.884	19.216	23.020	16.748	21.928	19.198	23.002	16.730	21.908
12	33	12.691	12.214	11.027	12.639	12.567	12.092	10.917	12.548	12.647	12.144	10.990	12.621	12.627	12.129	10.970	12.594
13	11	21.187	25.853	18.427	25.022	21.086	25.751	18.337	24.923	21.151	25.819	18.397	24.985	21.133	25.798	18.379	24.962
14	33	6.833	6.535	5.923	6.722	6.793	6.496	5.888	6.696	6.819	6.512	5.912	6.722	6.815	6.509	5.907	6.714
15	33	10.493	9.914	9.103	10.284	10.363	9.772	8.988	10.183	10.447	9.825	9.065	10.258	10.425	9.809	9.043	10.230
16	33	8.481	8.220	7.355	8.426	8.417	8.155	7.299	8.381	8.458	8.182	7.337	8.419	8.449	8.175	7.327	8.406
17	33	10.756	10.338	9.332	10.647	10.631	10.209	9.211	10.555	10.712	10.262	9.295	10.629	10.693	10.248	9.275	10.603
18	33	7.137	6.759	6.186	6.973	7.085	6.702	6.140	6.935	7.119	6.724	6.171	6.967	7.112	6.719	6.164	6.956
19	33	7.432	6.979	6.442	7.241	7.377	6.920	6.393	7.178	7.413	6.942	6.426	7.212	7.406	6.937	6.418	7.201
20	33	7.774	7.378	6.739	7.606	7.711	7.311	6.683	7.561	7.752	7.337	6.721	7.600	7.743	7.331	6.712	7.587
21	33	12.187	11.591	10.577	11.969	11.926	11.304	10.344	11.760	12.093	11.410	10.499	11.910	12.048	11.379	10.453	11.853
22	33	11.977	11.456	10.395	11.804	11.688	11.134	10.137	11.569	11.873	11.253	10.308	11.734	11.822	11.217	10.257	11.669
23	33	7.172	6.900	6.220	7.056	7.027	6.725	6.090	6.931	7.120	6.785	6.175	7.012	7.092	6.766	6.148	6.978
24	33	9.390	9.055	8.159	9.261	8.840	8.384	7.661	8.709	9.185	8.602	7.982	8.997	9.064	8.522	7.864	8.861
25	33	7.720	8.057	6.784	7.936	5.991	5.784	5.191	6.066	6.986	6.407	6.127	6.854	6.532	6.122	5.690	6.391
26	33	4.542	10.148	7.136	9.221	3.052	2.743	2.644	3.062	5.008	3.645	4.544	4.811	3.803	3.136	3.354	3.705
27	33	7.086	7.235	6.172	7.210	6.340	6.303	5.495	6.491	6.798	6.617	5.922	6.873	6.626	6.494	5.755	6.683
28	132	4.561	4.388	3.966	4.524	4.470	4.329	3.884	4.438	4.527	4.367	3.936	4.494	4.502	4.350	3.913	4.476
29	33	3.458	3.331	3.001	3.429	3.305	3.146	2.863	3.237	3.402	3.208	2.953	3.322	3.373	3.189	2.924	3.293
30	33	3.460	3.201	3.001	3.411	3.327	3.041	2.881	3.236	3.412	3.091	2.960	3.308	3.387	3.076	2.936	3.294

Table D4: ANSI Simulated Results for Case 3 at 30% penetration level and DG located at Bus 29

Bus		**Wind**				**PV**				**Hybrid**				**Diesel Hybrid**			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	9.733	11.925	8.583	11.270	9.700	11.893	8.553	11.240	9.721	11.913	8.572	11.259	9.714	11.906	8.565	11.255
2	132	8.583	9.489	7.511	9.174	8.532	9.447	7.465	9.128	8.563	9.474	7.494	9.157	8.552	9.463	7.483	9.150
3	132	5.304	5.319	4.614	5.363	5.260	5.289	4.575	5.324	5.287	5.308	4.600	5.349	5.277	5.300	4.590	5.342
4	132	6.803	6.655	5.925	6.837	6.712	6.594	5.843	6.753	6.768	6.633	5.894	6.806	6.746	6.617	5.873	6.789
5	132	5.686	5.573	4.952	5.686	5.668	5.562	4.935	5.670	5.679	5.569	4.946	5.680	5.675	5.566	4.942	5.678
6	132	7.738	7.483	6.748	7.746	7.570	7.373	6.594	7.585	7.674	7.442	6.690	7.687	7.628	7.411	6.647	7.651
7	132	4.991	4.781	4.336	4.948	4.953	4.756	4.301	4.913	4.977	4.771	4.323	4.936	4.967	4.765	4.314	4.929
8	132	5.794	5.821	5.052	5.858	5.703	5.757	4.969	5.772	5.759	5.797	5.021	5.826	5.734	5.779	4.997	5.808
9	33	13.094	13.320	11.386	13.384	12.961	13.207	11.266	13.284	13.043	13.267	11.342	13.352	13.013	13.243	11.312	13.319
10	33	14.805	14.305	12.860	14.787	14.601	14.129	12.676	14.637	14.727	14.212	12.793	14.750	14.689	14.184	12.755	14.704
11	11	19.230	23.033	16.759	21.937	19.161	22.966	16.698	21.878	19.204	23.009	16.737	21.914	19.187	22.991	16.721	21.896
12	33	12.660	12.167	11.000	12.609	12.564	12.090	10.913	12.540	12.623	12.129	10.969	12.594	12.606	12.116	10.951	12.572
13	11	21.161	25.827	18.404	24.990	21.082	25.747	18.334	24.915	21.131	25.798	18.378	24.961	21.115	25.780	18.363	24.942
14	33	6.822	6.518	5.914	6.714	6.793	6.496	5.888	6.694	6.811	6.507	5.905	6.712	6.808	6.505	5.901	6.706
15	33	10.445	9.847	9.061	10.236	10.355	9.767	8.981	10.170	10.411	9.802	9.032	10.221	10.396	9.792	9.017	10.202
16	33	8.464	8.194	7.341	8.410	8.416	8.154	7.297	8.377	8.446	8.174	7.325	8.404	8.438	8.168	7.317	8.394
17	33	10.719	10.283	9.300	10.611	10.628	10.207	9.218	10.546	10.684	10.244	9.270	10.598	10.669	10.233	9.254	10.578
18	33	7.120	6.733	6.171	6.957	7.083	6.701	6.138	6.931	7.106	6.716	6.159	6.953	7.101	6.712	6.154	6.945
19	33	7.415	6.952	6.427	7.215	7.376	6.919	6.392	7.174	7.400	6.934	6.415	7.197	7.395	6.930	6.409	7.189
20	33	7.755	7.349	6.722	7.588	7.709	7.310	6.682	7.557	7.737	7.328	6.708	7.583	7.731	7.323	6.701	7.574
21	33	12.081	11.450	10.484	11.861	11.909	11.294	10.330	11.733	12.015	11.361	10.428	11.830	11.986	11.341	10.398	11.792
22	33	11.853	11.295	10.286	11.676	11.668	11.121	10.119	11.537	11.782	11.195	10.225	11.641	11.750	11.172	10.193	11.601
23	33	7.098	6.805	6.154	6.978	7.012	6.716	6.077	6.911	7.065	6.750	6.126	6.959	7.051	6.740	6.111	6.941
24	33	9.059	8.663	7.862	8.892	8.766	8.339	7.597	8.618	8.945	8.454	7.764	8.779	8.891	8.417	7.709	8.712
25	33	6.443	6.504	5.616	6.503	5.733	5.616	4.967	5.773	6.153	5.899	5.361	6.135	6.000	5.790	5.210	5.963
26	33	2.667	2.586	2.315	2.668	2.554	2.448	2.213	2.518	2.623	2.493	2.277	2.575	2.603	2.479	2.256	2.563
27	33	8.420	9.044	7.421	8.748	6.447	6.380	5.588	6.656	7.545	7.106	6.625	7.572	7.063	6.780	6.153	7.065
28	132	4.635	4.436	4.035	4.597	4.484	4.337	3.896	4.446	4.577	4.399	3.982	4.541	4.531	4.369	3.939	4.503
29	33	8.342	11.025	7.836	10.047	3.705	3.390	3.210	3.737	5.745	4.396	5.188	5.436	4.564	3.848	4.015	4.386
30	33	4.680	4.772	4.135	4.840	3.467	3.118	3.003	3.354	4.133	3.479	3.633	3.917	3.826	3.315	3.333	3.674

Table D5: ANSI Simulated Results for Case 4 at 30% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.728	11.920	8.578	11.266	9.699	11.892	8.552	11.240	9.717	11.910	8.569	11.256	9.711	11.904	8.563	11.252
2	132	8.575	9.482	7.504	9.167	8.530	9.446	7.464	9.128	8.558	9.469	7.489	9.153	8.548	9.460	7.480	9.146
3	132	5.297	5.314	4.608	5.357	5.258	5.288	4.573	5.323	5.282	5.305	4.595	5.345	5.274	5.298	4.587	5.339
4	132	6.789	6.645	5.912	6.824	6.709	6.592	5.840	6.751	6.758	6.626	5.885	6.797	6.739	6.612	5.867	6.783
5	132	5.683	5.572	4.949	5.683	5.667	5.561	4.935	5.670	5.677	5.568	4.944	5.679	5.674	5.566	4.941	5.677
6	132	7.711	7.466	6.723	7.720	7.563	7.369	6.588	7.581	7.654	7.430	6.673	7.669	7.616	7.403	6.636	7.639
7	132	4.985	4.777	4.300	4.943	4.951	4.755	4.300	4.912	4.972	4.769	4.319	4.932	4.964	4.763	4.312	4.926
8	132	5.779	5.811	5.038	5.844	5.699	5.754	4.965	5.769	5.748	5.790	5.011	5.817	5.728	5.775	4.991	5.801
9	33	13.072	13.303	11.367	13.366	12.957	13.204	11.262	13.279	13.028	13.256	11.329	13.339	13.003	13.236	11.304	13.311
10	33	14.773	14.279	12.831	14.760	14.596	14.126	12.672	14.631	14.705	14.198	12.773	14.730	14.674	14.175	12.741	14.691
11	11	19.219	23.023	16.750	21.928	19.159	22.964	16.695	21.875	19.196	23.001	16.730	21.907	19.182	22.986	16.716	21.892
12	33	12.645	12.156	10.987	12.596	12.561	12.088	10.912	12.537	12.613	12.122	10.959	12.584	12.599	12.112	10.945	12.566
13	11	21.148	25.814	18.393	24.979	21.080	25.745	18.332	24.912	21.123	25.789	18.371	24.953	21.110	25.774	18.358	24.937
14	33	6.818	6.515	5.910	6.710	6.793	6.496	5.888	6.694	6.808	6.506	5.902	6.709	6.806	6.503	5.899	6.704
15	33	10.431	9.836	9.049	10.224	10.354	9.766	8.979	10.167	10.402	9.796	9.024	10.212	10.389	9.788	9.011	10.196
16	33	8.457	8.188	7.334	8.404	8.415	8.153	7.297	8.375	8.441	8.171	7.320	8.400	8.434	8.166	7.314	8.391
17	33	10.705	10.272	9.287	10.599	10.626	10.206	9.216	10.543	10.675	10.238	9.261	10.589	10.662	10.228	9.248	10.572
18	33	7.114	6.729	6.166	6.952	7.083	6.701	6.138	6.930	7.102	6.713	6.156	6.949	7.098	6.710	6.151	6.943
19	33	7.409	6.947	6.422	7.209	7.375	6.919	6.392	7.173	7.396	6.932	6.411	7.193	7.392	6.929	6.406	7.187
20	33	7.748	7.343	6.716	7.582	7.709	7.310	6.681	7.556	7.733	7.325	6.703	7.579	7.727	7.321	6.698	7.571
21	33	12.054	11.428	10.460	11.837	11.906	11.292	10.327	11.728	11.997	11.350	10.411	11.813	11.973	11.333	10.387	11.781
22	33	11.824	11.271	10.260	11.651	11.664	11.119	10.116	11.531	11.763	11.183	10.208	11.623	11.737	11.164	10.181	11.588
23	33	7.085	6.793	6.142	6.966	7.011	6.715	6.075	6.908	7.056	6.745	6.118	6.951	7.045	6.736	6.106	6.935
24	33	9.012	8.620	7.820	8.844	8.759	8.335	7.591	8.608	8.914	8.435	7.735	8.749	8.870	8.403	7.690	8.693
25	33	6.320	6.377	5.504	6.371	5.714	5.604	4.951	5.749	6.075	5.848	5.289	6.065	5.949	5.758	5.164	5.920
26	33	2.649	2.568	2.298	2.649	2.552	2.447	2.210	2.517	2.611	2.486	2.266	2.566	2.595	2.474	2.249	2.557
27	33	8.031	8.591	7.056	8.342	6.392	6.342	5.540	6.591	7.321	6.966	6.415	7.376	6.932	6.696	6.034	6.959
28	132	4.610	4.420	4.012	4.572	4.477	4.333	3.889	4.441	4.559	4.387	3.966	4.524	4.520	4.361	3.929	4.492
29	33	4.634	4.912	4.095	4.836	3.432	3.224	2.973	3.411	4.094	3.615	3.598	3.949	3.792	3.437	3.304	3.651
30	33	8.381	11.033	7.870	10.043	3.716	3.255	3.219	3.658	5.768	4.179	5.209	5.452	4.593	3.688	4.040	4.399

Table D6: ANSI Simulated Results for Case 5 at 30% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.794	12.021	8.642	11.357	9.698	11.890	8.551	11.236	9.739	11.934	8.590	11.273	9.729	11.922	8.879	11.267
2	132	8.694	9.692	7.621	9.341	8.529	9.445	7.463	9.122	8.601	9.508	7.531	9.186	8.581	9.488	7.510	9.173
3	132	5.365	5.444	4.675	5.454	5.257	5.287	4.572	5.320	5.303	5.320	4.616	5.361	5.291	5.310	4.603	5.353
4	132	6.928	6.915	6.050	7.019	6.707	6.591	5.839	6.746	6.802	6.657	5.928	6.832	6.774	6.637	5.900	6.813
5	132	5.869	5.913	5.131	5.941	5.671	5.563	4.938	5.665	5.760	5.626	5.024	5.744	5.728	5.602	4.990	5.721
6	132	7.992	8.018	7.004	8.112	7.562	7.368	6.588	7.572	7.747	7.493	6.763	7.744	7.687	7.451	6.702	7.701
7	132	5.609	5.939	4.952	5.795	4.982	4.773	4.327	4.914	5.264	4.961	4.599	5.184	5.139	4.876	4.473	5.082
8	132	5.894	6.043	5.153	6.012	5.696	5.752	4.963	5.764	5.780	5.814	5.042	5.841	5.755	5.795	5.018	5.825
9	33	13.160	13.372	11.454	13.434	12.957	13.204	11.263	13.280	13.043	13.267	11.343	13.349	13.022	13.251	11.322	13.325
10	33	14.850	14.336	12.909	14.819	14.597	14.126	12.673	14.629	14.701	14.195	12.769	14.717	14.686	14.183	12.753	14.697
11	11	19.263	23.071	16.793	21.960	19.159	22.964	16.696	21.876	19.204	23.009	16.737	21.912	19.192	22.996	16.725	21.899
12	33	12.696	12.192	11.038	12.638	12.562	12.089	10.912	12.537	12.618	12.125	10.964	12.585	12.609	12.118	10.954	12.573
13	11	21.188	25.859	18.432	25.009	21.081	25.745	18.332	24.913	21.126	25.792	18.374	24.953	21.117	25.782	18.365	24.942
14	33	6.831	6.525	5.923	6.722	6.794	6.496	5.889	6.694	6.809	6.506	5.903	6.708	6.808	6.505	5.902	6.706
15	33	10.459	9.856	9.077	10.248	10.353	9.766	8.979	10.166	10.396	9.793	9.018	10.204	10.393	9.790	9.015	10.197
16	33	8.480	8.205	7.357	8.423	8.415	8.154	7.297	8.375	8.442	8.171	7.322	8.399	8.439	8.169	7.318	8.394
17	33	10.743	10.300	9.326	10.630	10.627	10.206	9.217	10.543	10.675	10.238	9.261	10.585	10.669	10.233	9.255	10.576
18	33	7.128	6.738	6.180	6.964	7.083	6.701	6.138	6.930	7.101	6.713	6.155	6.946	7.100	6.712	6.153	6.944
19	33	7.424	6.958	6.437	7.224	7.376	6.919	6.392	7.173	7.395	6.931	6.410	7.191	7.394	6.930	6.409	7.188
20	33	7.765	7.356	6.734	7.597	7.709	7.310	6.682	7.555	7.732	7.325	6.703	7.576	7.730	7.323	6.701	7.573
21	33	12.095	11.459	10.503	11.870	11.906	11.292	10.327	11.724	11.982	11.340	10.396	11.791	11.976	11.335	10.390	11.780
22	33	11.861	11.299	10.299	11.681	11.664	11.119	10.116	11.527	11.742	11.169	10.188	11.596	11.737	11.165	10.182	11.586
23	33	7.092	6.800	6.151	6.973	7.010	6.714	6.074	6.905	7.041	6.735	6.104	6.934	7.042	6.734	6.103	6.931
24	33	9.004	8.618	7.819	8.843	8.753	8.331	7.586	8.594	8.847	8.390	7.672	8.677	8.850	8.392	7.674	8.672
25	33	6.228	6.313	5.434	6.298	5.688	5.586	4.928	5.706	5.876	5.712	5.100	8.564	5.880	5.715	5.105	5.852
26	33	2.638	2.561	2.290	2.640	2.550	2.446	2.208	2.519	2.582	2.466	2.238	2.545	2.585	2.468	2.240	2.551
27	33	7.691	8.309	6.783	8.031	6.307	6.282	5.466	6.469	6.753	6.583	5.784	6.829	6.737	6.574	5.866	6.775
28	132	4.673	4.576	4.078	4.674	4.465	4.326	3.880	4.432	4.549	4.382	3.958	4.511	4.527	4.367	3.937	4.499
29	33	5.802	7.248	5.337	6.747	3.467	3.245	3.003	3.451	4.080	3.596	3.565	3.910	4.001	3.563	3.508	3.879
30	33	4.200	4.299	3.711	4.340	3.376	3.068	2.924	3.247	3.637	3.215	3.162	3.491	3.624	3.211	3.155	3.506

Table D7: ANSI Simulated Results for Case 6 at 30% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	9.736	11.929	8.585	11.272	9.698	11.891	8.551	11.239	9.720	11.913	8.572	11.259	9.730	11.922	8.579	11.267
2	132	8.587	9.493	7.515	9.177	8.529	9.445	7.463	9.126	8.563	9.474	7.494	9.156	8.578	9.484	7.506	9.169
3	132	5.309	5.323	4.619	5.367	5.257	5.287	4.573	5.322	5.288	5.308	4.600	5.349	5.301	5.316	4.611	5.360
4	132	6.814	6.663	5.936	6.845	6.707	6.591	5.838	6.749	6.770	6.634	5.896	6.807	6.797	6.650	5.918	6.830
5	132	5.687	5.574	4.953	5.687	5.667	5.561	4.935	5.669	5.679	5.569	4.946	5.680	5.684	5.572	4.950	5.684
6	132	7.749	7.492	6.760	7.755	7.560	7.366	6.585	7.577	7.671	7.441	6.689	7.683	7.720	7.469	6.728	7.725
7	132	4.994	4.782	4.339	4.950	4.950	4.754	4.299	4.911	4.976	4.771	4.323	4.935	4.987	4.777	4.332	4.944
8	132	5.797	5.824	5.056	5.860	5.696	5.753	4.963	5.767	5.755	5.795	5.018	5.823	5.782	5.811	5.039	5.845
9	33	13.149	13.393	11.438	13.440	12.957	13.205	11.263	13.284	13.070	13.287	11.368	13.380	13.120	13.318	11.407	13.421
10	33	14.926	14.470	12.973	14.905	14.595	14.125	12.671	14.640	14.788	14.255	12.852	14.817	14.875	14.302	12.919	14.891
11	11	19.259	23.063	16.787	21.966	19.159	22.964	16.696	21.878	19.218	23.024	16.751	21.929	19.244	23.046	16.771	21.952
12	33	12.708	12.232	11.045	12.652	12.559	12.087	10.910	12.539	12.647	12.145	10.991	12.620	12.685	12.166	11.021	12.653
13	11	21.201	25.869	18.441	25.033	21.080	25.744	18.331	24.915	21.151	25.820	18.398	24.984	21.182	25.847	18.422	25.014
14	33	6.838	6.540	5.928	6.726	6.791	6.495	5.887	6.694	6.818	6.512	5.912	6.721	6.830	6.519	5.921	6.732
15	33	10.503	9.928	9.115	10.293	10.354	9.766	8.979	10.172	10.441	9.822	9.061	10.253	10.480	9.842	9.091	10.286
16	33	8.489	8.229	7.364	8.432	8.413	8.153	7.295	8.376	8.458	8.182	7.337	8.418	8.477	8.193	7.352	8.436
17	33	10.771	10.354	9.347	10.658	10.624	10.205	9.214	10.546	10.710	10.261	9.294	10.627	10.748	10.282	9.324	10.660
18	33	7.142	6.766	6.192	6.976	7.081	6.700	6.137	6.931	7.117	6.723	6.170	6.965	7.133	6.731	6.182	6.979
19	33	7.438	6.985	6.448	7.250	7.374	6.918	6.390	7.174	7.411	6.941	6.425	7.210	7.428	6.950	6.438	7.225
20	33	7.781	7.386	6.746	7.611	7.707	7.309	6.680	7.557	7.750	7.337	6.720	7.598	7.769	7.347	6.735	7.615
21	33	12.203	11.617	10.597	11.981	11.907	11.292	10.327	11.738	12.079	11.403	10.489	11.897	12.157	11.444	10.549	11.963
22	33	11.991	11.483	10.415	11.815	11.666	11.121	10.118	11.544	11.855	11.244	10.295	11.718	11.940	11.289	10.361	11.790
23	33	7.173	6.910	6.224	7.057	7.014	6.717	6.079	6.917	7.107	6.778	6.165	7.000	7.149	6.800	6.198	7.035
24	33	9.373	9.084	8.154	9.278	8.785	8.351	7.614	8.651	9.122	8.567	7.930	8.944	9.278	8.649	8.053	9.071
25	33	7.549	8.097	6.671	7.905	5.823	5.676	5.046	5.896	6.734	6.269	5.911	6.647	7.227	6.520	6.309	7.034
26	33	5.072	6.486	4.702	6.020	2.773	2.581	2.402	2.757	3.817	3.159	3.412	3.690	4.541	3.448	4.028	4.377
27	33	8.076	8.809	7.130	8.469	6.334	6.302	5.490	6.525	7.253	6.930	6.363	7.313	7.751	7.196	6.764	7.714
28	132	4.629	4.434	4.031	4.591	4.471	4.329	3.884	4.436	4.563	4.391	3.971	4.528	4.605	4.415	4.004	4.565
29	33	4.262	4.542	3.767	4.452	3.352	3.175	2.904	3.315	3.826	3.469	3.354	3.709	4.089	3.597	3.568	3.913
30	33	5.937	7.355	5.458	6.839	3.490	3.131	3.023	3.394	4.606	3.714	4.102	4.385	5.375	4.004	4.752	5.090

Table D8: ANSI Simulated Results for Case 1 at 42% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.872	12.130	8.716	11.458	9.705	11.899	8.559	11.221	9.784	11.982	8.634	11.308	9.837	12.029	8.676	11.355
2	132	8.845	9.920	7.764	9.548	8.558	9.469	7.491	9.108	8.688	9.584	7.615	9.254	8.782	9.654	7.692	9.335
3	132	5.442	5.575	4.748	5.564	5.275	5.299	4.589	5.313	5.350	5.355	4.661	5.398	5.406	5.389	4.706	5.445
4	132	7.089	7.198	6.203	7.248	6.754	6.621	5.881	6.743	6.900	6.725	6.023	6.912	7.014	6.792	6.116	7.010
5	132	6.148	6.330	5.397	6.308	5.729	5.601	4.991	5.683	5.911	5.730	5.169	5.865	6.053	5.812	5.286	5.986
6	132	8.337	8.646	7.337	8.611	7.672	7.435	6.685	7.580	7.950	7.632	6.961	7.916	8.184	7.764	7.153	8.120
7	132	6.809	8.113	6.157	7.633	5.277	4.956	4.585	5.287	5.850	5.327	5.170	5.702	6.417	5.612	5.649	6.222
8	132	6.016	6.278	5.270	6.198	5.734	5.779	4.998	5.760	5.857	5.871	5.118	5.903	5.953	5.930	5.196	5.986
9	33	13.219	13.399	11.511	13.481	13.016	13.246	11.315	13.354	13.098	13.309	11.395	13.391	13.173	13.356	11.456	13.446
10	33	14.854	14.298	12.915	14.826	14.655	14.164	12.724	14.697	14.737	14.219	12.804	14.737	14.809	14.260	12.862	14.790
11	11	19.292	23.101	16.821	21.979	19.192	22.996	16.725	21.918	19.231	23.038	16.764	21.934	19.269	23.071	16.794	21.963
12	33	12.719	12.193	11.061	12.663	12.592	12.108	10.939	12.576	12.647	12.145	10.992	12.606	12.691	12.170	11.028	12.639
13	11	21.204	25.877	18.448	25.016	21.109	25.774	18.357	24.949	21.148	25.816	18.395	24.970	21.183	25.848	18.423	24.999
14	33	6.835	6.523	5.928	6.730	6.798	6.499	5.893	6.701	6.815	6.510	5.909	6.713	6.827	6.517	5.919	6.723
15	33	10.450	9.828	9.070	10.246	10.367	9.774	8.991	10.184	10.405	9.799	9.027	10.208	10.432	9.814	9.050	10.230
16	33	8.488	8.202	7.365	8.434	8.427	8.162	7.308	8.392	8.454	8.180	7.333	8.407	8.475	8.192	7.350	8.423
17	33	10.751	10.288	9.334	10.642	10.650	10.221	9.238	10.573	10.694	10.251	9.280	10.597	10.729	10.270	9.308	10.624
18	33	7.127	6.730	6.180	6.968	7.088	6.705	6.143	6.938	7.106	6.716	6.160	6.950	7.119	6.723	6.171	6.960
19	33	7.425	6.950	6.439	7.215	7.383	6.923	6.398	7.183	7.402	6.936	6.417	7.195	7.416	6.943	6.428	7.206
20	33	7.767	7.348	6.736	7.603	7.718	7.316	6.689	7.567	7.740	7.330	6.711	7.581	7.757	7.339	6.724	7.594
21	33	12.062	11.392	10.473	11.846	11.935	11.310	10.353	11.758	11.990	11.346	10.406	11.789	12.034	11.370	10.441	11.822
22	33	11.814	11.217	10.258	11.644	11.691	11.136	10.140	11.558	11.745	11.172	10.192	11.589	11.787	11.195	10.226	11.621
23	33	7.055	6.744	6.117	6.941	7.015	6.717	6.079	6.910	7.033	6.730	6.097	6.923	7.046	6.737	6.107	6.933
24	33	8.828	8.380	7.657	8.645	8.761	8.336	7.593	8.594	8.792	8.356	7.623	8.615	8.814	8.369	7.640	8.632
25	33	5.709	5.601	4.950	5.689	5.674	5.577	4.917	5.664	5.690	5.588	4.932	5.673	5.702	5.595	4.941	5.682
26	33	2.557	2.451	2.216	2.532	2.551	2.446	2.209	2.526	2.554	2.448	2.212	2.529	2.556	2.450	2.214	2.530
27	33	6.276	6.260	5.444	6.359	6.230	6.227	5.400	6.329	6.249	6.241	5.419	6.338	6.266	6.251	5.432	6.351
28	132	4.680	4.687	4.086	4.726	4.481	4.336	3.894	4.425	4.568	4.397	3.979	4.526	4.636	4.435	4.034	4.584
29	33	3.302	3.145	2.862	3.243	3.291	3.138	2.851	3.231	3.296	3.141	2.856	3.237	3.300	3.143	2.859	3.240
30	33	3.326	3.042	2.882	3.251	3.316	3.036	2.872	3.241	3.321	3.039	2.877	3.246	3.324	3.041	2.880	3.249

Table D9: ANSI Simulated Results for Case 2 at 42% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	9.727	11.918	8.576	11.263	9.711	11.903	8.563	11.247	9.719	11.911	8.570	11.257	9.724	11.916	8.574	11.261
2	132	8.572	9.480	7.501	9.163	8.550	9.462	7.481	9.140	8.561	9.471	7.491	9.154	8.568	9.476	7.497	9.160
3	132	5.297	5.314	4.608	5.355	5.278	5.301	4.590	5.335	5.286	5.307	4.599	5.347	5.293	5.311	4.604	5.352
4	132	6.790	6.645	5.912	6.821	6.752	6.619	5.877	6.779	6.767	6.631	5.893	6.803	6.782	6.639	5.904	6.814
5	132	5.682	5.570	4.948	5.682	5.674	5.565	4.941	5.674	5.678	5.568	4.944	5.679	5.680	5.569	4.946	5.681
6	132	7.701	7.457	6.711	7.703	7.640	7.416	6.655	7.634	7.661	7.433	6.677	7.671	7.687	7.447	6.697	7.691
7	132	4.982	4.774	4.327	4.939	4.967	4.765	4.314	4.923	4.973	4.769	4.320	4.932	4.979	4.772	4.324	4.936
8	132	5.769	5.803	5.028	5.831	5.737	5.780	4.998	5.795	4.748	5.789	5.011	5.815	5.762	5.797	5.021	5.825
9	33	13.138	13.379	11.423	13.434	13.050	13.270	11.344	13.385	13.089	13.299	11.383	13.401	13.121	13.318	11.406	13.428
10	33	14.925	14.455	12.964	14.911	14.745	14.221	12.801	14.816	14.836	14.283	12.891	14.867	14.895	14.313	12.934	14.918
11	11	19.254	23.056	16.780	21.965	19.211	23.013	16.741	21.935	19.228	23.033	16.759	21.941	19.245	23.046	16.771	21.956
12	33	12.703	12.222	11.036	12.650	12.621	12.127	10.964	12.614	12.664	12.155	11.005	12.639	12.689	12.168	11.024	12.661
13	11	21.198	25.863	18.436	25.035	21.135	25.800	18.380	24.984	21.166	25.833	18.410	25.002	21.187	25.851	18.425	25.022
14	33	6.835	6.537	5.925	6.725	6.806	6.503	5.899	6.714	6.824	6.515	5.916	6.727	6.831	6.519	5.922	6.734
15	33	10.506	9.923	9.114	10.296	10.421	9.807	9.038	10.252	10.465	9.835	9.081	10.278	10.492	9.849	9.100	10.300
16	33	8.486	8.224	7.360	8.432	8.443	8.171	7.321	8.414	8.467	8.188	7.344	8.429	8.480	8.194	7.353	8.440
17	33	10.768	10.346	9.341	10.658	10.684	10.242	9.266	10.620	10.729	10.272	9.310	10.648	10.754	10.285	9.328	10.670
18	33	7.141	6.763	6.190	6.977	7.105	6.714	6.157	6.961	7.125	6.728	6.177	6.975	7.136	6.733	6.185	6.984
19	33	7.437	6.982	6.446	7.245	7.398	6.932	6.411	7.205	7.420	6.946	6.432	7.220	7.431	6.952	6.440	7.229
20	33	7.779	7.382	6.743	7.611	7.735	7.326	6.704	7.593	7.760	7.342	6.728	7.609	7.773	7.349	6.737	7.620
21	33	12.214	11.609	10.599	11.994	12.045	11.377	10.448	11.901	12.131	11.433	10.532	11.950	12.185	11.460	10.571	11.996
22	33	12.007	11.478	10.420	11.833	11.823	11.217	10.254	11.726	11.915	11.278	10.345	11.778	11.975	11.309	10.389	11.829
23	33	7.188	6.912	6.233	7.071	7.100	6.770	6.153	7.013	7.142	6.798	6.195	7.034	7.172	6.814	6.217	7.059
24	33	9.461	9.110	8.217	9.322	9.142	8.565	7.923	9.031	9.275	8.655	8.061	9.085	9.396	8.715	8.151	9.183
25	33	8.046	8.343	7.058	8.241	6.991	6.392	6.057	7.099	7.323	6.595	6.429	7.165	7.778	6.802	6.778	7.523
26	33	9.952	13.985	9.555	12.572	5.099	3.731	4.416	5.190	6.196	4.024	5.701	5.956	8.267	4.470	7.446	7.835
27	33	7.192	7.322	6.259	7.310	6.752	6.577	5.852	6.935	6.925	6.699	6.035	6.998	7.097	6.790	6.163	7.140
28	132	4.574	4.395	3.977	4.533	4.532	4.367	3.938	4.482	4.544	4.377	3.951	4.507	4.563	4.387	3.966	4.523
29	33	3.475	3.344	3.015	3.443	3.378	3.190	2.927	3.321	3.425	3.222	2.973	3.345	3.458	3.238	2.997	3.373
30	33	3.474	3.211	3.013	3.423	3.389	3.075	2.936	3.269	3.431	3.102	2.978	3.321	3.459	3.115	2.998	3.340

Table D10: ANSI Simulated Results for Case 3 at 42% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.738	11.930	8.586	11.274	9.716	11.908	8.567	11.250	9.726	11.919	8.577	11.264	9.734	11.925	8.582	11.270
2	132	8.590	9.495	7.517	9.179	8.559	9.469	7.489	9.145	8.572	9.481	7.502	9.164	8.584	9.489	7.511	9.174
3	132	5.311	5.324	4.620	5.368	5.285	5.305	4.596	5.339	5.295	5.131	4.607	5.355	5.305	5.319	4.614	5.363
4	132	6.818	6.664	5.937	6.848	6.768	6.629	5.891	6.789	6.785	6.643	5.909	6.820	6.806	6.655	5.925	6.837
5	132	5.689	5.575	4.954	5.688	5.677	5.567	4.943	5.675	5.682	5.571	4.948	5.682	5.686	5.573	4.952	5.686
6	132	7.767	7.501	6.772	7.768	7.682	7.442	6.692	7.661	7.706	7.463	6.719	7.713	7.745	7.484	6.749	7.747
7	132	4.997	4.784	4.341	4.953	4.976	4.770	4.321	4.928	4.983	4.776	4.329	4.941	4.992	4.780	4.336	4.948
8	132	5.809	5.831	5.065	5.870	5.762	5.797	5.021	5.812	5.776	5.809	5.036	5.840	5.797	5.821	5.052	5.858
9	33	13.114	13.334	11.403	13.402	13.034	13.258	11.330	13.365	13.066	13.283	11.362	13.374	13.097	13.301	11.385	13.398
10	33	14.832	14.323	12.883	14.812	14.690	14.185	12.753	14.746	14.759	14.233	12.821	14.783	14.806	14.258	12.856	14.822
11	11	12.240	23.043	16.768	21.948	19.201	23.004	16.733	21.923	19.216	23.020	16.747	21.926	19.232	23.033	16.759	21.940
12	33	12.673	12.175	11.011	12.621	12.604	12.116	10.949	12.590	12.638	12.138	10.982	12.609	12.661	12.150	10.999	12.628
13	11	21.171	25.837	18.413	25.002	21.119	25.784	18.366	24.962	21.144	25.810	18.390	24.975	21.162	25.826	18.403	24.992
14	33	6.825	6.520	5.917	6.717	6.801	6.500	5.895	6.706	6.815	6.510	5.908	6.716	6.822	6.513	5.913	6.722
15	33	10.456	9.854	9.071	10.247	10.389	9.788	9.010	10.214	10.424	9.810	9.044	10.235	10.445	9.821	9.059	10.253
16	33	8.470	8.197	7.346	8.416	8.434	8.165	7.313	8.401	8.453	8.178	7.331	8.412	8.464	8.184	7.339	8.421
17	33	10.731	10.291	9.309	10.621	10.663	10.229	9.248	10.592	10.698	10.253	9.282	10.613	10.719	10.264	9.298	10.630
18	33	7.124	6.736	6.175	6.961	7.095	6.708	6.148	6.948	7.111	6.719	6.164	6.959	7.120	6.723	6.170	6.966
19	33	7.420	6.955	6.431	7.219	7.388	6.926	6.403	7.192	7.406	6.937	6.419	7.203	7.415	6.942	6.426	7.211
20	33	7.760	7.352	6.727	7.593	7.724	7.319	6.695	7.578	7.744	7.332	6.713	7.590	7.754	7.337	6.721	7.599
21	33	12.103	11.465	10.502	11.881	11.976	11.335	10.388	11.819	12.042	11.377	10.451	11.857	12.081	11.398	10.480	11.890
22	33	11.876	11.311	10.305	11.698	11.740	11.166	10.182	11.629	11.810	11.213	10.250	11.671	11.853	11.234	10.282	11.707
23	33	7.109	6.813	6.163	6.988	7.045	6.736	6.105	6.953	7.078	6.758	6.137	6.973	7.098	6.769	6.152	6.990
24	33	9.099	8.693	7.895	8.926	8.889	8.414	7.704	8.769	8.992	8.483	7.805	8.826	9.061	8.518	7.857	8.883
25	33	6.560	6.604	5.715	6.611	6.066	5.832	5.256	6.161	6.279	5.977	5.473	6.258	6.457	6.070	5.609	6.404
26	33	2.683	2.599	2.327	2.681	2.600	2.476	2.252	2.549	2.641	2.504	2.293	2.587	2.668	2.518	2.312	2.606
27	33	8.850	9.458	7.791	9.173	7.413	7.021	6.425	7.749	7.937	7.341	6.982	7.944	8.502	7.612	7.419	8.395
28	132	4.664	4.453	4.059	4.620	4.597	4.407	3.994	4.527	4.608	4.418	4.010	4.568	4.644	4.438	4.037	4.599
29	33	10.757	14.903	10.261	13.429	5.523	4.390	4.784	5.757	6.934	4.828	6.349	6.558	9.048	5.349	8.124	8.456
30	33	4.964	5.042	4.382	5.128	4.083	3.441	3.537	4.014	4.383	3.597	3.862	4.122	4.741	3.732	4.140	4.410

Table D11: ANSI Simulated Results for Case 4 at 42% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	9.732	11.924	8.581	11.269	9.713	11.905	8.564	11.247	9.722	11.914	8.573	11.260	9.728	11.920	8.578	11.266
2	132	8.581	9.487	7.509	9.172	8.553	9.464	7.484	9.141	8.565	9.475	7.496	9.158	8.576	9.482	7.503	9.167
3	132	5.303	5.318	4.613	5.361	5.280	5.302	4.592	5.336	5.289	5.309	4.601	5.350	5.298	5.314	4.608	5.357
4	132	6.801	6.653	5.922	6.833	6.756	6.622	5.881	6.781	6.773	6.635	5.898	6.809	6.791	6.645	5.912	6.824
5	132	5.685	5.573	4.951	5.685	5.675	5.566	4.942	5.674	5.680	5.569	4.946	5.680	5.683	5.571	4.949	5.683
6	132	7.736	7.481	6.744	7.739	7.659	7.427	6.671	7.644	7.682	7.447	6.697	7.692	7.717	7.466	6.724	7.721
7	132	4.990	4.780	4.335	4.947	4.971	4.767	4.317	4.924	4.978	4.772	4.325	4.936	4.986	4.777	4.330	4.943
8	132	5.792	5.819	5.049	5.854	5.750	5.788	5.010	5.803	5.763	5.800	5.024	5.829	5.782	5.811	5.039	5.844
9	33	13.090	13.315	11.381	13.382	13.018	13.247	11.316	13.348	13.048	13.270	11.346	13.358	13.075	13.286	11.366	13.380
10	33	14.796	14.295	12.850	14.781	14.669	14.172	12.735	14.723	14.733	14.216	12.798	14.758	14.774	14.237	12.828	14.793
11	11	19.228	23.031	16.757	21.937	19.193	22.996	16.725	21.914	19.207	23.011	16.739	21.917	19.220	23.023	16.749	21.930
12	33	12.656	12.162	10.996	12.606	12.595	12.110	10.941	12.579	12.626	12.130	10.971	12.597	12.645	12.141	10.985	12.613
13	11	21.158	25.823	18.401	24.989	21.111	25.775	18.358	24.952	21.133	25.800	18.380	24.965	21.149	25.813	18.392	24.980
14	33	6.820	6.517	5.912	6.712	6.799	6.499	5.893	6.704	6.812	6.508	5.905	6.713	6.817	6.510	5.909	6.718
15	33	10.441	9.842	9.057	10.233	10.381	9.783	9.003	10.204	10.413	9.803	9.034	10.224	10.431	9.812	9.047	10.239
16	33	8.462	8.191	7.338	8.409	8.429	8.163	7.309	8.395	8.447	8.174	7.326	8.406	8.456	8.180	7.333	8.414
17	33	10.715	10.278	9.295	10.608	10.654	10.224	9.241	10.582	10.687	10.245	9.272	10.601	10.705	10.255	9.285	10.617
18	33	7.118	6.731	6.169	6.955	7.092	6.707	6.146	6.944	7.107	6.716	6.160	6.954	7.114	6.720	6.165	6.960
19	33	7.413	6.950	6.425	7.212	7.385	6.924	6.400	7.188	7.401	6.935	6.415	7.199	7.409	6.938	6.421	7.205
20	33	7.752	7.346	6.720	7.586	7.720	7.317	6.691	7.573	7.738	7.329	6.708	7.585	7.747	7.333	6.715	7.592
21	33	12.073	11.441	10.475	11.854	11.960	11.325	10.374	11.800	12.020	11.364	10.431	11.836	12.054	11.381	10.456	11.865
22	33	11.844	11.284	10.276	11.669	11.722	11.155	10.167	11.609	11.787	11.198	10.229	11.648	11.823	11.217	10.256	11.679
23	33	7.094	6.800	6.150	6.975	7.037	6.731	6.098	6.944	7.067	6.752	6.128	6.962	7.085	6.760	6.140	6.977
24	33	9.046	8.645	7.848	8.873	8.860	8.396	7.679	8.737	8.954	8.459	7.771	8.790	9.013	8.489	7.815	8.840
25	33	6.417	6.458	5.585	6.459	5.990	5.784	5.190	6.077	6.180	5.914	5.383	6.168	6.331	5.993	5.497	6.292
26	33	2.662	2.579	2.309	2.660	2.589	2.469	2.243	2.537	2.627	2.495	2.279	2.575	2.649	2.507	2.296	2.592
27	33	8.365	8.907	7.342	8.665	7.187	6.875	6.229	7.502	7.637	7.160	6.702	7.678	8.091	7.385	7.052	8.043
28	132	4.635	4.435	4.033	4.592	4.574	4.393	3.974	4.509	4.586	4.404	3.990	4.547	4.617	4.421	4.014	4.574
29	33	4.915	5.185	4.339	5.121	4.038	3.577	3.498	4.073	4.340	3.744	3.824	4.177	4.694	3.892	4.100	4.450
30	33	10.797	14.924	10.296	13.435	5.503	4.148	4.767	5.626	6.957	4.564	6.370	6.578	9.081	5.028	8.152	8.477

Table D12: ANSI Simulated Results for Case 5 at 42% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.826	12.067	8.673	11.398	9.706	11.900	8.560	11.230	9.762	11.959	8.613	11.291	9.800	11.993	8.643	11.326
2	132	8.754	9.783	7.677	9.422	8.553	9.465	7.485	9.118	8.642	9.544	7.571	9.218	8.709	9.593	7.625	9.276
3	132	5.403	5.502	4.711	5.503	5.277	5.300	4.590	5.321	5.332	5.342	4.644	5.384	5.374	5.67	4.678	5.420
4	132	7.007	7.039	6.125	7.120	6.756	6.622	5.882	6.756	6.863	6.699	5.987	6.883	6.950	6.750	6.057	6.957
5	132	5.950	6.057	5.210	6.058	5.696	5.580	4.961	5.658	5.806	5.658	5.069	5.781	5.892	5.709	5.139	5.854
6	132	8.156	8.284	7.161	8.326	7.672	7.435	6.684	7.604	7.869	7.577	6.881	7.850	8.041	7.675	7.022	8.001
7	132	5.914	6.564	5.261	6.312	5.114	4.854	4.442	5.054	5.423	5.065	4.756	5.325	5.715	5.224	5.003	5.593
8	132	5.964	6.153	5.219	6.103	5.746	5.786	5.007	5.778	5.837	5.856	5.097	5.889	5.913	5.903	5.159	5.955
9	33	13.225	13.421	11.515	13.489	13.019	13.249	11.318	13.364	13.107	13.315	11.404	13.407	13.179	13.361	11.462	13.462
10	33	14.922	14.386	12.975	14.880	14.657	14.166	12.726	14.721	14.780	14.249	12.845	14.795	14.867	14.298	12.913	14.863
11	11	19.296	23.104	16.824	21.990	19.195	22.999	16.728	21.923	19.237	23.043	16.769	21.943	19.274	23.075	16.798	21.973
12	33	12.735	12.218	11.074	12.671	12.590	12.108	10.937	12.582	12.658	12.153	11.002	12.624	12.705	12.179	11.040	12.662
13	11	21.219	25.892	18.461	25.040	21.109	25.774	18.357	24.955	21.159	25.828	18.405	24.987	21.196	25.862	18.435	25.020
14	33	6.841	6.531	5.932	6.731	6.795	6.497	5.890	6.702	6.819	6.513	5.913	6.719	6.832	6.520	5.923	6.731
15	33	10.486	9.874	9.102	10.272	10.369	9.776	8.994	10.197	10.427	9.813	9.049	10.236	10.463	9.832	9.077	10.266
16	33	8.498	8.217	7.373	8.439	8.426	8.161	7.306	8.395	8.461	8.184	7.340	8.418	8.483	8.197	7.357	8.436
17	33	10.776	10.322	9.356	10.658	10.648	10.220	9.236	10.580	10.710	10.261	9.295	10.620	10.750	10.284	9.327	10.653
18	33	7.139	6.746	6.190	6.974	7.087	6.704	6.142	6.941	7.114	6.721	6.167	6.960	7.129	6.729	6.179	6.973
19	33	7.437	6.966	6.448	7.234	7.381	6.922	6.397	7.186	7.409	6.940	6.424	7.206	7.426	6.949	6.437	7.219
20	33	7.780	7.366	6.747	7.610	7.716	7.315	6.688	7.571	7.748	7.336	6.718	7.593	7.768	7.346	6.734	7.609
21	33	12.144	11.493	10.547	11.913	11.941	11.314	10.358	11.785	12.040	11.379	10.453	11.851	12.104	11.413	10.503	11.902
22	33	11.911	11.335	10.345	11.725	11.700	11.142	10.148	11.590	11.804	11.211	10.248	11.659	11.869	11.246	10.299	11.713
23	33	7.111	6.814	6.168	6.990	7.022	6.722	6.086	6.930	7.067	6.752	6.129	6.961	7.094	6.767	6.149	6.983
24	33	9.061	8.665	7.869	8.897	8.805	8.363	7.631	8.681	8.932	8.448	7.755	8.765	9.011	8.489	7.815	8.830
25	33	6.362	6.443	5.552	6.437	5.842	5.689	5.062	5.922	6.078	5.853	5.297	6.062	6.250	5.946	5.430	6.202
26	33	2.657	2.579	2.306	2.659	2.567	2.456	2.224	2.519	2.613	2.487	2.268	2.568	2.639	2.501	2.288	2.588
27	33	8.111	8.779	7.163	8.475	6.768	6.603	5.866	7.064	7.306	6.965	6.416	7.347	7.784	7.215	6.795	7.726
28	132	4.743	4.667	4.143	4.754	4.543	4.374	3.948	4.469	4.619	4.429	4.025	4.575	4.694	4.471	4.086	4.640
29	33	7.003	9.257	6.548	8.492	4.242	3.713	3.675	4.382	5.116	4.141	4.607	4.879	6.170	4.522	5.489	5.839
30	33	4.461	4.594	3.949	4.640	3.669	3.229	3.178	3.594	3.974	3.404	3.493	3.791	4.262	3.527	3.723	4.031

Table D13: ANSI Simulated Results for Case 6 at 42% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.742	11.935	8.591	11.277	9.712	11.904	8.563	11.245	9.727	11.920	8.578	11.264	9.736	11.928	8.585	11.272
2	132	8.597	9.501	7.524	9.184	8.553	9.464	7.484	9.137	8.573	9.482	7.503	9.164	8.588	9.493	7.515	9.177
3	132	5.318	5.329	4.627	5.374	5.280	5.302	4.592	5.333	5.297	5.315	4.609	5.356	5.310	5.323	4.619	5.367
4	132	6.834	6.675	5.953	6.861	6.759	6.624	5.883	6.777	6.790	6.647	5.914	6.823	6.818	6.663	5.936	6.845
5	132	5.691	5.577	4.956	5.689	5.674	5.566	4.941	5.673	5.682	5.571	4.949	5.682	5.687	5.574	4.953	5.686
6	132	7.788	7.516	6.794	7.786	7.661	7.429	6.674	7.637	7.708	7.465	6.723	7.714	7.759	7.493	6.762	7.756
7	132	5.002	4.787	4.346	4.956	4.970	4.767	4.317	4.922	4.984	4.776	4.330	4.941	4.995	4.782	4.339	4.950
8	132	5.817	5.837	5.073	5.876	5.749	5.788	5.009	5.798	5.775	5.809	5.036	5.839	5.802	5.825	5.057	5.861
9	33	13.184	13.419	11.468	13.471	13.040	13.263	11.335	13.384	13.104	13.312	11.399	13.414	13.154	13.342	11.437	13.455
10	33	14.981	14.510	13.019	14.954	14.703	14.196	12.766	14.788	14.843	14.290	12.901	14.874	14.930	14.337	12.967	14.947
11	11	19.277	23.080	16.802	21.984	19.206	23.009	16.737	21.935	19.236	23.042	16.767	21.947	19.262	23.063	16.787	21.970
12	33	12.732	12.248	11.065	12.673	12.605	12.117	10.950	12.604	12.671	12.161	11.013	12.645	12.709	12.181	11.042	12.678
13	11	21.221	25.889	18.458	25.056	21.123	25.788	18.369	24.976	21.171	25.841	18.416	25.006	21.202	25.867	18.439	25.037
14	33	6.844	6.544	5.933	6.731	6.798	6.499	5.893	6.709	6.825	6.516	5.918	6.728	6.837	6.523	5.926	6.739
15	33	10.527	9.946	9.135	10.314	10.398	9.793	9.018	10.235	10.465	9.837	9.083	10.278	10.504	9.857	9.112	10.311
16	33	8.501	8.237	7.374	8.443	8.433	8.165	7.313	8.407	8.469	8.190	7.347	8.431	8.489	8.201	7.362	8.448
17	33	10.793	10.371	9.367	10.678	10.664	10.231	9.250	10.607	10.733	10.276	9.315	10.652	10.771	10.296	9.344	10.684
18	33	7.151	6.772	6.199	6.984	7.095	6.709	6.149	6.954	7.126	6.729	6.178	6.975	7.142	6.737	6.190	6.989
19	33	7.447	6.992	6.456	7.258	7.388	6.926	6.403	7.198	7.421	6.947	6.434	7.221	7.437	6.956	6.446	7.235
20	33	7.791	7.394	6.755	7.620	7.724	7.319	6.695	7.585	7.761	7.344	6.730	7.610	7.780	7.353	6.744	7.627
21	33	12.251	11.653	10.638	12.024	11.998	11.349	10.407	11.866	12.128	11.434	10.533	11.948	12.205	11.473	10.591	12.013
22	33	12.045	11.524	10.459	11.864	11.768	11.185	10.207	11.685	11.909	11.277	10.343	11.773	11.994	11.321	10.408	11.845
23	33	7.200	6.932	6.246	7.082	7.068	6.751	6.125	6.989	7.134	6.795	6.189	7.028	7.175	6.817	6.221	7.062
24	33	9.483	9.177	8.248	9.382	9.013	8.490	7.812	8.933	9.227	8.632	8.026	9.047	9.387	8.713	8.148	9.177
25	33	8.009	8.566	7.078	8.392	6.544	6.141	5.670	6.736	7.093	6.482	6.244	6.985	7.645	6.743	6.678	7.418
26	33	6.274	8.459	5.912	7.747	3.719	3.113	3.221	3.806	4.424	3.430	4.003	4.269	5.457	3.773	4.872	5.228
27	33	8.537	9.301	7.539	8.965	6.981	6.751	6.050	7.330	7.607	7.154	6.693	7.656	8.167	7.434	7.132	8.105
28	132	4.664	4.455	4.062	4.620	4.567	4.389	3.968	4.498	4.597	4.412	4.001	4.556	4.639	4.436	4.034	4.593
29	33	4.529	4.844	4.009	4.755	3.691	3.382	3.197	3.726	4.019	3.578	3.535	3.890	4.324	3.717	3.777	4.125
30	33	7.154	9.396	6.682	8.615	4.302	3.576	3.727	4.356	5.220	3.980	4.702	4.955	6.303	4.326	5.607	5.933

Table D14: ANSI Simulated Results for Case 1 at 85% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.935	12.189	8.769	11.510	9.748	11.942	8.598	11.268	9.839	12.037	8.683	11.353	9.894	12.083	8.725	11.403
2	132	8.965	10.014	7.864	9.645	8.648	9.541	7.570	9.158	8.792	9.669	7.709	9.337	8.891	9.737	7.783	9.421
3	132	5.514	5.622	4.808	5.620	5.329	5.335	4.637	5.341	5.412	5.397	4.717	5.447	5.470	5.430	4.760	5.495
4	132	7.242	7.296	6.332	7.371	6.874	6.696	5.985	6.807	7.031	6.809	6.140	7.019	7.151	6.874	6.232	7.120
5	132	6.343	6.459	5.562	6.464	5.870	5.690	5.114	5.847	6.073	5.832	5.315	5.995	6.226	5.913	5.432	6.122
6	132	8.673	8.871	7.622	8.889	7.925	7.592	6.906	7.832	8.226	7.802	7.211	8.147	8.479	7.933	7.405	8.362
7	132	7.906	9.067	7.147	8.572	5.844	5.296	5.078	5.929	6.575	5.718	5.842	6.346	7.296	6.025	6.415	6.987
8	132	6.146	6.366	5.379	6.303	5.837	5.847	5.087	5.870	5.968	5.946	5.217	5.994	6.070	6.004	5.295	6.079
9	33	13.323	13.466	11.597	13.565	13.121	13.320	11.406	13.464	13.192	13.374	11.478	13.469	13.267	13.418	11.536	13.523
10	33	14.952	14.355	12.997	14.906	14.754	14.226	12.810	14.800	14.826	14.275	12.883	14.812	14.899	14.314	12.938	14.864
11	11	19.345	23.148	16.865	22.024	19.250	23.051	16.775	21.979	19.280	23.084	16.806	21.975	19.317	23.115	16.834	22.005
12	33	12.779	12.227	11.109	12.712	12.648	12.143	10.988	12.636	12.700	12.178	11.039	12.652	12.745	12.202	11.073	12.685
13	11	21.251	25.920	18.487	25.059	21.157	25.821	18.399	25.003	21.191	25.859	18.433	25.009	21.226	25.889	18.459	25.039
14	33	6.849	6.531	5.939	6.743	6.808	6.505	5.902	6.714	6.828	6.518	5.920	6.725	6.840	6.525	5.930	6.734
15	33	10.485	9.847	9.099	10.276	10.396	9.792	9.017	10.217	10.436	9.818	9.055	10.236	10.464	9.832	9.076	10.257
16	33	8.514	8.218	7.387	8.457	8.451	8.177	7.328	8.418	8.478	8.195	7.354	8.428	8.499	8.206	7.370	8.444
17	33	10.797	10.315	9.372	10.680	10.693	10.248	9.275	10.619	10.735	10.276	9.316	10.633	10.771	10.295	9.343	10.659
18	33	7.143	6.739	6.193	6.981	7.101	6.712	6.154	6.952	7.120	6.725	6.173	6.963	7.133	6.732	6.182	6.972
19	33	7.443	6.960	6.453	7.230	7.397	6.931	6.410	7.199	7.418	6.945	6.431	7.209	7.432	6.952	6.441	7.220
20	33	7.788	7.359	6.753	7.621	7.735	7.326	6.704	7.587	7.759	7.342	6.727	7.598	7.775	7.350	6.740	7.610
21	33	12.119	11.424	10.521	11.894	11.988	11.342	10.398	11.815	12.042	11.377	10.451	11.834	12.086	11.400	10.485	11.866
22	33	11.870	11.248	10.303	11.690	11.741	11.167	10.184	11.612	11.794	11.202	10.236	11.632	11.838	11.225	10.269	11.664
23	33	7.070	6.753	6.130	6.954	7.027	6.725	6.090	6.924	7.047	6.739	6.109	6.935	7.061	6.745	6.119	6.946
24	33	8.856	8.396	7.679	8.669	8.782	8.349	7.611	8.619	8.816	8.371	7.644	8.637	8.839	8.383	7.661	8.654
25	33	5.724	5.610	4.962	5.702	5.687	5.585	4.928	5.678	5.703	5.597	4.943	5.685	5.715	5.603	4.952	5.694
26	33	2.560	2.452	2.218	2.534	2.553	2.447	2.211	2.526	2.556	2.450	2.214	2.530	2.558	2.451	2.216	2.532
27	33	6.298	6.274	5.462	6.377	6.252	6.241	5.419	6.352	6.269	6.254	5.436	6.355	6.286	6.264	5.449	6.367
28	132	4.771	4.745	4.162	4.798	4.554	4.381	3.958	4.486	4.646	4.446	4.049	4.589	4.718	4.483	4.103	4.649
29	33	3.307	3.148	2.866	3.247	3.295	3.140	2.854	3.233	3.300	3.144	2.860	3.241	3.304	3.146	2.863	3.244
30	33	3.331	3.044	2.886	3.254	3.319	3.038	2.875	3.243	3.325	3.041	2.880	3.249	3.328	3.043	2.883	3.252

Table D15: ANSI Simulated Results for Case 2 at 85% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.730	11.921	8.579	11.265	9.720	11.911	8.570	11.254	9.724	11.916	8.574	11.261	9.728	11.919	8.577	11.264
2	132	8.578	9.484	7.505	9.166	8.564	9.493	7.493	9.151	8.569	9.477	7.498	9.160	8.575	9.481	7.503	9.164
3	132	5.302	5.317	4.611	5.358	5.290	5.309	4.601	5.345	5.294	5.312	4.605	5.353	5.300	5.315	4.609	5.357
4	132	6.801	6.651	5.921	6.828	6.778	6.636	5.899	6.801	6.785	6.642	5.907	6.815	6.796	6.648	5.915	6.824
5	132	5.683	5.571	4.949	5.682	5.678	5.568	4.945	5.677	5.681	5.570	4.947	5.680	5.682	5.571	4.948	5.682
6	132	7.722	7.468	6.728	7.717	7.685	7.444	6.693	7.672	7.693	7.452	6.704	7.695	7.712	7.462	6.718	7.710
7	132	4.987	4.777	4.331	4.941	4.977	4.771	4.322	4.931	4.980	4.773	4.326	4.937	4.985	4.775	4.329	4.940
8	132	5.779	5.809	5.036	5.838	5.760	5.795	5.018	5.815	5.765	5.800	5.024	5.827	5.775	5.805	5.031	5.834
9	33	13.161	13.394	11.441	13.456	13.105	13.307	11.391	13.434	13.126	13.324	11.413	13.437	13.149	13.337	11.430	13.457
10	33	14.961	14.478	12.991	14.946	14.843	14.282	12.886	14.908	14.898	14.320	12.492	14.932	14.941	14.342	12.972	14.969
11	11	19.266	23.066	16.790	21.978	19.239	23.040	16.765	21.961	19.248	23.050	16.775	21.961	19.260	23.060	16.784	21.972
12	33	12.717	12.231	11.048	12.665	12.664	12.153	11.000	12.654	12.690	12.170	11.027	12.666	12.709	12.180	11.040	12.683
13	11	21.210	25.875	18.446	25.050	21.170	25.834	18.410	25.019	21.188	25.855	18.428	25.027	21.203	25.867	18.439	25.042
14	33	6.839	6.538	5.928	6.728	6.818	6.511	5.910	6.727	6.831	6.519	5.922	6.735	6.836	6.522	5.926	6.740
15	33	10.521	9.933	9.126	10.312	10.466	9.833	9.077	10.294	10.493	9.851	9.104	10.306	10.512	9.861	9.118	10.323
16	33	8.493	8.228	7.365	8.438	8.464	8.185	7.339	8.434	8.480	8.195	7.354	8.442	8.489	8.200	7.361	8.451
17	33	10.782	10.355	9.352	10.672	10.726	10.268	9.303	10.661	10.755	10.287	9.331	10.675	10.773	10.297	9.344	10.691
18	33	7.147	6.766	6.194	6.982	7.122	6.725	6.172	6.978	7.136	6.734	6.185	6.986	7.143	6.737	6.191	6.992
19	33	7.442	6.985	6.450	7.248	7.416	6.943	6.427	7.223	7.431	6.952	6.441	7.231	7.439	6.956	6.447	7.238
20	33	7.786	7.386	6.784	7.617	7.756	7.338	6.722	7.613	7.772	7.349	6.738	7.622	7.781	7.354	6.744	7.630
21	33	12.246	11.630	10.625	12.026	12.136	11.430	10.526	11.985	12.188	11.465	10.579	12.008	12.228	11.485	10.607	12.042
22	33	12.044	11.501	10.449	11.869	11.923	11.277	10.341	11.819	11.979	11.315	10.398	11.843	12.023	11.337	10.429	11.881
23	33	7.208	6.925	6.248	7.090	7.151	6.800	6.197	7.059	7.175	6.818	6.222	7.067	7.197	6.829	6.238	7.086
24	33	9.551	9.169	8.287	9.389	9.344	8.683	8.098	9.210	9.416	8.733	8.178	9.220	9.508	8.777	8.245	9.294
25	33	8.500	8.682	7.420	8.609	7.745	6.795	6.710	7.762	7.910	6.892	6.928	7.703	8.299	7.055	7.219	8.010
26	33	17.355	24.727	16.187	21.976	8.264	4.647	7.158	8.153	9.843	4.759	9.178	9.412	13.979	5.211	12.660	13.071
27	33	7.328	7.419	6.366	7.441	7.036	6.755	6.097	7.190	7.130	6.821	6.205	7.195	7.263	6.889	6.303	7.306
28	132	4.591	4.405	3.990	4.545	4.567	4.388	3.968	4.513	4.569	4.392	3.972	4.527	4.584	4.400	3.983	4.539
29	33	3.496	3.357	3.031	3.458	3.433	3.223	2.973	3.370	3.461	3.242	3.003	3.381	3.485	3.254	3.020	3.402
30	33	3.492	3.222	3.027	3.436	3.346	3.101	2.976	3.303	3.462	3.117	3.002	3.340	3.482	3.127	3.017	3.354

Table D16: ANSI Simulated Results for Case 3 at 85% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	9.744	11.935	8.591	11.279	9.730	11.921	8.579	11.262	9.735	11.927	8.584	11.271	9.741	11.932	8.588	11.276
2	132	8.601	9.502	7.526	9.187	8.581	9.486	7.508	9.163	8.587	9.492	7.514	9.175	8.596	9.498	7.521	9.183
3	132	5.320	5.329	4.627	5.375	5.304	5.318	4.613	5.355	5.308	5.322	4.617	5.365	5.316	5.326	4.623	5.371
4	132	6.838	6.676	5.954	6.863	6.808	6.655	5.926	6.823	6.813	6.660	5.932	6.841	6.830	6.669	5.945	6.855
5	132	5.692	5.577	4.957	5.690	5.685	5.572	4.950	5.681	5.687	5.574	4.953	5.686	5.691	5.576	4.955	5.689
6	132	7.808	7.523	6.805	7.798	7.760	7.490	6.759	7.729	7.760	7.495	6.765	7.757	7.792	7.512	6.788	7.783
7	132	5.006	4.789	4.348	4.959	4.993	4.780	4.336	4.942	4.995	4.783	4.339	4.950	5.002	4.786	4.344	4.956
8	132	5.831	5.844	5.082	5.886	5.804	5.824	5.057	5.848	5.805	5.828	5.060	5.864	5.822	5.837	5.073	5.878
9	33	13.141	13.352	11.425	13.427	13.092	13.297	11.379	13.415	13.105	13.309	11.395	13.409	13.129	13.323	11.413	13.429
10	33	14.869	14.345	12.912	14.847	14.773	14.237	12.825	14.824	14.813	14.265	12.867	14.836	14.851	14.285	12.894	14.868
11	11	19.255	23.056	16.780	21.962	19.231	23.032	16.758	21.951	19.236	23.039	16.765	21.946	19.249	23.049	16.774	21.957
12	33	12.690	12.185	11.024	12.637	12.644	12.140	10.983	12.627	12.664	12.153	11.003	12.634	12.681	12.163	11.016	12.649
13	11	21.186	25.850	18.425	25.019	21.152	25.816	18.394	24.995	21.165	25.831	18.407	24.998	21.179	25.843	18.418	25.011
14	33	6.829	6.522	5.920	6.720	6.811	6.507	5.904	6.717	6.821	6.513	5.914	6.723	6.827	6.516	5.917	6.728
15	33	10.471	9.863	9.082	10.261	10.425	9.809	9.041	10.248	10.447	9.823	9.063	10.258	10.463	9.831	9.075	10.272
16	33	8.478	8.202	7.352	8.423	8.453	8.177	7.300	8.419	8.465	8.186	7.341	8.424	8.474	8.190	7.348	8.432
17	33	10.746	10.300	9.321	10.636	10.700	10.252	9.280	10.627	10.721	10.266	9.302	10.636	10.738	10.275	9.314	10.650
18	33	7.130	6.739	6.179	6.966	7.109	6.717	6.161	6.962	7.120	6.724	6.171	6.968	7.126	6.727	6.176	6.973
19	33	7.425	6.958	6.435	7.222	7.403	6.935	6.416	7.207	7.415	6.943	6.427	7.213	7.422	6.946	6.432	7.219
20	33	7.767	7.356	6.732	7.599	7.742	7.330	6.710	7.595	7.755	7.338	6.722	7.602	7.763	7.342	6.728	7.608
21	33	12.132	11.482	10.525	11.908	12.045	11.376	10.447	11.885	12.085	11.403	10.487	11.901	12.117	11.418	10.510	11.927
22	33	11.908	11.330	10.330	11.728	11.814	11.211	10.246	11.701	11.857	11.240	10.290	11.718	11.891	11.257	10.314	11.747
23	33	7.123	6.823	6.174	7.002	7.079	6.757	6.135	6.986	7.100	6.771	6.156	6.995	7.116	6.779	6.167	7.008
24	33	9.153	8.728	7.938	8.965	9.009	8.486	7.808	8.883	9.071	8.528	7.871	8.903	9.126	8.555	7.912	8.949
25	33	6.725	6.724	5.847	6.740	6.377	6.022	5.525	6.450	6.497	6.105	5.658	6.467	6.648	6.179	5.770	6.590
26	33	2.703	2.613	2.344	2.697	2.646	2.504	2.292	2.593	2.671	2.521	2.318	2.606	2.693	2.532	2.333	2.621
27	33	9.508	9.990	8.327	9.784	8.387	7.586	7.268	8.661	8.684	7.744	7.627	8.639	9.218	7.978	8.030	9.065
28	132	4.705	4.476	4.092	4.651	4.671	4.452	4.058	4.593	4.660	4.449	4.054	4.611	4.690	4.465	4.076	4.636
29	33	18.166	25.661	17.529	22.848	8.550	5.531	7.406	8.706	10.581	5.717	9.828	9.967	14.768	6.283	13.345	13.662
30	33	5.414	5.387	4.751	5.521	4.714	3.724	4.083	4.583	4.871	3.799	4.285	4.559	5.221	3.916	4.551	4.826

Table D17: ANSI Simulated Results for Case 4 at 85% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.737	11.929	8.586	11.273	9.725	11.916	8.574	11.258	9.735	11.926	8.583	11.271	9.729	11.922	8.579	11.266
2	132	8.590	9.494	7.516	9.178	8.572	9.479	7.501	9.157	8.586	9.490	7.512	9.174	8.578	9.485	7.506	9.168
3	132	5.311	5.323	4.619	5.367	5.297	5.313	4.606	5.349	5.307	5.320	4.616	5.364	5.300	5.316	4.611	5.358
4	132	6.819	6.663	5.936	6.846	6.792	6.644	5.911	6.810	6.811	6.658	5.929	6.839	6.797	6.650	5.918	6.827
5	132	5.688	5.575	4.953	5.687	5.682	5.570	4.947	5.679	5.687	5.574	4.952	5.686	5.684	5.572	4.950	5.684
6	132	7.771	7.500	6.772	7.765	7.727	7.470	6.730	7.703	7.757	7.490	6.758	7.752	7.729	7.475	6.737	7.729
7	132	4.998	4.784	4.341	4.952	4.986	4.776	4.330	4.937	4.995	4.782	4.338	4.949	4.988	4.778	4.333	4.944
8	132	5.811	5.831	5.064	5.868	5.786	5.813	5.041	5.834	5.803	5.825	5.057	5.861	5.788	5.816	5.046	5.849
9	33	13.114	13.330	11.400	13.404	13.069	13.281	11.359	13.393	13.103	13.305	11.390	13.407	13.082	13.292	11.374	13.389
10	33	14.828	14.314	12.875	14.811	14.742	14.218	12.799	14.792	14.812	14.260	12.860	14.832	14.779	14.244	12.836	14.804
11	11	19.241	23.042	16.767	21.950	19.219	23.021	16.748	21.938	19.235	23.036	16.762	21.944	19.224	23.027	16.754	21.935
12	33	12.670	12.171	11.007	12.620	12.629	12.131	10.970	12.612	12.663	12.151	11.000	12.632	12.648	12.143	10.989	12.619
13	11	21.170	25.834	18.411	25.003	21.139	25.803	18.383	24.981	21.164	25.828	18.405	24.996	21.152	25.817	18.396	24.984
14	33	6.824	6.518	5.915	6.716	6.808	6.505	5.901	6.713	6.821	6.513	5.913	6.723	4.817	6.511	5.910	6.719
15	33	10.453	9.849	9.067	10.245	10.412	9.801	9.030	10.235	10.446	9.821	9.060	10.256	10.432	9.814	9.050	10.244
16	33	8.468	8.195	7.343	8.415	8.446	8.173	7.324	8.412	8.465	8.185	7.340	8.423	8.457	8.181	7.334	8.417
17	33	10.728	10.286	9.305	10.620	10.687	10.243	9.269	10.613	10.721	10.264	9.299	10.634	10.706	10.257	9.288	10.622
18	33	7.122	6.734	6.173	6.960	7.104	6.714	6.157	6.957	7.120	6.723	6.170	6.967	7.114	6.720	6.166	6.962
19	33	7.418	6.952	6.429	7.215	7.398	6.932	6.412	7.201	7.415	6.942	6.426	7.212	7.409	6.939	6.422	7.207
20	33	7.758	7.349	6.724	7.592	7.736	7.326	6.705	7.588	7.755	7.337	6.721	7.600	7.747	7.334	6.716	7.594
21	33	12.098	11.455	10.495	11.878	12.020	11.361	10.426	11.858	12.084	11.399	10.482	11.897	12.057	11.385	10.462	11.874
22	33	11.871	11.300	10.298	11.695	11.787	11.195	10.223	11.672	11.856	11.236	10.284	11.714	11.827	11.221	10.263	11.689
23	33	7.106	6.808	6.159	6.987	7.067	6.749	6.124	6.973	7.100	6.769	6.153	6.993	7.086	6.762	6.143	6.981
24	33	9.092	8.675	7.884	8.906	8.965	8.459	7.769	8.836	9.068	8.521	7.861	8.896	9.021	8.497	7.827	8.857
25	33	6.552	6.556	5.694	6.565	6.255	5.948	5.420	6.325	6.489	6.085	5.630	6.447	6.362	6.022	5.537	6.344
26	33	2.680	2.590	2.323	2.673	2.629	2.494	2.277	2.575	2.670	2.519	2.314	2.605	2.652	2.510	2.301	2.592
27	33	8.866	9.308	7.749	9.142	7.982	7.349	6.917	8.246	8.644	7.681	7.523	8.565	8.227	7.490	7.210	8.232
28	132	4.670	4.454	4.061	4.619	4.638	4.432	4.030	4.566	4.657	4.445	4.047	4.606	4.631	4.431	4.028	4.584
29	33	5.362	5.542	4.706	5.510	4.670	3.892	4.045	4.650	5.171	4.096	4.508	4.879	4.824	3.967	4.244	4.613
30	33	18.209	25.687	17.567	22.859	8.514	5.162	7.375	8.536	14.802	5.838	13.375	13.686	10.603	5.344	9.849	9.995

Table D18: ANSI Simulated Results for Case 5 at 85% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.906	12.163	8.746	11.485	9.726	11.920	8.578	11.237	9.811	12.010	8.659	11.330	9.866	12.058	8.702	11.379
2	132	8.900	9.966	7.812	9.592	8.595	9.499	7.523	9.128	8.733	9.621	7.656	9.289	8.830	9.691	7.733	9.372
3	132	5.494	5.611	4.793	5.604	5.309	5.321	4.618	5.332	5.391	5.382	4.698	5.429	5.451	5.418	4.745	5.479
4	132	7.202	7.275	6.304	7.340	6.829	6.668	5.946	6.787	6.988	6.782	6.102	6.983	7.113	6.852	6.201	7.089
5	132	6.166	6.342	5.413	6.321	5.743	5.610	5.003	5.699	5.929	5.741	5.185	5.878	6.065	5.817	5.294	5.993
6	132	8.573	8.814	7.549	8.812	7.827	7.531	6.820	7.712	8.128	7.743	7.123	8.065	8.387	7.883	7.330	8.288
7	132	6.875	8.173	6.216	7.696	5.316	4.980	4.619	5.329	5.905	5.356	5.219	5.747	6.448	5.624	5.670	6.240
8	132	6.135	6.364	5.376	6.298	5.816	5.834	5.069	5.840	5.948	5.933	5.200	5.979	6.058	5.998	5.287	6.072
9	33	13.373	13.526	11.648	13.613	13.110	13.313	11.397	13.465	13.216	13.393	11.502	13.505	13.311	13.451	11.577	13.576
10	33	15.077	14.486	13.113	15.013	14.760	14.232	12.816	14.839	14.901	14.327	12.954	14.908	15.009	14.385	13.037	14.991
11	11	19.372	23.177	16.892	22.055	19.245	23.047	16.772	21.980	19.294	23.099	16.820	21.995	19.341	23.139	16.857	22.033
12	33	12.822	12.273	11.151	12.746	12.641	12.140	10.981	12.642	12.723	12.194	11.061	12.685	12.783	12.226	11.107	12.732
13	11	21.289	25.962	18.523	25.106	21.154	25.819	18.396	25.010	21.212	25.883	18.453	25.040	21.259	25.924	18.489	25.081
14	33	6.862	6.544	5.951	6.750	6.804	6.503	5.898	6.715	6.834	6.523	5.927	6.736	6.851	6.531	5.939	6.749
15	33	10.544	9.910	9.153	10.324	10.404	9.797	9.024	10.240	10.472	9.841	9.089	10.281	10.516	9.864	9.123	10.316
16	33	8.537	8.242	7.408	8.473	8.448	8.175	7.326	8.422	8.490	8.204	7.366	8.447	8.518	8.219	7.388	8.469
17	33	10.846	10.367	9.418	10.719	10.691	10.247	9.273	10.632	10.764	10.296	9.343	10.672	10.814	10.323	9.382	10.711
18	33	7.163	6.761	6.212	6.996	7.100	6.712	6.154	6.959	7.132	6.733	6.184	6.979	7.151	6.743	6.198	6.995
19	33	7.463	6.983	6.472	7.255	7.395	6.931	6.409	7.205	7.430	6.953	6.442	7.226	7.450	6.963	6.458	7.243
20	33	7.812	7.385	6.775	7.639	7.733	7.325	6.703	7.593	7.772	7.351	6.740	7.617	7.796	7.363	6.759	7.637
21	33	12.245	11.556	10.636	12.002	12.010	11.356	10.418	11.868	12.122	11.429	10.527	11.931	12.198	11.468	10.584	11.991
22	33	12.013	11.400	10.434	11.815	11.772	11.187	10.211	11.676	11.888	11.263	10.323	11.742	11.965	11.303	10.382	11.803
23	33	7.147	6.838	6.199	7.023	7.051	6.740	6.111	6.964	7.099	6.772	6.157	6.994	7.129	6.788	6.180	7.018
24	33	9.163	8.735	7.956	8.979	8.902	8.422	7.715	8.791	9.029	8.507	7.840	8.862	9.113	8.549	7.903	8.931
25	33	6.594	6.628	5.746	6.639	6.079	5.842	5.268	6.178	6.303	5.993	5.496	6.281	6.486	6.087	5.634	6.430
26	33	2.687	2.602	2.332	2.685	2.602	2.477	2.254	2.552	2.645	2.506	2.296	2.589	2.672	2.520	2.316	2.609
27	33	8.919	9.512	7.854	9.235	7.448	7.044	6.456	7.788	7.991	7.372	7.030	7.991	8.560	7.643	7.471	8.444
28	132	4.898	4.834	4.282	4.918	6.638	4.432	4.030	4.561	4.732	4.500	4.128	4.668	4.831	4.553	4.206	4.752
29	33	10.835	14.992	10.333	13.509	5.563	4.408	4.819	5.797	7.008	4.850	6.416	6.626	9.109	5.362	8.177	8.509
30	33	4.977	5.050	4.392	5.138	4.096	3.447	3.548	4.026	4.400	3.604	3.876	4.136	4.752	3.737	4.150	4.418

Table D19: ANSI Simulated Results for Case 6 at 85% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	9.752	11.943	8.599	11.284	9.728	11.920	8.578	11.258	9.739	11.931	8.588	11.273	9.747	11.938	8.594	11.281
2	132	8.613	9.513	7.537	9.196	8.579	9.485	7.507	9.157	8.592	9.497	7.520	9.179	8.606	9.506	7.530	9.190
3	132	5.333	5.338	4.639	5.384	5.305	5.318	4.613	5.352	5.315	5.326	4.624	5.369	5.326	5.333	4.633	5.379
4	132	6.866	6.694	5.979	6.884	6.811	6.656	5.929	6.818	6.828	6.671	5.947	6.852	6.853	6.684	5.965	6.872
5	132	5.696	5.580	4.960	5.693	5.683	5.571	4.949	5.679	5.689	5.575	4.954	5.687	5.693	5.578	4.958	5.691
6	132	7.849	7.551	6.843	7.831	7.760	7.490	6.759	7.715	7.780	7.509	6.784	7.771	7.825	7.533	6.818	7.808
7	132	5.014	4.794	4.356	4.965	4.992	4.779	4.335	4.938	4.999	4.785	4.343	4.952	5.009	4.791	4.350	4.960
8	132	5.849	5.857	5.099	5.900	5.801	5.822	5.054	5.838	5.812	5.833	5.068	5.868	5.836	5.847	5.086	5.888
9	33	13.236	13.455	11.510	13.519	13.129	13.324	11.412	13.469	13.169	13.356	11.454	13.475	13.213	13.381	11.486	13.511
10	33	15.061	14.562	13.083	15.029	14.842	14.283	12.886	14.930	14.946	14.353	12.989	14.977	15.021	14.392	13.044	15.041
11	11	19.305	23.105	16.825	22.012	19.253	23.054	16.778	21.981	19.271	23.073	16.796	21.981	19.293	23.091	16.813	22.000
12	33	12.767	12.270	11.093	12.706	12.667	12.155	11.003	12.667	12.716	12.188	11.051	12.691	12.749	12.205	11.076	12.719
13	11	21.250	25.916	18.482	25.088	21.175	25.840	18.414	25.033	21.209	25.877	18.448	25.047	21.236	25.900	18.468	25.073
14	33	6.852	6.549	5.940	6.740	6.815	6.509	5.907	6.728	6.837	6.524	5.928	6.742	6.847	6.529	5.935	6.751
15	33	10.561	9.968	9.163	10.346	10.459	9.829	9.071	10.298	10.510	9.863	9.121	10.324	10.543	9.879	9.146	10.352
16	33	8.517	8.248	7.387	8.458	8.463	8.184	7.339	8.439	8.491	8.203	7.366	8.454	8.508	8.212	7.378	8.468
17	33	10.826	10.391	9.393	10.709	10.723	10.267	9.301	10.668	10.776	10.302	9.352	10.696	10.809	10.319	9.376	10.724
18	33	7.163	6.780	6.209	6.996	7.118	6.722	6.169	6.979	7.143	6.739	6.193	6.993	7.156	6.745	6.202	7.005
19	33	7.460	7.000	6.466	7.267	7.412	6.940	6.424	7.224	7.439	6.957	6.449	7.240	7.453	6.964	6.459	7.252
20	33	7.807	7.403	6.768	7.635	7.752	7.336	6.719	7.615	7.782	7.356	6.747	7.632	7.798	7.364	6.759	7.646
21	33	12.321	11.698	10.694	12.090	12.119	11.422	10.512	11.990	12.218	11.486	10.609	12.039	12.285	11.520	10.659	12.096
22	33	12.122	11.575	10.522	11.937	11.902	11.266	10.323	11.822	12.008	11.336	10.429	11.874	12.083	11.373	10.483	11.937
23	33	7.239	6.959	6.278	7.118	7.135	6.791	6.183	7.056	7.183	6.824	6.232	7.077	7.220	6.843	6.259	7.107
24	33	9.650	9.294	8.383	9.515	9.275	8.645	8.038	9.187	9.429	8.747	8.198	9.240	9.572	8.817	8.305	9.357
25	33	8.809	9.236	7.745	9.106	7.416	6.647	6.425	7.594	7.867	6.892	6.926	7.702	8.457	7.142	7.378	8.168
26	33	10.102	14.162	9.692	12.744	5.222	3.780	4.523	5.313	6.336	4.060	5.828	6.074	8.401	4.492	7.564	7.942
27	33	9.360	10.028	8.232	9.712	7.836	7.288	6.792	8.209	8.383	7.595	7.379	8.391	8.993	7.872	7.847	8.881
28	132	4.721	4.487	4.108	4.664	4.657	4.443	4.046	4.570	4.661	4.451	4.056	4.610	4.700	4.471	4.086	4.643
29	33	5.046	5.312	4.452	5.249	4.165	3.646	3.608	4.205	4.463	3.804	3.933	4.296	4.822	3.949	4.211	4.573
30	33	11.002	15.159	10.480	13.666	5.671	4.217	4.912	5.792	7.144	4.613	6.539	6.734	9.267	5.062	8.316	8.626

Table D20: IEC Simulated Results for Case 1 at 10% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.559	12.825	9.299	12.112	10.545	12.789	9.288	12.072	10.567	12.809	9.306	12.094	10.577	12.819	9.315	12.103
2	132	10.082	11.048	8.814	10.701	10.058	10.949	8.793	10.623	10.097	10.979	8.827	10.662	10.117	10.994	8.844	10.679
3	132	6.153	6.124	5.348	6.190	6.139	6.053	5.336	6.149	6.163	6.068	5.356	6.171	6.174	6.075	5.366	6.181
4	132	8.170	7.900	7.105	8.156	8.141	7.745	7.080	8.076	8.191	7.775	7.122	8.124	8.215	7.790	7.144	8.147
5	132	7.546	7.181	6.565	7.452	7.506	6.971	6.531	7.340	7.573	7.009	6.589	7.406	7.607	7.029	6.619	7.436
6	132	9.577	9.216	8.333	9.527	9.519	8.890	8.283	9.370	9.622	8.949	8.372	9.476	9.676	8.981	8.420	9.526
7	132	6.325	6.331	5.489	6.372	6.215	5.712	5.393	6.009	6.427	5.830	5.577	6.235	6.546	5.897	5.683	6.351
8	132	7.160	7.105	6.233	7.186	7.135	6.969	6.212	7.113	7.178	6.996	6.249	7.156	7.199	7.010	6.268	7.175
9	33	15.988	16.092	13.890	16.259	15.972	16.082	13.877	16.253	16.003	16.102	13.903	16.271	16.019	16.113	13.918	16.283
10	33	19.227	18.037	16.683	19.029	19.210	18.028	16.669	19.021	19.241	18.046	16.695	19.040	19.258	18.056	16.710	19.053
11	11	23.035	27.526	20.069	26.200	23.028	27.520	20.063	26.197	23.043	27.533	20.075	26.206	23.051	27.541	20.082	26.212
12	33	16.126	15.077	14.001	15.914	16.116	15.072	13.993	15.909	16.134	15.082	14.008	15.921	16.143	15.088	14.016	15.928
13	11	25.527	30.855	22.192	29.812	25.520	30.849	22.187	29.808	25.533	30.860	22.197	29.817	25.539	30.867	22.203	29.822
14	33	8.259	7.711	7.157	8.058	8.256	7.709	7.154	8.056	8.260	7.712	7.158	8.059	8.262	7.713	7.160	8.061
15	33	13.089	11.941	11.347	12.687	13.082	11.938	11.341	12.683	13.094	11.944	11.351	12.691	13.099	11.947	11.356	12.696
16	33	10.241	9.725	8.877	10.107	10.237	9.722	8.873	10.105	10.245	9.727	8.880	10.110	10.248	9.729	8.883	10.113
17	33	13.397	12.514	11.614	13.138	13.389	12.509	11.607	13.134	13.403	12.517	11.619	13.143	13.410	12.522	11.626	13.149
18	33	8.671	7.980	7.512	8.386	8.668	7.979	7.509	8.384	8.672	7.981	7.513	8.387	8.675	7.983	7.515	8.389
19	33	9.164	8.317	7.939	8.821	9.161	8.315	7.937	8.818	9.166	8.318	7.941	8.823	9.169	8.320	7.943	8.825
20	33	9.510	8.768	8.240	9.210	9.506	8.766	8.237	9.208	9.513	8.769	8.242	9.212	9.516	8.771	8.245	9.215
21	33	15.422	14.109	13.370	14.959	15.411	14.103	13.361	14.953	15.430	14.113	13.377	14.966	15.439	14.119	13.385	14.973
22	33	14.969	13.811	12.977	14.596	14.959	13.805	12.968	14.591	14.977	13.815	12.983	14.603	14.986	13.820	12.991	14.610
23	33	8.475	7.937	7.343	8.264	8.472	7.935	7.340	8.263	8.477	7.938	7.344	8.266	8.479	7.939	7.346	8.268
24	33	10.907	10.075	9.449	10.551	10.901	10.072	9.445	10.548	10.910	10.077	9.452	10.554	10.914	10.079	9.456	10.557
25	33	6.941	6.721	6.013	6.879	6.938	6.720	6.011	6.877	6.943	6.722	6.015	6.880	6.945	6.724	6.017	6.882
26	33	3.060	2.870	2.651	3.017	3.060	2.870	2.650	3.017	3.061	2.870	2.651	3.018	3.061	2.870	2.651	3.018
27	33	7.997	7.913	6.929	8.099	7.993	7.911	6.926	8.098	8.000	7.915	6.932	8.102	8.004	7.918	6.936	8.105
28	132	5.371	5.146	4.662	5.306	5.354	5.051	4.648	5.259	5.383	5.068	4.673	5.288	5.397	5.077	4.686	5.301
29	33	4.081	3.799	3.535	3.977	4.080	3.799	3.534	3.976	4.082	3.800	3.535	3.978	4.082	3.800	3.536	3.978
30	33	4.282	3.751	3.709	4.148	4.282	3.751	3.708	4.147	4.283	3.752	3.710	4.148	4.284	3.752	3.710	4.149

Table D21: IEC Simulated Results for Case 2 at 10% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.551	12.794	9.292	12.081	10.547	12.790	9.289	12.077	10.553	12.796	9.294	12.083	10.555	12.798	9.296	12.085
2	132	10.064	10.953	8.798	10.636	10.057	10.948	8.793	10.629	10.067	10.956	8.801	10.639	10.071	10.959	8.804	10.642
3	132	6.145	6.057	5.341	6.158	6.140	6.054	5.336	6.152	6.149	6.059	5.344	6.161	6.152	6.061	5.347	6.164
4	132	8.152	7.752	7.089	8.095	8.142	7.746	7.080	8.082	8.160	7.757	7.096	8.101	8.168	7.762	7.103	8.108
5	132	7.499	6.968	6.525	7.350	7.497	6.966	6.523	7.347	7.500	6.968	6.526	7.351	7.502	6.969	6.527	7.352
6	132	9.532	8.898	8.294	9.404	9.514	8.887	8.279	9.380	9.548	8.907	8.308	9.417	9.563	8.916	8.321	9.431
7	132	6.141	5.671	5.329	6.000	6.136	5.668	5.325	5.995	6.144	5.672	5.331	6.002	6.147	5.674	5.334	6.005
8	132	7.146	6.976	6.222	7.132	7.137	6.970	6.214	7.120	7.154	6.981	6.229	7.138	7.162	6.986	6.235	7.145
9	33	15.997	16.135	13.898	16.268	15.973	16.083	13.878	16.259	16.013	16.109	13.912	16.285	16.029	16.120	13.926	16.299
10	33	19.268	18.171	16.718	19.055	19.209	18.029	16.668	19.040	19.299	18.080	16.745	19.106	19.332	18.100	16.774	19.136
11	11	23.040	27.531	20.073	26.207	23.029	27.521	20.064	26.201	23.048	27.538	20.080	26.214	23.056	27.546	20.087	26.221
12	33	16.137	15.123	14.011	15.913	16.113	15.070	13.990	15.913	16.149	15.091	14.021	15.940	16.162	15.099	14.032	15.952
13	11	25.536	30.864	22.200	29.823	25.520	30.849	22.187	29.813	25.545	30.872	22.208	29.832	25.554	30.881	22.216	29.841
14	33	8.262	7.726	7.159	8.054	8.253	7.708	7.152	8.056	8.265	7.715	7.162	8.065	8.268	7.717	7.165	8.069
15	33	13.110	12.009	11.365	12.701	13.084	11.939	11.343	12.694	13.123	11.960	11.376	12.722	13.136	11.968	11.388	12.734
16	33	10.247	9.748	8.882	10.105	10.235	9.721	8.871	10.106	10.252	9.731	8.886	10.120	10.258	9.735	8.891	10.125
17	33	13.410	12.566	11.626	13.139	13.385	12.508	11.604	13.139	13.422	12.529	11.636	13.166	13.435	12.536	11.647	13.178
18	33	8.676	8.005	7.517	8.386	8.666	7.978	7.508	8.386	8.681	7.986	7.521	8.397	8.686	7.989	7.525	8.402
19	33	9.170	8.343	7.944	8.848	9.159	8.314	7.935	8.813	9.174	8.323	7.948	8.826	9.179	8.326	7.953	8.830
20	33	9.517	8.796	8.246	9.209	9.504	8.765	8.235	9.210	9.522	8.775	8.250	9.224	9.528	8.778	8.256	9.230
21	33	15.471	14.254	13.413	14.997	15.416	14.106	13.365	14.979	15.500	14.153	13.438	15.040	15.531	14.170	13.465	15.067
22	33	15.028	13.976	13.028	14.647	14.968	13.811	12.976	14.622	15.060	13.862	13.056	14.689	15.095	13.882	13.086	14.720
23	33	8.508	8.028	7.371	8.301	8.482	7.941	7.349	8.283	8.524	7.965	7.385	8.312	8.540	7.975	7.399	8.326
24	33	11.068	10.459	9.589	10.827	10.970	10.111	9.505	10.658	11.139	10.206	9.650	10.767	11.210	10.246	9.713	10.826
25	33	7.469	7.881	6.470	7.747	7.251	6.919	6.281	7.288	7.697	7.176	6.667	7.537	7.923	7.310	6.870	7.712
26	33	3.841	4.690	3.326	4.753	3.596	3.172	3.114	3.560	4.232	3.472	3.664	4.035	4.632	3.659	4.030	4.449
27	33	8.227	8.422	7.129	8.424	8.097	7.983	7.016	8.262	8.328	8.128	7.216	8.410	8.429	8.193	7.306	8.495
28	132	5.381	5.067	4.671	5.287	5.369	5.060	4.661	5.270	5.393	5.074	4.682	5.298	5.405	5.081	4.693	5.309
29	33	4.119	3.895	3.568	4.060	4.088	3.803	3.541	3.968	4.136	3.831	3.583	4.014	4.155	3.842	3.599	4.029
30	33	4.315	3.840	3.737	4.220	4.287	3.753	3.713	4.139	4.330	3.775	3.751	4.180	4.347	3.783	3.765	4.193

Table D22: IEC Simulated Results for Case 3 at 10% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.552	12.795	9.293	12.082	10.547	12.791	9.289	12.077	10.555	12.798	9.295	12.085	10.558	12.801	9.298	12.087
2	132	10.066	10.955	8.800	10.638	10.058	10.949	8.794	10.629	10.071	10.959	8.804	10.642	10.076	10.962	8.808	10.646
3	132	6.147	6.058	5.342	6.160	6.141	6.054	5.337	6.152	6.151	6.061	5.346	6.163	6.156	6.064	5.350	6.167
4	132	8.156	7.754	7.092	8.098	8.144	7.747	7.082	8.082	8.166	7.760	7.101	8.106	8.176	7.766	7.110	8.115
5	132	7.500	6.968	6.525	7.350	7.497	6.966	6.523	7.347	7.502	6.969	6.527	7.352	7.504	6.970	6.528	7.353
6	132	9.544	8.905	8.304	9.414	9.521	8.891	8.285	9.384	9.565	8.917	8.323	9.432	9.585	8.929	8.341	9.452
7	132	6.143	5.672	5.330	6.002	6.138	5.669	5.326	5.995	6.147	5.674	5.334	6.005	6.151	5.677	5.338	6.009
8	132	7.154	6.981	6.228	7.138	7.141	6.973	6.218	7.121	7.165	6.988	6.238	7.147	7.176	6.995	6.247	7.157
9	33	15.988	16.104	13.890	16.255	15.971	16.081	13.875	16.253	16.001	16.101	13.901	16.273	16.014	16.110	13.913	16.283
10	33	19.239	18.079	16.693	19.022	19.203	18.025	16.663	19.023	19.258	18.056	16.710	19.064	19.280	18.069	16.729	19.082
11	11	23.036	27.526	20.069	26.201	23.027	27.519	20.062	26.198	23.042	27.532	20.074	26.207	23.048	27.539	20.080	26.213
12	33	16.128	15.090	14.003	15.907	16.112	15.070	13.989	15.908	16.136	15.084	14.010	15.926	16.145	15.089	14.018	15.934
13	11	25.529	30.857	22.194	29.815	25.518	30.847	22.185	29.808	25.535	30.863	22.200	29.821	25.542	30.869	22.205	29.827
14	33	8.259	7.715	7.157	8.054	8.254	7.708	7.153	8.055	8.261	7.712	7.159	8.061	8.263	7.714	7.161	8.063
15	33	13.096	11.964	11.353	12.685	13.080	11.937	11.339	12.685	13.103	11.949	11.359	12.702	13.111	11.954	11.366	12.710
16	33	10.242	9.731	8.878	10.103	10.235	9.721	8.871	10.104	10.246	9.728	8.881	10.113	10.250	9.730	8.885	10.117
17	33	13.400	12.529	11.617	13.131	13.385	12.507	11.604	13.134	13.408	12.520	11.623	13.151	13.416	12.525	11.631	13.158
18	33	8.672	7.988	7.513	8.382	8.666	7.978	7.508	8.384	8.675	7.983	7.516	8.391	8.678	7.984	7.518	8.394
19	33	9.165	8.325	7.941	8.832	9.159	8.314	7.935	8.815	9.168	8.319	7.943	8.823	9.171	8.321	7.946	8.825
20	33	9.512	8.776	8.241	9.206	9.504	8.765	8.235	9.208	9.515	8.771	8.244	9.216	9.519	8.773	8.248	9.220
21	33	15.438	14.157	13.384	14.958	15.406	14.100	13.356	14.958	15.453	14.126	13.397	14.993	15.471	14.136	13.412	15.009
22	33	14.988	13.866	12.993	14.599	14.954	13.802	12.964	14.597	15.005	13.831	13.008	14.635	15.024	13.842	13.024	14.652
23	33	8.486	7.969	7.352	8.270	8.471	7.934	7.339	8.267	8.493	7.947	7.358	8.283	8.501	7.952	7.365	8.290
24	33	10.958	10.212	9.493	10.658	10.903	10.073	9.447	10.571	10.986	10.120	9.518	10.631	11.017	10.137	9.545	10.659
25	33	7.097	7.117	6.148	7.125	6.979	6.747	6.046	6.968	7.173	6.865	6.213	7.101	7.253	6.914	6.284	7.169
26	33	3.081	2.932	2.669	3.071	3.060	2.869	2.650	3.008	3.092	2.888	2.678	3.038	3.104	2.895	2.689	3.047
27	33	8.472	9.102	7.341	8.945	8.194	8.053	7.101	8.422	8.699	8.360	7.537	8.744	8.934	8.507	7.747	8.933
28	132	5.400	5.078	4.688	5.304	5.383	5.068	4.674	5.278	5.421	5.090	4.706	5.323	5.441	5.102	4.724	5.342
29	33	4.857	5.762	4.207	5.756	4.524	4.056	3.919	4.505	5.258	4.412	4.553	4.961	5.678	4.614	4.935	5.380
30	33	4.580	4.542	3.967	4.635	4.422	3.819	3.830	4.184	4.720	3.965	4.088	4.495	4.864	4.034	4.217	4.628

Table D23: IEC Simulated Results for Case 4 at 10% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.551	12.794	9.292	9.292	10.546	12.790	9.288	12.076	10.553	12.796	9.294	12.083	10.556	12.798	9.296	12.085
2	132	10.063	10.953	8.798	8.798	10.057	10.948	8.792	10.629	10.067	10.956	8.801	10.639	10.072	10.959	8.805	10.643
3	132	6.145	6.057	5.340	5.340	6.139	6.053	5.336	6.152	6.148	6.059	5.343	6.161	6.152	6.061	5.347	6.164
4	132	8.151	7.751	7.088	7.088	8.140	7.745	7.079	8.080	8.159	7.756	7.095	8.100	8.168	7.761	7.102	8.108
5	132	7.499	6.968	6.525	6.525	7.497	6.966	6.522	7.347	7.501	6.968	6.526	7.351	7.502	6.969	6.527	7.352
6	132	9.533	8.899	8.295	8.295	9.512	8.886	8.277	9.378	9.551	8.909	8.310	9.420	9.568	8.919	8.326	9.436
7	132	6.141	5.671	5.329	5.329	6.136	5.668	5.325	5.995	6.144	5.673	5.332	6.003	6.148	5.675	5.335	6.006
8	132	7.148	6.978	6.223	6.223	7.137	6.970	6.214	7.119	7.157	6.983	6.231	7.141	7.167	6.989	6.239	7.149
9	33	15.982	16.099	13.885	13.885	15.966	16.078	13.871	16.248	15.993	16.095	13.894	16.265	16.003	16.102	13.904	16.274
10	33	19.229	18.071	16.685	16.685	19.198	18.022	16.658	19.016	19.245	18.049	16.699	19.052	19.262	18.059	16.714	19.067
11	11	23.032	27.524	20.066	20.066	23.025	27.517	20.060	26.195	23.038	27.528	20.071	26.204	23.043	27.534	20.075	26.208
12	33	16.124	15.087	13.999	13.999	16.110	15.069	13.988	15.905	16.130	15.080	14.005	15.921	16.138	15.085	14.012	15.928
13	11	25.526	30.854	22.192	22.192	25.517	30.845	22.184	29.806	25.531	30.859	22.196	29.817	25.536	30.864	22.201	29.822
14	33	8.258	7.714	7.156	7.156	8.254	7.708	7.152	8.055	8.260	7.712	7.158	8.060	8.262	7.713	7.159	8.062
15	33	13.092	11.960	11.350	11.350	13.079	11.936	11.338	12.683	13.098	11.946	11.355	12.698	13.105	11.950	11.360	12.704
16	33	10.241	9.730	8.876	8.876	10.234	9.721	8.871	10.103	10.244	9.726	8.879	10.111	10.247	9.728	8.882	10.114
17	33	13.396	12.526	11.614	11.614	13.383	12.506	11.602	13.131	13.402	12.517	11.619	13.146	13.409	12.521	11.625	13.152
18	33	8.671	7.987	7.512	7.512	8.666	7.978	7.508	8.383	8.673	7.982	7.514	8.389	8.675	7.983	7.516	8.391
19	33	9.164	8.323	7.939	7.939	9.158	8.314	7.935	8.815	9.166	8.318	7.941	8.822	9.169	8.320	7.944	8.823
20	33	9.510	8.775	8.240	8.240	9.504	8.764	8.234	9.207	9.513	8.770	8.242	9.214	9.516	8.771	8.245	9.217
21	33	15.430	14.149	13.377	13.377	15.403	14.099	13.354	14.952	15.443	14.121	13.388	14.983	15.457	14.128	13.400	14.996
22	33	14.980	13.858	12.986	12.986	14.950	13.800	12.961	14.591	14.994	13.825	12.998	14.625	15.009	13.833	13.011	14.639
23	33	8.483	7.965	7.349	7.349	8.470	7.934	7.338	8.264	8.488	7.944	7.354	8.279	8.495	7.948	7.359	8.285
24	33	10.944	10.196	9.482	9.482	10.897	10.069	9.441	10.561	10.967	10.109	9.501	10.614	10.992	10.123	9.523	10.637
25	33	7.061	7.071	6.117	6.117	6.957	6.733	6.027	6.940	7.121	6.833	6.169	7.057	7.187	6.874	6.227	7.113
26	33	3.076	2.925	2.664	2.664	3.058	2.868	2.648	3.008	3.085	2.884	2.672	3.032	3.095	2.890	2.680	3.040
27	33	8.367	8.955	7.250	7.250	8.121	8.003	7.037	8.333	8.547	8.267	7.406	8.617	8.736	8.387	7.575	8.773
28	132	5.390	5.072	4.679	4.679	5.374	5.062	4.665	5.271	5.407	5.082	4.694	5.310	5.424	5.092	4.709	5.326
29	33	4.350	4.563	3.767	3.767	4.197	3.867	3.635	4.113	4.478	4.020	3.878	4.288	4.611	4.093	3.998	4.405
30	33	5.056	5.891	4.378	4.378	4.697	3.957	4.068	4.522	5.459	4.290	4.727	5.131	5.885	4.471	5.115	5.553

Table D24: IEC Simulated Results for Case 5 at 10% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.562	12.827	9.301	12.114	10.545	12.789	9.287	12.074	10.561	12.804	9.301	12.089	10.571	12.813	9.309	12.098
2	132	10.085	11.051	8.817	10.704	10.056	10.948	8.792	10.624	10.085	10.969	8.816	10.652	10.103	10.984	8.832	10.668
3	132	6.158	6.127	5.352	6.194	6.139	6.053	5.335	6.149	6.158	6.065	5.351	6.168	6.170	6.073	5.362	6.178
4	132	8.181	7.907	7.114	8.164	8.140	7.745	7.079	8.076	8.180	7.769	7.113	8.116	8.207	7.785	7.137	8.140
5	132	7.539	7.177	6.559	7.447	7.500	6.968	6.525	7.342	7.538	6.989	6.558	7.379	7.563	7.004	6.580	7.401
6	132	9.601	9.230	8.353	9.547	9.515	8.888	8.280	9.372	9.598	8.936	8.351	9.457	9.655	8.969	8.402	9.509
7	132	6.295	6.311	5.462	6.345	6.171	5.687	5.355	5.997	6.288	5.753	5.456	6.119	6.373	5.802	5.532	6.199
8	132	7.174	7.115	6.246	7.198	7.136	6.970	6.213	7.115	7.174	6.993	6.245	7.153	7.199	7.009	6.267	7.176
9	33	16.005	16.114	13.905	16.271	15.969	16.080	13.874	16.251	16.005	16.103	13.904	16.275	16.028	16.119	13.925	16.293
10	33	19.253	18.082	16.706	19.040	19.202	18.024	16.662	19.019	19.253	18.053	16.706	19.056	19.284	18.071	16.733	19.082
11	11	23.044	27.534	20.079	26.209	23.026	27.518	20.061	26.197	23.044	27.534	20.076	26.208	23.055	27.545	20.086	26.218
12	33	16.137	15.093	14.010	15.917	16.112	15.070	13.989	15.907	16.136	15.084	14.010	15.925	16.151	15.092	14.023	15.938
13	11	25.535	30.863	22.200	29.821	25.518	30.847	22.185	29.807	25.535	30.863	22.199	29.821	25.546	30.873	22.209	29.830
14	33	8.261	7.715	7.158	8.056	8.254	7.709	7.153	8.055	8.261	7.712	7.159	8.060	8.264	7.714	7.162	8.064
15	33	13.099	11.962	11.356	12.691	13.079	11.936	11.339	12.683	13.099	11.947	11.356	12.698	13.110	11.953	11.365	12.708
16	33	10.246	9.732	8.881	10.107	10.235	9.721	8.871	10.104	10.246	9.727	8.881	10.112	10.252	9.731	8.886	10.118
17	33	13.406	12.531	11.622	13.140	13.385	12.507	11.604	13.133	13.406	12.520	11.622	13.148	13.419	12.527	11.633	13.159
18	33	8.674	7.988	7.515	8.385	8.666	7.978	7.508	8.383	8.674	7.982	7.515	8.390	8.678	7.985	7.519	8.393
19	33	9.167	8.325	7.942	8.832	9.159	8.314	7.935	8.815	9.167	8.319	7.942	8.823	9.172	8.322	7.946	8.826
20	33	9.514	8.776	8.244	9.210	9.504	8.765	8.235	9.207	9.514	8.770	8.244	9.215	9.520	8.774	8.248	9.220
21	33	15.444	14.153	13.389	14.968	15.405	14.100	13.356	14.953	15.444	14.121	13.389	14.982	15.466	14.134	13.408	15.002
22	33	14.993	13.861	12.997	14.608	14.953	13.802	12.963	14.591	14.993	13.824	12.998	14.622	15.017	13.838	13.018	14.642
23	33	8.486	7.964	7.352	8.271	8.470	7.934	7.338	8.263	8.486	7.943	7.352	8.276	8.495	7.948	7.359	8.284
24	33	10.951	10.187	9.488	10.632	10.897	10.069	9.441	10.555	10.952	10.100	9.488	10.597	10.983	10.118	9.515	10.625
25	33	7.066	7.034	6.121	7.055	6.947	6.726	6.018	6.915	7.069	6.801	6.123	7.003	7.142	6.847	6.188	7.066
26	33	3.078	2.919	2.665	3.059	3.058	2.868	2.648	3.010	3.078	2.880	2.666	3.028	3.089	2.886	2.675	3.037
27	33	8.370	8.826	7.252	8.770	8.068	7.965	6.991	8.244	8.376	8.158	7.258	8.451	8.582	8.290	7.441	8.619
28	132	5.407	5.168	4.694	5.337	5.366	5.058	4.658	5.265	5.406	5.082	4.693	5.308	5.435	5.099	4.719	5.335
29	33	4.661	5.172	4.037	5.163	4.272	3.910	3.700	4.199	4.671	4.122	4.045	4.463	4.986	4.288	4.328	4.769
30	33	4.513	4.344	3.909	4.494	4.337	3.777	3.756	4.148	4.517	3.868	3.912	4.332	4.641	3.930	4.022	4.444

Table D25: IEC Simulated Results for Case 6 at 10% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.554	12.796	9.294	12.083	10.546	12.789	9.288	12.076	10.554	12.797	9.294	12.083	10.558	12.801	9.298	12.087
2	132	10.068	10.957	8.802	10.640	10.056	10.947	8.792	10.628	10.069	10.957	8.802	10.640	10.076	10.962	8.808	10.646
3	132	6.150	6.060	5.344	6.161	6.139	6.053	5.335	6.151	6.150	6.060	5.345	6.162	6.156	6.064	5.350	6.167
4	132	8.162	7.758	7.098	8.102	8.139	7.744	7.078	8.079	8.163	7.758	7.098	8.103	8.177	7.767	7.111	8.115
5	132	7.501	6.968	6.526	7.351	7.496	6.966	6.522	7.347	7.501	6.969	6.526	7.351	7.503	6.970	6.528	7.353
6	132	9.554	8.911	8.313	9.422	9.510	8.885	8.275	9.375	9.555	8.911	8.314	9.423	9.584	8.928	8.340	9.449
7	132	6.145	5.673	5.332	6.003	6.136	5.668	5.324	5.994	6.145	5.673	5.332	6.003	6.151	5.676	5.337	6.008
8	132	7.158	6.984	6.232	7.141	7.135	6.969	6.212	7.117	7.159	6.984	6.233	7.142	7.173	6.994	6.246	7.155
9	33	16.006	16.141	13.906	16.276	15.966	16.078	13.871	16.251	16.007	16.105	13.907	16.280	16.031	16.121	13.928	16.300
10	33	19.278	18.177	16.727	19.064	19.195	18.021	16.656	19.023	19.280	18.069	16.729	19.087	19.325	18.096	16.768	19.128
11	11	23.045	27.535	20.077	26.211	23.025	27.517	20.060	26.197	23.045	27.536	20.077	26.211	23.057	27.547	20.088	26.222
12	33	16.142	15.126	14.015	15.918	16.108	15.068	13.986	15.907	16.143	15.087	14.016	15.934	16.161	15.098	14.031	15.950
13	11	25.540	30.867	22.203	29.827	25.516	30.845	22.183	29.808	25.540	30.868	22.204	29.828	25.553	30.880	22.215	29.840
14	33	8.263	7.726	7.160	8.055	8.252	7.707	7.151	8.054	8.263	7.714	7.160	8.063	8.268	7.716	7.164	8.068
15	33	13.112	12.011	11.367	12.703	13.078	11.936	11.338	12.686	13.113	11.955	11.368	12.713	13.131	11.965	11.384	12.730
16	33	10.249	9.749	8.883	10.107	10.233	9.720	8.870	10.104	10.249	9.729	8.884	10.117	10.257	9.734	8.891	10.124
17	33	13.414	12.568	11.629	13.143	13.381	12.505	11.600	13.133	13.415	12.525	11.630	13.159	13.432	12.535	11.645	13.176
18	33	8.678	8.006	7.518	8.387	8.664	7.977	7.507	8.384	8.678	7.985	7.518	8.394	8.684	7.988	7.524	8.400
19	33	9.171	8.343	7.945	8.849	9.157	8.313	7.933	8.812	9.171	8.321	7.946	8.824	9.178	8.325	7.952	8.829
20	33	9.518	8.797	8.247	9.210	9.502	8.764	8.233	9.207	9.519	8.773	8.247	9.220	9.527	8.777	8.254	9.228
21	33	15.477	14.257	13.417	15.002	15.402	14.098	13.353	14.961	15.478	14.140	13.419	15.019	15.518	14.163	13.454	15.055
22	33	15.033	13.979	13.032	14.652	14.951	13.801	12.961	14.602	15.035	13.848	13.033	14.665	15.079	13.873	13.072	14.706
23	33	8.509	8.029	7.372	8.302	8.472	7.935	7.340	8.271	8.510	7.957	7.373	8.299	8.530	7.969	7.390	8.317
24	33	11.067	10.458	9.588	10.825	10.921	10.083	9.462	10.603	11.070	10.167	9.591	10.708	11.157	10.217	9.667	10.782
25	33	7.449	7.868	6.453	7.733	7.075	6.809	6.129	7.100	7.459	7.037	6.461	7.344	7.720	7.194	6.693	7.552
26	33	3.653	4.180	3.164	4.191	3.297	3.005	2.855	3.229	3.662	3.198	3.171	3.531	3.969	3.359	3.448	3.840
27	33	8.472	9.091	7.341	8.949	8.077	7.973	6.999	8.279	8.482	8.226	7.349	8.559	8.742	8.390	7.580	8.776
28	132	5.405	5.081	4.692	5.307	5.369	5.059	4.661	5.267	5.406	5.081	4.693	5.308	5.431	5.097	4.716	5.332
29	33	4.319	4.435	3.741	4.380	4.127	3.826	3.574	4.025	4.323	3.936	3.744	4.159	4.452	4.008	3.859	4.272
30	33	4.888	5.298	4.233	5.270	4.460	3.838	3.863	4.240	4.898	4.047	4.242	4.651	5.233	4.202	4.542	4.971

Table D26: IEC Simulated Results for Case 1 at 30% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.616	12.878	9.348	12.161	10.545	12.789	9.288	12.072	10.602	12.842	9.336	12.120	10.577	12.819	9.315	12.103
2	132	10.194	11.135	8.910	10.796	10.058	10.949	8.793	10.623	10.169	11.034	8.889	10.714	10.117	10.994	8.844	10.679
3	132	6.220	6.167	5.405	6.246	6.139	6.053	5.336	6.149	6.206	6.095	5.393	6.203	6.174	6.075	5.366	6.181
4	132	8.317	7.990	7.231	8.282	8.141	7.745	7.080	8.076	8.288	7.832	7.206	8.198	8.215	7.790	7.144	8.147
5	132	7.746	7.299	6.738	7.622	7.506	6.971	6.531	7.340	7.705	7.083	6.702	7.505	7.607	7.029	6.619	7.436
6	132	9.905	9.413	8.616	9.815	9.519	8.890	8.283	9.370	9.845	9.075	8.565	9.650	9.676	8.981	8.420	9.526
7	132	7.103	6.827	6.161	6.991	6.215	5.712	5.393	6.009	6.984	6.123	6.058	6.688	6.546	5.897	5.683	6.351
8	132	7.288	7.188	6.344	7.297	7.135	6.969	6.212	7.113	7.263	7.049	6.322	7.221	7.199	7.010	6.268	7.175
9	33	16.091	16.160	13.978	16.337	15.972	16.082	13.877	16.253	16.076	16.151	13.966	16.334	16.019	16.113	13.918	16.283
10	33	19.329	18.096	16.770	19.107	19.210	18.028	16.669	19.021	19.314	18.088	16.758	19.103	19.258	18.056	16.710	19.053
11	11	23.085	27.572	20.111	26.240	23.028	27.520	20.063	26.197	23.079	27.567	20.106	26.239	23.051	27.541	20.082	26.212
12	33	16.183	15.110	14.050	15.959	16.116	15.072	13.993	15.909	16.173	15.105	14.042	15.956	16.143	15.088	14.016	15.928
13	11	25.567	30.893	22.227	29.846	25.520	30.849	22.187	29.808	25.561	30.887	22.222	29.844	25.539	30.867	22.203	29.822
14	33	8.271	7.718	7.167	8.068	8.256	7.709	7.154	8.056	8.268	7.716	7.164	8.066	8.262	7.713	7.160	8.061
15	33	13.121	11.959	11.374	12.714	13.082	11.938	11.341	12.683	13.114	11.955	11.368	12.710	13.099	11.947	11.356	12.696
16	33	10.264	9.738	8.897	10.126	10.237	9.722	8.873	10.105	10.260	9.736	8.893	10.124	10.248	9.729	8.883	10.113
17	33	13.440	12.539	11.651	13.172	13.389	12.509	11.607	13.134	13.432	12.534	11.645	13.169	13.410	12.522	11.626	13.149
18	33	8.684	7.988	7.523	8.397	8.668	7.979	7.509	8.384	8.681	7.986	7.521	8.395	8.675	7.983	7.515	8.389
19	33	9.179	8.325	7.952	8.833	9.161	8.315	7.937	8.818	9.176	8.323	7.949	8.830	9.169	8.320	7.943	8.825
20	33	9.528	8.778	8.255	9.225	9.506	8.766	8.237	9.208	9.524	8.776	8.252	9.223	9.516	8.771	8.245	9.215
21	33	15.478	14.140	13.418	15.004	15.411	14.103	13.361	14.953	15.468	14.134	13.410	15.000	15.439	14.119	13.385	14.973
22	33	15.023	13.840	13.023	14.639	14.959	13.805	12.968	14.591	15.013	13.835	13.014	14.635	14.986	13.820	12.991	14.610
23	33	8.488	7.944	7.354	8.276	8.472	7.935	7.340	8.263	8.485	7.943	7.351	8.274	8.479	7.939	7.346	8.268
24	33	10.931	10.088	9.470	10.571	10.901	10.072	9.445	10.548	10.925	10.085	9.465	10.568	10.914	10.079	9.456	10.557
25	33	6.955	6.730	6.025	6.890	6.938	6.720	6.011	6.877	6.952	6.728	6.022	6.888	6.945	6.724	6.017	6.882
26	33	3.063	2.871	2.652	3.019	3.060	2.870	2.650	3.017	3.062	2.871	2.652	3.018	3.061	2.870	2.651	3.018
27	33	8.020	7.928	6.949	8.117	7.993	7.911	6.926	8.098	8.016	7.926	6.946	8.116	8.004	7.918	6.936	8.105
28	132	5.458	5.199	4.737	5.381	5.354	5.051	4.648	5.259	5.440	5.101	4.723	5.332	5.397	5.077	4.686	5.301
29	33	4.086	3.802	3.539	3.981	4.080	3.799	3.534	3.976	4.085	3.801	3.538	3.980	4.082	3.800	3.536	3.978
30	33	4.287	3.753	3.713	4.151	4.282	3.751	3.708	4.147	4.286	3.753	3.712	4.150	4.284	3.752	3.710	4.149

Table D27: IEC Simulated Results for Case 2 at 30% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.564	12.807	9.304	12.092	10.547	12.790	9.289	12.077	10.559	12.802	9.299	12.087	10.555	12.798	9.296	12.085
2	132	10.087	10.971	8.818	10.654	10.057	10.948	8.793	10.629	10.078	10.964	8.810	10.646	10.071	10.959	8.804	10.642
3	132	6.168	6.071	5.360	6.175	6.140	6.054	5.336	6.152	6.159	6.606	5.353	6.168	6.152	6.061	5.347	6.164
4	132	8.205	7.783	7.135	8.135	8.142	7.746	7.080	8.082	8.184	7.771	7.117	8.119	8.168	7.762	7.103	8.108
5	132	7.507	6.972	6.531	7.355	7.497	6.966	6.523	7.347	7.504	6.970	6.529	7.353	7.502	6.969	6.527	7.352
6	132	9.637	8.958	8.385	9.487	9.514	8.887	8.279	9.380	9.596	8.935	8.350	9.454	9.563	8.916	8.321	9.431
7	132	6.160	5.682	5.345	6.015	6.136	5.668	5.325	5.995	6.153	5.677	5.339	6.009	6.147	5.674	5.334	6.005
8	132	7.198	7.008	6.266	7.172	7.137	6.970	6.214	7.120	7.178	6.996	6.249	7.156	7.162	6.986	6.235	7.145
9	33	16.101	16.212	13.988	16.360	15.973	16.083	13.878	16.259	16.060	16.141	13.952	16.332	16.029	16.120	13.926	16.299
10	33	19.465	18.307	16.889	19.232	19.209	18.029	16.668	19.040	19.386	18.132	16.820	19.197	19.332	18.100	16.774	19.136
11	11	23.093	27.580	20.118	26.258	23.029	27.521	20.064	26.201	23.072	27.561	20.101	26.238	23.056	27.546	20.087	26.221
12	33	16.211	15.173	14.075	15.980	16.113	15.070	13.990	15.913	16.181	15.110	14.049	15.975	16.162	15.099	14.032	15.952
13	11	25.592	30.918	22.249	29.883	25.520	30.849	22.187	29.813	25.570	30.896	22.229	29.860	25.554	30.881	22.216	29.841
14	33	8.280	7.738	7.175	8.070	8.253	7.708	7.152	8.056	8.272	7.719	7.168	8.074	8.268	7.717	7.165	8.069
15	33	13.190	12.065	11.435	12.772	13.084	11.939	11.343	12.694	13.158	11.980	11.406	12.759	13.136	11.968	11.388	12.734
16	33	10.280	9.771	8.910	10.135	10.235	9.721	8.871	10.106	10.266	9.740	8.898	10.135	10.258	9.735	8.891	10.125
17	33	13.483	12.615	11.688	13.204	13.385	12.508	11.604	13.139	13.453	12.547	11.663	13.200	13.435	12.536	11.647	13.178
18	33	8.703	8.024	7.540	8.409	8.666	7.978	7.508	8.386	8.692	7.993	7.531	8.410	8.686	7.989	7.525	8.402
19	33	9.197	8.361	7.968	8.872	9.159	8.314	7.935	8.813	9.186	8.329	7.958	8.832	9.179	8.326	7.953	8.830
20	33	9.549	8.818	8.274	9.238	9.504	8.765	8.235	9.210	9.536	8.783	8.262	9.239	9.528	8.778	8.256	9.230
21	33	15.654	14.378	13.571	15.160	15.416	14.106	13.365	14.979	15.580	14.197	13.507	15.123	15.531	14.170	13.465	15.067
22	33	15.234	14.119	13.206	14.833	14.968	13.811	12.976	14.622	15.151	13.914	13.134	14.784	15.095	13.882	13.086	14.720
23	33	8.609	8.103	7.458	8.391	8.482	7.941	7.349	8.283	8.569	7.991	7.424	8.357	8.540	7.975	7.399	8.326
24	33	11.545	10.808	10.002	11.258	10.970	10.111	9.505	10.658	11.354	10.325	9.837	10.973	11.210	10.246	9.713	10.826
25	33	9.329	9.493	8.081	9.446	7.251	6.919	6.281	7.288	8.521	7.637	7.381	8.277	7.923	7.310	6.870	7.712
26	33	10.488	12.730	9.077	12.429	3.596	3.172	3.114	3.560	6.464	4.281	5.596	5.955	4.632	3.659	4.030	4.449
27	33	8.933	8.995	7.740	9.057	8.097	7.983	7.016	8.262	8.645	8.329	7.491	8.717	8.429	8.193	7.306	8.495
28	132	5.467	5.117	4.746	5.358	5.369	5.060	4.661	5.270	5.434	5.098	4.717	5.330	5.405	5.081	4.693	5.309
29	33	4.231	3.977	3.665	4.158	4.088	3.803	3.541	3.968	4.186	3.859	3.625	4.046	4.155	3.842	3.599	4.029
30	33	4.412	3.905	3.821	4.305	4.287	3.753	3.713	4.139	4.373	3.796	3.787	4.207	4.347	3.783	3.765	4.193

Table D28: IEC Simulated Results for Case 3 at 30% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.573	12.815	9.311	12.100	10.547	12.791	9.289	12.077	10.564	12.806	9.303	12.092	10.558	12.801	9.298	12.087
2	132	10.102	10.983	8.831	10.667	10.058	10.949	8.794	10.629	10.087	10.971	8.818	10.654	10.076	10.962	8.808	10.646
3	132	6.180	6.079	5.371	6.186	6.141	6.054	5.337	6.152	6.166	6.070	5.359	6.174	6.156	6.064	5.350	6.167
4	132	8.232	7.799	7.158	8.160	8.144	7.747	7.082	8.082	8.200	7.780	7.130	8.133	8.176	7.766	7.110	8.115
5	132	7.513	6.975	6.536	7.360	7.497	6.966	6.523	7.347	7.507	6.972	6.531	7.356	7.504	6.970	6.528	7.353
6	132	9.708	8.998	8.446	9.553	9.521	8.891	8.285	9.384	9.640	8.960	8.388	9.493	9.585	8.929	8.341	9.452
7	132	6.174	5.689	5.357	6.027	6.138	5.669	5.326	5.995	6.161	5.682	5.346	6.016	6.151	5.677	5.338	6.009
8	132	7.239	7.034	6.302	7.209	7.141	6.973	6.218	7.121	7.204	7.012	6.271	7.178	7.176	6.995	6.247	7.157
9	33	16.085	16.172	13.974	16.337	15.971	16.081	13.875	16.253	16.044	16.130	13.939	16.313	16.014	16.110	13.913	16.283
10	33	19.384	18.172	16.819	19.148	19.203	18.025	16.663	19.023	19.321	18.093	16.764	19.126	19.280	18.069	16.729	19.082
11	11	23.084	27.572	20.111	26.246	23.027	27.519	20.062	26.198	23.064	27.553	20.093	26.228	23.048	27.539	20.080	26.213
12	33	16.190	15.128	14.056	15.960	16.112	15.070	13.989	15.908	16.162	15.099	14.033	15.953	16.145	15.089	14.018	15.934
13	11	25.575	30.901	22.234	29.862	25.518	30.847	22.185	29.808	25.555	30.882	22.217	29.843	25.542	30.869	22.205	29.827
14	33	8.273	7.723	7.169	8.066	8.254	7.708	7.153	8.055	8.267	7.716	7.163	8.067	8.263	7.714	7.161	8.063
15	33	13.149	11.997	11.398	12.732	13.080	11.937	11.339	12.685	13.125	11.961	11.378	12.726	13.111	11.954	11.366	12.710
16	33	10.269	9.748	8.901	10.126	10.235	9.721	8.871	10.104	10.257	9.734	8.890	10.125	10.250	9.730	8.885	10.117
17	33	13.455	12.563	11.665	13.179	13.385	12.507	11.604	13.134	13.431	12.534	11.643	13.175	13.416	12.525	11.631	13.158
18	33	8.691	8.000	7.529	8.399	8.666	7.978	7.508	8.384	8.682	7.987	7.522	8.399	8.678	7.984	7.518	8.394
19	33	9.185	8.337	7.958	8.849	9.159	8.314	7.935	8.815	9.176	8.324	7.950	8.827	9.171	8.321	7.946	8.825
20	33	9.536	8.791	8.262	9.227	9.504	8.765	8.235	9.208	9.525	8.776	8.253	9.227	9.519	8.773	8.248	9.220
21	33	15.552	14.229	13.482	15.058	15.409	14.100	13.356	14.958	15.501	14.153	13.438	15.043	15.471	14.136	13.412	15.009
22	33	15.111	13.946	13.100	14.708	14.954	13.802	12.964	14.597	15.056	13.860	13.052	14.689	15.024	13.842	13.024	14.652
23	33	8.537	8.006	7.396	8.316	8.471	7.934	7.339	8.267	8.514	7.960	7.376	8.306	8.501	7.952	7.365	8.290
24	33	11.167	10.363	9.674	10.842	10.903	10.073	9.447	10.571	11.074	10.169	9.594	10.721	11.017	10.137	9.545	10.659
25	33	7.697	7.614	6.667	7.686	6.979	6.747	6.046	6.968	7.429	7.020	6.435	7.351	7.253	6.914	6.284	7.169
26	33	3.162	2.994	2.738	3.144	3.060	2.869	2.650	3.008	3.126	2.907	2.707	3.059	3.104	2.865	2.689	3.047
27	33	10.539	11.030	9.130	10.845	8.194	8.053	7.101	8.422	9.566	8.881	8.288	9.550	8.934	8.507	7.747	8.933
28	132	5.566	5.174	4.832	5.449	5.383	5.068	4.674	5.278	5.498	5.135	4.773	5.387	5.441	5.102	4.724	5.342
29	33	11.570	13.881	10.014	13.513	4.524	4.056	3.919	4.505	7.493	5.295	6.487	6.828	5.678	4.614	4.935	5.380
30	33	5.904	5.705	5.113	5.967	4.422	3.819	3.830	4.184	5.274	4.211	4.567	4.929	4.864	4.034	4.217	4.628

Table D29: IEC Simulated Results for Case 4 at 30% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.568	12.810	9.307	12.095	10.546	12.790	9.288	12.076	10.560	12.803	9.300	12.089	10.556	12.798	9.296	12.085
2	132	10.094	10.976	8.824	10.660	10.057	10.948	8.792	10.629	10.081	10.966	8.813	10.649	10.072	10.959	8.805	10.643
3	132	6.172	6.074	5.364	6.179	6.139	6.053	5.336	6.152	6.160	6.067	5.354	6.170	6.152	6.061	5.347	6.164
4	132	8.214	7.789	7.142	8.144	8.140	7.745	7.079	8.080	8.187	7.773	7.119	8.122	8.168	7.761	7.102	8.108
5	132	7.510	6.973	6.534	7.357	7.497	6.966	6.522	7.347	7.505	6.971	6.530	7.354	7.502	6.969	6.527	7.352
6	132	9.670	8.977	8.414	9.519	9.512	8.886	8.277	9.378	9.613	8.944	8.364	9.468	9.568	8.919	8.326	9.436
7	132	6.167	5.685	5.351	6.021	6.136	5.668	5.325	5.995	6.156	5.679	5.341	6.011	6.148	5.675	5.335	6.006
8	132	7.220	7.022	6.285	7.192	7.137	6.970	6.214	7.119	7.190	7.003	6.259	7.166	7.167	6.989	6.239	7.149
9	33	16.063	16.155	13.954	16.319	15.966	16.078	13.871	16.248	16.028	16.119	13.925	16.299	16.003	16.102	13.904	16.274
10	33	19.349	18.146	16.788	19.119	19.198	18.022	16.658	19.016	19.295	18.078	16.742	19.103	19.262	18.059	16.714	19.067
11	11	23.073	27.561	20.101	26.236	23.025	27.517	20.060	26.195	23.056	27.545	20.086	26.221	23.043	27.534	20.075	26.208
12	33	16.174	15.117	14.043	15.948	16.110	15.069	13.988	15.905	16.152	15.093	14.023	15.943	16.138	15.085	14.012	15.928
13	11	25.564	30.890	22.224	29.851	25.517	30.845	22.184	29.806	25.547	30.874	22.210	29.835	25.536	30.864	22.201	29.822
14	33	8.269	7.720	7.166	8.063	8.254	7.708	7.152	8.055	8.264	7.714	7.161	8.065	8.262	7.713	7.159	8.062
15	33	13.135	11.987	11.387	12.720	13.079	11.936	11.338	12.683	13.115	11.956	11.370	12.717	13.105	11.950	11.360	12.704
16	33	10.262	9.743	8.895	10.120	10.234	9.721	8.871	10.103	10.252	9.731	8.886	10.120	10.247	9.728	8.882	10.114
17	33	13.441	12.554	11.653	13.168	13.383	12.506	11.602	13.131	13.421	12.528	11.635	13.166	13.409	12.521	11.625	13.152
18	33	8.686	7.996	7.525	8.395	8.666	7.978	7.508	8.383	8.679	7.985	7.519	8.396	8.675	7.983	7.516	8.391
19	33	9.180	8.333	7.953	8.844	9.158	8.314	7.935	8.815	9.173	8.322	7.947	8.825	9.169	8.320	7.944	8.823
20	33	9.529	8.786	8.257	9.221	9.504	8.764	8.234	9.207	9.520	8.774	8.249	9.223	9.516	8.771	8.245	9.217
21	33	15.523	14.208	13.457	15.034	15.403	14.099	13.354	14.952	15.480	14.142	13.421	15.024	15.457	14.128	13.400	14.996
22	33	15.080	13.923	13.073	14.681	14.950	13.800	12.961	14.591	15.034	13.848	13.033	14.668	15.009	13.833	13.011	14.639
23	33	8.524	7.995	7.385	8.304	8.470	7.934	7.338	8.264	8.505	7.954	7.368	8.297	8.495	7.948	7.359	8.285
24	33	11.114	10.319	9.629	10.791	10.897	10.069	9.441	10.561	11.037	10.148	9.562	10.687	10.992	10.123	9.523	10.637
25	33	7.544	7.471	6.535	7.533	6.957	6.733	6.027	6.940	7.325	6.958	6.345	7.259	7.187	6.874	6.227	7.113
26	33	3.141	2.975	2.720	3.124	3.085	2.868	2.648	3.008	3.111	2.899	2.695	3.048	3.095	2.890	2.680	3.040
27	33	9.974	10.453	8.642	10.294	8.121	8.003	7.037	8.333	9.220	8.680	7.988	9.255	8.736	8.387	7.575	8.773
28	132	5.529	5.153	4.799	5.414	5.374	5.062	4.665	5.271	5.471	5.120	4.750	5.362	5.424	5.092	4.709	5.326
29	33	5.583	5.715	4.835	5.720	4.197	3.867	3.635	4.113	4.990	4.283	4.321	4.747	4.611	4.093	3.998	4.405
30	33	11.793	14.051	10.208	13.648	4.697	3.957	4.068	4.522	7.692	5.058	6.660	7.001	5.885	4.471	5.115	5.553

Table D30: IEC Simulated Results for Case 5 at 30% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.632	12.905	9.362	12.187	10.545	12.789	9.287	12.074	10.583	12.824	9.319	12.105	10.571	12.813	9.309	12.098
2	132	10.222	11.197	8.934	10.846	10.056	10.948	8.792	10.624	10.128	11.002	8.853	10.684	10.103	10.984	8.832	10.668
3	132	6.248	6.215	5.429	6.283	6.139	6.053	5.335	6.149	6.185	6.082	5.375	6.187	6.170	6.073	5.362	6.178
4	132	8.381	8.099	7.286	8.362	8.140	7.745	7.079	8.076	8.242	7.805	7.166	8.163	8.207	7.785	7.137	8.140
5	132	7.748	7.396	6.739	7.664	7.500	6.968	6.525	7.342	7.610	7.030	6.620	7.433	7.563	7.004	6.580	7.401
6	132	10.049	9.656	8.740	9.993	9.515	8.888	8.280	9.372	9.739	9.015	8.473	9.566	9.655	8.969	8.402	9.509
7	132	7.099	7.184	6.157	7.189	6.171	5.687	5.355	5.997	6.570	5.907	5.700	6.350	6.373	5.802	5.532	6.199
8	132	7.363	7.297	6.409	7.386	7.136	6.970	6.213	7.115	7.230	7.029	6.294	7.196	7.199	7.009	6.267	7.176
9	33	16.177	16.231	14.052	16.406	15.969	16.080	13.874	16.251	16.056	16.137	13.948	16.320	16.028	16.119	13.925	16.293
10	33	19.461	18.212	16.884	19.205	19.202	18.024	16.662	19.019	19.308	18.085	16.753	19.107	19.284	18.071	16.733	19.082
11	11	23.128	27.613	20.148	26.280	23.026	27.518	20.061	26.197	23.069	27.558	20.098	26.232	23.055	27.545	20.086	26.218
12	33	16.238	15.154	14.097	15.998	16.112	15.070	13.989	15.907	16.164	15.100	14.034	15.951	16.151	15.092	14.023	15.938
13	11	25.608	30.932	22.261	29.888	25.518	30.847	22.185	29.807	25.555	30.882	22.217	29.841	25.546	30.873	22.209	29.830
14	33	8.283	7.728	7.177	8.075	8.254	7.709	7.153	8.055	8.266	7.715	7.163	8.066	8.264	7.714	7.162	8.064
15	33	13.169	12.006	11.415	12.748	13.079	11.936	11.339	12.683	13.115	11.956	11.370	12.714	13.110	11.953	11.365	12.708
16	33	10.288	9.759	8.917	10.141	10.235	9.721	8.871	10.104	10.257	9.734	8.890	10.123	10.252	9.731	8.886	10.118
17	33	13.489	12.582	11.693	13.206	13.385	12.507	11.604	13.133	13.428	12.532	11.641	13.169	13.419	12.527	11.633	13.159
18	33	8.700	8.004	7.537	8.407	8.666	7.978	7.508	8.383	8.680	7.986	7.520	8.396	8.678	7.985	7.519	8.393
19	33	9.197	8.342	7.968	8.858	9.159	8.314	7.935	8.815	9.174	8.323	7.948	8.827	9.172	8.322	7.946	8.826
20	33	9.549	8.798	8.274	9.238	9.504	8.765	8.235	9.207	9.523	8.775	8.251	9.223	9.520	8.774	8.248	9.220
21	33	15.582	14.242	13.508	15.081	15.405	14.100	13.356	14.953	15.476	14.139	13.416	15.014	15.466	14.134	13.408	15.002
22	33	15.136	13.955	13.120	14.725	14.953	13.802	12.963	14.591	15.025	13.842	13.025	14.654	15.017	13.838	13.018	14.642
23	33	8.536	8.002	7.395	8.314	8.470	7.934	7.338	8.263	8.495	7.949	7.360	8.286	8.495	7.948	7.359	8.284
24	33	11.128	10.326	9.640	10.803	10.897	10.069	9.441	10.555	10.982	10.117	9.514	10.630	10.983	10.118	9.515	10.625
25	33	7.509	7.442	6.504	7.502	6.947	6.726	6.018	6.915	7.138	6.844	6.184	7.076	7.142	6.847	6.188	7.066
26	33	3.139	2.973	2.718	3.121	3.058	2.868	2.648	3.010	3.087	2.885	2.673	3.033	3.089	2.886	2.675	3.037
27	33	9.781	10.271	8.473	10.110	8.068	7.965	6.991	8.244	8.597	8.299	7.449	8.672	8.582	8.290	7.441	8.619
28	132	5.612	5.335	4.871	5.533	5.366	5.058	4.658	5.265	5.460	5.113	4.740	5.350	5.435	5.099	4.719	5.335
29	33	7.810	9.040	6.761	8.836	4.272	3.910	3.700	4.199	5.074	4.324	4.395	4.792	4.986	4.288	4.328	4.769
30	33	5.386	5.209	4.664	5.431	4.337	3.777	3.756	4.148	4.652	3.932	4.029	4.429	4.641	3.93	4.022	4.444

Table D31: IEC Simulated Results for Case 6 at 30% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.574	12.816	9.312	12.100	10.546	12.789	9.288	12.076	10.563	12.806	9.303	12.091	10.558	12.801	9.298	12.087
2	132	10.104	10.984	8.833	10.668	10.056	10.947	8.792	10.628	10.085	10.970	8.817	10.652	10.076	10.962	8.808	10.646
3	132	6.183	6.081	5.373	6.188	6.139	6.053	5.335	6.151	6.166	6.070	5.358	6.173	6.156	6.064	5.350	6.167
4	132	8.239	7.803	7.164	8.165	8.139	7.744	7.078	8.079	8.199	7.780	7.130	8.130	8.177	7.767	7.111	8.115
5	132	7.513	6.975	6.536	7.360	7.496	6.966	6.522	7.347	7.506	6.972	6.531	7.355	7.503	6.970	6.528	7.353
6	132	9.714	9.002	8.452	9.556	9.510	8.885	8.275	9.375	9.632	8.955	8.381	9.483	9.584	8.928	8.340	9.449
7	132	6.175	5.690	5.358	6.027	6.136	5.668	5.324	5.994	6.159	5.681	5.345	6.014	6.151	5.676	5.337	6.008
8	132	7.239	7.034	6.302	7.208	7.135	6.969	6.212	7.117	7.198	7.008	6.266	7.172	7.173	6.994	6.246	7.155
9	33	16.131	16.235	14.014	16.382	15.966	16.078	13.871	16.251	16.066	16.145	13.958	16.336	16.031	16.121	13.928	16.300
10	33	19.499	18.337	16.918	19.254	19.195	18.021	16.656	19.023	19.380	18.128	16.816	19.189	19.325	18.096	16.768	19.128
11	11	23.107	27.594	20.131	26.269	23.025	27.517	20.060	26.197	23.075	27.564	20.103	26.240	23.057	27.547	20.088	26.222
12	33	16.229	15.187	14.090	15.992	16.108	15.068	13.986	15.907	16.182	15.110	14.050	15.974	16.161	15.098	14.031	15.950
13	11	25.604	30.930	22.259	29.893	25.516	30.845	22.183	29.808	25.570	30.897	22.230	29.860	25.553	30.880	22.215	29.840
14	33	8.284	7.741	7.178	8.072	8.252	7.707	7.151	8.054	8.272	7.719	7.168	8.074	8.268	7.716	7.164	8.068
15	33	13.200	12.075	11.443	12.778	13.078	11.936	11.338	12.686	13.152	11.977	11.402	12.753	13.131	11.965	11.384	12.730
16	33	10.287	9.777	8.916	10.139	10.233	9.720	8.870	10.104	10.266	9.740	8.898	10.135	10.257	9.734	8.891	10.124
17	33	13.497	12.627	11.701	13.213	13.381	12.505	11.600	13.133	13.452	12.546	11.662	13.198	13.432	12.535	11.645	13.176
18	33	8.707	8.028	7.544	8.412	8.664	7.977	7.507	8.384	8.691	7.992	7.529	8.408	8.684	7.988	7.524	8.400
19	33	9.202	8.366	7.973	8.879	9.157	8.313	7.933	8.812	9.185	8.329	7.958	8.832	9.178	8.325	7.952	8.829
20	33	9.555	8.824	8.279	9.241	9.502	8.764	8.233	9.207	9.535	8.782	8.261	9.238	9.527	8.777	8.254	9.228
21	33	15.671	14.399	13.585	15.170	15.402	14.098	13.353	14.961	15.566	14.189	13.494	15.108	15.518	14.163	13.454	15.055
22	33	15.249	14.140	13.219	14.840	14.951	13.801	12.961	14.602	15.132	13.903	13.118	14.765	15.079	13.873	13.072	14.706
23	33	8.610	8.110	7.459	8.390	8.472	7.935	7.340	8.271	8.556	7.984	7.412	8.345	8.530	7.969	7.390	8.317
24	33	11.523	10.826	9.983	11.265	10.921	10.083	9.462	10.603	11.280	10.284	9.773	10.908	11.157	10.217	9.667	10.782
25	33	9.125	9.478	7.903	9.378	7.075	6.809	6.129	7.100	8.190	7.457	7.094	8.000	7.720	7.194	6.693	7.552
26	33	6.785	7.993	5.873	7.832	3.297	3.005	2.855	3.229	4.793	3.709	4.150	4.508	3.969	3.359	3.448	3.840
27	33	10.108	10.737	8.757	10.500	8.077	7.973	6.999	8.279	9.181	8.656	7.954	9.214	8.742	8.390	7.580	8.776
28	132	5.553	5.167	4.820	5.436	5.369	5.059	4.661	5.267	5.478	5.123	4.755	5.367	5.431	5.097	4.716	5.332
29	33	5.188	5.328	4.493	5.314	4.127	3.826	3.574	4.025	4.687	4.130	4.059	4.481	4.452	4.008	3.859	4.272
30	33	8.120	9.277	7.030	9.047	4.460	3.838	3.863	4.240	6.050	4.520	5.239	5.612	5.233	4.202	4.542	4.971

Table D32: IEC Simulated Results for Case 1 at 42% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.748	13.044	9.463	12.320	10.548	12.793	9.291	12.069	10.626	12.865	9.357	12.139	10.661	12.898	9.387	12.170
2	132	10.460	11.493	9.140	11.126	10.047	10.962	8.809	10.607	10.218	11.071	8.931	10.751	10.287	11.124	8.991	10.811
3	132	6.390	6.393	5.551	6.445	6.151	6.061	5.346	6.142	6.235	6.114	5.418	6.225	6.276	6.140	5.454	6.260
4	132	8.707	8.502	7.568	8.730	8.176	7.766	7.111	8.069	8.355	7.871	7.264	8.250	8.445	7.925	7.343	8.330
5	132	8.115	7.899	7.056	8.111	7.548	6.995	6.569	7.328	7.797	7.134	6.782	7.575	7.922	7.204	6.893	7.685
6	132	11.109	10.795	9.661	11.106	9.615	8.944	8.369	9.374	10.001	9.162	8.700	9.774	10.206	9.278	8.883	9.962
7	132	9.041	10.093	7.837	9.863	6.487	5.869	5.631	6.386	7.416	6.338	6.432	7.044	7.999	6.625	6.958	7.602
8	132	7.715	7.703	6.713	7.767	7.166	6.989	6.241	7.108	7.322	7.085	6.373	7.266	7.400	7.134	6.442	7.336
9	33	23.655	27.278	20.551	26.624	16.019	16.115	13.918	16.317	16.126	16.184	14.009	16.376	16.185	16.224	14.061	16.420
10	33	28.813	32.515	25.013	31.990	19.254	18.056	16.708	19.083	19.363	18.116	16.800	19.145	19.423	18.151	16.852	19.189
11	11	25.945	30.197	22.591	28.739	23.054	27.545	20.086	26.232	23.104	27.590	20.127	26.261	23.132	27.617	20.152	26.282
12	33	16.462	15.894	14.291	16.268	16.135	15.084	14.010	15.939	16.200	15.120	14.065	15.979	16.233	15.139	14.094	16.005
13	11	25.775	31.095	22.407	30.070	25.538	30.866	22.202	29.834	25.580	30.906	22.238	29.862	25.603	30.928	22.258	29.880
14	33	8.337	7.929	7.224	8.192	8.256	7.710	7.155	8.060	8.273	7.719	7.169	8.071	8.280	7.724	7.175	8.078
15	33	13.425	12.719	11.637	13.168	13.088	11.941	11.346	12.696	13.128	11.963	11.380	12.723	13.147	11.973	11.397	12.738
16	33	10.786	10.696	9.348	10.758	10.243	9.726	8.879	10.116	10.270	9.742	8.902	10.133	10.284	9.750	8.914	10.144
17	33	15.860	16.250	13.749	16.066	13.403	12.518	11.620	13.156	13.452	12.546	11.662	13.187	13.478	12.561	11.684	13.207
18	33	8.992	8.605	7.790	8.888	8.669	7.980	7.511	8.389	8.686	7.989	7.525	8.400	8.694	7.994	7.532	8.407
19	33	9.728	9.278	8.428	9.644	9.163	8.317	7.939	8.816	9.182	8.327	7.955	8.834	9.191	8.332	7.963	8.842
20	33	10.336	10.089	8.955	10.308	9.510	8.768	8.240	9.215	9.532	8.780	8.259	9.230	9.543	8.787	8.269	9.239
21	33	19.186	19.738	16.633	19.562	15.428	14.113	13.377	14.981	15.494	14.149	13.432	15.022	15.527	14.167	13.461	15.048
22	33	18.326	18.884	15.887	18.675	14.975	13.815	12.982	14.617	15.038	13.849	13.035	14.657	15.069	13.867	13.063	14.682
23	33	8.665	8.363	7.507	8.582	8.473	7.936	7.341	8.267	8.491	7.946	7.356	8.279	8.499	7.950	7.363	8.286
24	33	11.453	11.093	9.922	11.433	10.904	10.074	9.448	10.556	10.936	10.091	9.474	10.578	10.951	10.100	9.487	10.590
25	33	6.994	6.846	6.059	6.923	6.941	6.721	6.013	6.883	6.958	6.732	6.027	6.894	6.966	6.737	6.035	6.901
26	33	3.068	2.889	2.657	3.038	3.060	2.870	2.650	3.016	3.063	2.871	2.653	3.019	3.064	2.872	2.654	3.020
27	33	8.050	7.984	6.975	8.127	8.002	7.918	6.934	8.111	8.028	7.933	6.956	8.126	8.041	7.942	6.968	8.136
28	132	5.721	5.527	4.965	5.674	5.375	5.064	4.667	5.256	5.480	5.124	4.757	5.363	5.533	5.156	4.804	5.410
29	33	4.091	3.812	3.543	3.996	4.081	3.799	3.535	3.976	4.087	3.803	3.540	3.981	4.089	3.804	3.542	3.984
30	33	4.291	3.763	3.717	4.165	4.282	3.751	3.709	4.146	4.287	3.754	3.713	4.151	4.290	3.755	3.716	4.153

Table D33: IEC Simulated Results for Case 2 at 42% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.623	12.862	9.355	12.138	10.554	12.797	9.295	12.081	10.561	12.804	9.301	12.089	10.564	12.806	9.303	12.091
2	132	10.199	11.057	8.915	10.740	10.071	10.959	8.804	10.636	10.082	10.967	8.814	10.649	10.086	10.970	8.817	10.652
3	132	6.248	6.122	5.429	6.237	6.153	6.062	5.348	6.160	6.163	6.068	5.356	6171	6.167	6.071	5.360	6.174
4	132	8.387	7.890	7.292	8.280	8.174	7.765	7.108	8.101	8.194	7.777	7.125	8.126	8.203	7.782	7.133	8.133
5	132	7.551	6.997	6.569	7.387	7.501	6.969	6.526	7.349	7.505	6.971	6.530	7.354	7.507	6.972	6.531	7.355
6	132	10.311	9.334	8.972	10.044	9.581	8.925	8.337	9.424	9.616	8.946	8.367	9.468	9.633	8.956	8.382	9.483
7	132	6.278	5.748	5.448	6.107	6.148	5.675	5.335	6.002	6.156	5.679	5.342	6.011	6.159	5.681	5.345	6.014
8	132	7.449	7.164	6.484	7.374	7.170	6.991	6.242	7.140	7.187	7.002	6.257	7.163	7.196	7.008	6.265	7.170
9	33	22.967	26.682	19.961	26.055	16.034	16.124	13.931	16.327	16.079	16.153	13.969	16.350	16.097	16.166	13.985	16.367
10	33	28.136	32.005	24.436	31.471	19.311	18.090	16.756	19.165	19.420	18.152	16.850	19.234	19.456	18.174	16.882	19.268
11	11	25.746	30.021	22.421	28.585	23.061	27.551	20.091	26.237	23.082	27.570	20.109	26.248	23.091	27.578	20.117	26.256
12	33	16.371	15.861	14.214	16.201	16.150	15.093	14.022	15.960	16.194	15.118	14.060	15.988	16.208	15.126	14.072	16.002
13	11	25.716	31.039	22.356	30.029	25.550	30.878	22.213	29.851	25.579	30.906	22.238	29.871	25.590	30.916	22.247	29.882
14	33	8.322	7.928	7.211	8.187	8.259	7.712	7.157	8.067	8.275	7.721	7.171	8.078	8.279	7.723	7.174	8.082
15	33	13.424	12.759	11.637	13.192	13.125	11.962	11.378	12.744	13.172	11.987	11.418	12.774	13.186	11.996	11.431	12.788
16	33	10.728	10.665	9.299	10.712	10.249	9.730	8.884	10.127	10.272	9.743	8.903	10.142	10.278	9.747	8.909	10.148
17	33	15.688	16.143	13.602	15.927	13.419	12.528	11.634	13.183	13.465	12.554	11.673	13.214	13.479	12.562	11.685	13.227
18	33	8.972	8.605	7.774	8.881	8.678	7.985	7.518	8.402	8.696	7.995	7.534	8.415	8.702	7.998	7.539	8.420
19	33	9.693	9.266	8.398	9.622	9.170	8.321	7.945	8.815	9.190	8.332	7.962	8.835	9.196	8.335	7.967	8.838
20	33	10.285	10.066	8.911	10.272	9.518	8.773	8.247	9.230	9.541	8.786	8.267	9.246	9.547	8.789	8.272	9.252
21	33	19.100	19.763	16.562	19.544	15.508	14.159	13.446	15.092	15.612	14.215	13.534	15.157	15.645	14.233	13.563	15.188
22	33	18.318	18.985	15.882	18.739	15.074	13.873	13.068	14.751	15.187	13.934	13.165	14.821	15.225	13.956	13.198	14.857
23	33	8.763	8.490	7.592	8.701	8.537	7.973	7.396	8.347	8.587	8.002	7.439	8.375	8.605	8.012	7.455	8.392
24	33	12.084	11.825	10.468	12.143	11.245	10.267	9.743	10.957	11.442	10.374	9.913	11.058	11.527	10.421	9.987	11.133
25	33	9.664	9.873	8.371	9.840	8.278	7.534	7.171	8.361	8.900	7.837	7.709	8.621	9.261	8.024	8.029	8.924
26	33	14.193	17.740	12.282	17.374	5.800	4.208	5.023	5.863	8.192	4.722	7.091	7.451	10.257	5.158	8.967	9.452
27	33	9.026	9.098	7.820	9.139	8.496	8.247	7.362	8.703	8.778	8.412	7.606	8.846	8.906	8.491	7.719	8.960
28	132	5.627	5.209	4.884	5.486	5.427	5.094	4.712	5.311	5.450	5.107	4.732	5.343	5.465	5.116	4.744	5.355
29	33	4.244	3.990	3.676	4.175	4.146	3.837	3.591	4.024	4.206	3.870	3.643	4.061	4.226	3.882	3.660	4.080
30	33	4.422	3.917	3.830	4.319	4.335	3.777	3.755	4.161	4.389	3.804	3.802	4.218	4.407	3.813	3.817	4.231

Table D34: IEC Simulated Results for Case 3 at 42% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.631	12.870	9.362	12.146	10.557	12.800	9.298	12.082	10.568	12.810	9.307	12.095	10.572	12.814	9.311	12.099
2	132	10.213	10.068	8.928	10.753	10.078	10.964	8.810	10.640	10.094	10.976	8.824	10.659	10.101	10.982	8.830	10.665
3	132	6.259	6.129	5.439	6.247	6.159	6.066	5.353	6.163	6.173	6.074	5.364	6.179	6.179	6.078	5.370	6.185
4	132	8.413	7.906	7.315	8.305	8.188	7.773	7.120	8.109	8.215	7.789	7.144	8.144	8.229	7.798	7.156	8.157
5	132	7.556	7.000	6.574	7.392	7.503	6.970	6.528	7.350	7.510	6.973	6.534	7.357	7.512	6.975	6.536	7.359
6	132	10.385	9.374	9.036	10.113	9.624	8.950	8.375	9.451	9.674	8.979	8.417	9.520	9.703	8.996	8.443	9.547
7	132	6.291	5.755	5.459	6.119	6.155	5.679	5.341	6.006	6.167	5.685	5.351	6.021	6.173	5.689	5.356	6.025
8	132	7.492	7.190	6.521	7.413	7.194	7.006	6.264	7.155	7.221	7.023	6.287	7.192	7.237	7.033	6.300	7.206
9	33	23.015	26.720	20.002	26.084	16.025	16.118	13.922	16.314	16.064	16.143	13.956	16.331	16.082	16.155	13.972	16.346
10	33	28.130	31.962	24.429	31.432	19.268	18.064	16.719	19.106	19.349	18.110	16.788	19.155	19.378	18.127	16.814	19.181
11	11	25.760	30.033	22.433	28.592	23.056	27.546	20.087	26.230	23.074	27.562	20.102	26.238	23.083	27.571	20.110	26.246
12	33	16.357	15.838	14.202	16.184	16.139	15.086	14.013	15.943	16.174	15.106	14.043	15.965	16.187	15.113	14.054	15.976
13	11	25.704	31.028	22.347	30.014	25.540	30.869	22.205	29.837	25.564	30.891	22.224	29.852	25.573	30.899	22.232	29.861
14	33	8.317	7.919	7.207	8.179	8.257	7.710	7.155	8.062	8.269	7.717	7.166	8.070	8.272	7.719	7.168	8.073
15	33	13.389	12.713	11.607	13.151	13.100	11.948	11.356	12.713	13.135	11.967	11.387	12.736	13.146	11.973	11.396	12.746
16	33	10.726	10.659	9.297	10.708	10.245	9.727	8.880	10.119	10.262	9.737	8.895	10.130	10.267	9.741	8.899	10.135
17	33	15.688	16.134	13.602	15.922	13.406	12.520	11.623	13.163	13.441	12.540	11.653	13.186	13.453	12.547	11.662	13.196
18	33	8.965	8.593	7.767	8.871	8.671	7.981	7.513	8.393	8.686	7.989	7.525	8.403	8.690	7.991	7.528	8.407
19	33	9.688	9.257	8.394	9.615	9.165	8.318	7.940	8.815	9.180	8.326	7.953	8.830	9.184	8.328	7.957	8.833
20	33	10.281	10.058	8.908	10.266	9.512	8.769	8.242	9.220	9.529	8.779	8.257	9.232	9.534	8.782	8.261	9.236
21	33	19.021	19.653	16.493	19.445	15.450	14.125	13.395	15.018	15.522	14.165	13.457	15.065	15.546	14.178	13.477	15.087
22	33	18.210	18.842	15.788	18.608	15.001	13.830	13.005	14.662	15.080	13.873	13.072	14.713	15.105	13.888	13.094	14.737
23	33	8.693	8.406	7.531	8.624	8.490	7.946	7.355	8.294	8.524	7.965	7.385	8.316	8.535	7.971	7.394	8.326
24	33	11.678	11.366	10.117	11.708	10.988	10.122	9.520	10.684	11.114	10.192	9.629	10.762	11.157	10.216	9.666	10.801
25	33	7.819	7.806	6.773	7.878	7.247	6.918	6.279	7.296	7.549	7.092	6.539	7.467	7.671	7.165	6.647	7.576
26	33	3.175	3.018	2.750	3.168	3.091	2.887	2.677	3.017	3.141	2.916	2.720	3.069	3.158	2.926	2.735	3.081
27	33	10.958	11.474	9.494	11.246	9.118	8.667	7.902	9.498	10.008	9.133	8.670	9.960	10.455	9.381	9.067	10.340
28	132	5.740	5.273	4.982	5.590	5.496	5.134	4.772	5.356	5.533	5.155	4.803	5.416	5.562	5.173	4.829	5.444
29	33	15.278	18.937	13.222	18.485	6.457	5.092	5.593	6.672	9.224	5.808	7.986	8.296	11.324	6.329	9.891	10.317
30	33	6.196	5.982	5.366	6.268	5.025	4.111	4.353	4.839	5.563	4.330	4.818	5.157	5.853	4.448	5.075	5.412

Table D35: IEC Simulated Results for Case 4 at 42% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.626	12.865	9.357	12.141	10.554	12.797	9.295	12.080	10.564	12.806	9.303	12.091	10.567	12.810	9.306	12.094
2	132	10.204	11.061	8.919	10.745	10.071	10.959	8.805	10.636	10.087	10.971	8.818	10.653	10.092	10.975	8.823	10.658
3	132	6.251	6.124	5.432	6.240	6.153	6.062	5.348	6.159	6.166	6.070	5.359	6.174	6.171	6.074	5.363	6.178
4	132	8.393	7.894	7.298	8.288	8.174	7.765	7.109	8.100	8.200	7.780	7.130	8.131	8.212	7.788	7.141	8.142
5	132	7.553	6.998	6.571	7.390	7.501	6.969	6.527	7.349	7.507	6.972	6.531	7.355	7.509	6.973	6.533	7.357
6	132	10.337	9.348	8.995	10.072	9.594	8.933	8.348	9.429	9.641	8.960	8.388	9.491	9.666	8.975	8.411	9.514
7	132	6.283	5.750	5.452	6.112	6.150	5.676	5.337	6.002	6.161	5.682	5.346	6.015	6.166	5.685	5.350	6.019
8	132	7.469	7.176	6.501	7.393	7.179	6.996	6.250	7.144	7.204	7.012	6.272	7.177	7.217	7.021	6.284	7.189
9	33	22.961	26.672	19.956	26.037	16.008	16.106	13.908	16.297	16.044	16.130	13.939	16.314	16.060	16.140	13.952	16.328
10	33	28.044	31.887	24.355	31.356	19.245	18.051	16.700	19.081	19.318	18.092	16.762	19.127	19.343	18.106	16.783	19.149
11	11	25.743	30.018	22.419	28.579	23.047	27.538	20.079	26.221	23.064	27.553	20.093	26.229	23.072	27.560	20.100	26.236
12	33	16.340	15.826	14.187	16.169	16.129	15.081	14.005	15.933	16.161	15.098	14.032	15.953	16.172	15.105	14.041	15.962
13	11	25.692	31.016	22.336	30.002	25.533	30.862	22.198	29.829	25.554	30.881	22.216	29.843	25.562	30.889	22.223	29.850
14	33	8.313	7.916	7.203	8.176	8.255	7.709	7.154	8.059	8.266	7.715	7.163	8.067	8.268	7.717	7.165	8.070
15	33	13.374	12.702	11.594	13.138	13.092	11.944	11.350	12.704	13.123	11.961	11.377	12.725	13.133	11.966	11.385	12.734
16	33	10.717	10.653	9.290	10.701	10.241	9.725	8.877	10.114	10.256	9.734	8.890	10.124	10.261	9.737	8.894	10.129
17	33	15.666	16.118	13.583	15.904	13.398	12.516	11.616	13.154	13.429	12.533	11.642	13.175	13.439	12.539	11.651	13.184
18	33	8.959	8.589	7.762	8.866	8.669	7.980	7.511	8.390	8.682	7.987	7.521	8.399	8.685	7.989	7.524	8.402
19	33	9.681	9.253	8.388	9.609	9.162	8.316	7.938	8.814	9.176	8.323	7.949	8.827	9.179	8.325	7.953	8.829
20	33	10.273	10.052	8.901	10.259	9.509	8.767	8.239	9.216	9.524	8.776	8.252	9.227	9.528	8.778	8.256	9.231
21	33	18.972	19.615	16.451	19.402	15.434	14.116	13.381	14.999	15.498	14.152	13.436	15.042	15.518	14.163	13.453	15.061
22	33	18.159	18.801	15.744	18.563	14.983	13.820	12.990	14.642	15.053	13.859	13.050	14.688	15.075	13.871	13.068	14.708
23	33	8.678	8.394	7.518	8.610	8.483	7.941	7.349	8.285	8.513	7.959	7.375	8.305	8.522	7.964	7.383	8.314
24	33	11.614	11.312	10.062	11.648	10.958	10.105	9.494	10.649	11.069	10.167	9.590	10.721	11.106	10.187	9.622	10.754
25	33	7.645	7.644	6.623	7.704	7.158	6.862	6.201	7.198	7.422	7.016	6.429	7.354	7.523	7.077	6.518	7.444
26	33	3.153	2.998	2.731	3.146	3.080	2.881	2.667	3.012	3.124	2.906	2.705	3.056	3.138	2.914	2.718	3.067
27	33	10.289	10.793	8.914	10.594	8.816	8.472	7.639	9.170	9.561	8.881	8.283	9.576	9.908	9.081	8.591	9.875
28	132	5.696	5.248	4.944	5.550	5.464	5.115	4.743	5.331	5.500	5.136	4.775	5.386	5.525	5.151	4.797	5.410
29	33	5.863	8.989	5.077	6.009	4.738	4.174	4.104	4.726	5.261	4.414	4.556	4.989	5.535	4.543	4.800	5.215
30	33	15.504	19.135	13.417	18.637	6.550	4.826	5.674	6.591	9.424	5.501	8.159	8.473	11.539	5.953	10.076	10.495

Table D36: IEC Simulated Results for Case 5 at 42% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.710	12.991	9.430	12.265	10.549	12.794	9.292	12.067	10.604	12.844	9.338	12.122	10.629	12.868	9.360	12.144
2	132	10.374	11.362	9.066	11.001	10.071	10.959	8.806	10.617	10.169	11.034	8.889	10.715	10.216	11.071	8.931	10.757
3	132	6.352	6.318	5.518	6.383	6.152	6.061	5.347	6.147	6.214	6.101	5.400	6.210	6.244	6.120	5.427	6.236
4	132	8.622	8.329	7.494	8.595	8.176	7.766	7.111	8.080	8.308	7.844	7.224	8.215	8.375	7.884	7.283	8.275
5	132	7.881	7.589	6.854	7.825	7.519	6.979	6.543	7.332	7.666	7.061	6.669	7.475	7.742	7.105	6.736	7.542
6	132	10.894	10.361	9.475	10.776	9.611	8.942	8.365	9.396	9.889	9.100	8.603	9.688	10.038	9.185	8.736	9.825
7	132	7.677	8.075	6.657	8.001	6.308	5.765	5.475	6.131	6.799	6.028	5.898	6.537	7.096	6.187	6.166	6.821
8	132	7.667	7.566	6.672	7.668	7.177	6.995	6.249	7.123	7.296	7.069	6.351	7.248	7.357	7.108	6.406	7.304
9	33	23.490	27.137	20.410	26.487	16.016	16.113	13.916	16.317	16.120	16.180	14.004	16.377	16.173	16.216	14.051	16.418
10	33	28.690	32.431	24.909	31.898	19.247	18.053	16.702	19.091	19.390	18.133	16.823	19.183	19.454	18.170	16.879	19.235
11	11	25.898	30.155	22.551	28.703	23.053	27.544	20.085	26.232	23.102	27.588	20.126	26.261	23.127	27.612	20.148	26.281
12	33	16.451	15.895	14.282	16.260	16.130	15.082	14.006	15.939	16.202	15.122	14.067	15.987	16.234	15.140	14.095	16.013
13	11	25.769	31.090	22.402	30.070	25.535	30.864	22.200	29.835	25.583	30.909	22.241	29.868	25.605	30.931	22.260	29.888
14	33	8.336	7.931	7.224	8.194	8.254	7.709	7.153	8.059	8.274	7.720	7.170	8.074	8.281	7.724	7.176	8.081
15	33	13.440	12.742	11.650	13.192	13.087	11.941	11.346	12.702	13.143	11.971	11.393	12.741	13.165	11.983	11.412	12.760
16	33	10.776	10.691	9.340	10.749	10.240	9.725	8.876	10.116	10.272	9.743	8.904	10.138	10.286	9.751	8.915	10.149
17	33	15.829	16.231	13.722	16.042	13.398	12.516	11.616	13.157	13.460	12.550	11.668	13.199	13.486	12.566	11.691	13.221
18	33	8.992	8.609	7.790	8.892	8.667	7.979	7.509	8.389	8.690	7.991	7.529	8.406	8.699	7.996	7.536	8.414
19	33	9.724	9.279	8.424	9.643	9.160	8.315	7.937	8.812	9.185	8.329	7.958	8.835	9.195	8.334	7.966	8.842
20	33	10.328	10.087	8.949	10.304	9.507	8.767	8.238	9.216	9.536	8.783	8.262	9.237	9.547	8.789	8.272	9.247
21	33	19.209	19.784	16.654	19.607	15.426	14.112	13.374	14.995	15.533	14.170	13.465	15.069	15.575	14.194	13.503	15.105
22	33	18.375	18.955	15.929	18.748	14.974	13.815	12.981	14.634	15.084	13.876	13.076	14.712	15.128	13.901	13.115	14.749
23	33	8.705	8.412	7.542	8.633	8.476	7.937	7.343	8.278	8.517	7.961	7.379	8.308	8.533	7.970	7.392	8.322
24	33	11.670	11.352	10.110	11.699	10.926	10.087	9.467	10.614	11.066	10.164	9.587	10.711	11.117	10.193	9.631	10.757
25	33	7.654	7.663	6.630	7.729	7.060	6.800	6.116	7.088	7.361	6.979	6.376	7.285	7.484	7.054	6.485	7.391
26	33	3.156	3.002	2.733	3.151	3.068	2.874	2.657	3.006	3.117	2.902	2.700	3.054	3.134	2.912	2.715	3.067
27	33	10.234	10.791	8.865	10.543	8.491	8.259	7.358	8.813	9.313	8.732	8.069	9.313	9.710	8.966	8.422	9.643
28	132	5.822	5.513	5.052	5.727	5.437	5.099	4.721	5.298	5.546	5.163	4.814	5.422	5.607	5.198	4.868	5.478
29	33	9.657	11.649	8.359	11.372	5.092	4.385	4.411	5.193	6.661	5.000	5.767	6.130	7.702	5.385	6.713	7.146
30	33	5.682	5.528	4.921	5.766	4.614	3.915	3.997	4.417	5.100	4.136	4.417	4.793	5.345	4.245	4.635	5.013

Table D37: IEC Simulated Results for Case 6 at 42% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.635	12.874	9.365	12.148	10.553	12.796	9.294	12.078	10.568	12.810	9.307	12.094	10.573	12.815	9.311	12.099
2	132	10.220	11.074	8.934	10.757	10.070	10.958	8.804	10.633	10.094	10.976	8.824	10.658	10.103	10.983	8.832	10.666
3	132	6.267	6.134	5.446	6.252	6.153	6.062	5.348	6.157	6.173	6.075	5.365	6.179	6.182	6.080	5.372	6.186
4	132	8.431	7.916	7.331	8.318	8.175	7.765	7.109	8.096	8.217	7.791	7.145	8.144	8.236	7.802	7.162	8.161
5	132	7.558	7.001	6.576	7.393	7.501	6.968	6.526	7.348	7.509	6.973	6.533	7.357	7.512	6.975	6.536	7.359
6	132	10.420	9.393	9.066	10.138	9.593	8.932	8.348	9.421	9.671	8.977	8.414	9.514	9.708	8.999	8.448	9.548
7	132	6.297	5.758	5.464	6.123	6.149	5.675	5.336	6.000	6.166	5.685	5.351	6.019	6.174	5.689	5.357	6.025
8	132	7.504	7.197	6.532	7.421	7.176	6.995	6.248	7.138	7.217	7.021	6.283	7.187	7.236	7.033	6.300	7.204
9	33	23.082	26.785	20.060	26.153	16.021	16.116	13.920	16.322	16.096	16.164	13.983	16.364	16.126	16.185	14.009	16.390
10	33	28.299	32.149	24.576	31.610	19.267	18.065	16.719	19.131	19.430	18.158	16.859	19.240	19.486	18.191	16.908	19.291
11	11	25.780	30.051	22.451	28.612	23.055	27.546	20.087	26.235	23.090	27.577	20.116	26.255	23.105	27.592	20.129	26.268
12	33	16.401	15.882	14.240	16.226	16.134	15.084	14.009	15.948	16.201	15.122	14.066	15.994	16.224	15.135	14.086	16.015
13	11	25.737	31.059	22.375	30.048	25.539	30.868	22.204	29.843	25.584	30.911	22.242	29.876	25.601	30.927	22.256	29.891
14	33	8.329	7.933	7.217	8.193	8.254	7.708	7.153	8.062	8.276	7.721	7.172	8.079	8.282	7.725	7.177	8.085
15	33	13.446	12.776	11.656	13.214	13.103	11.950	11.359	12.726	13.172	11.987	11.418	12.773	13.194	12.000	11.438	12.794
16	33	10.743	10.676	9.312	10.724	10.242	9.726	8.877	10.121	10.274	9.745	8.905	10.144	10.284	9.751	8.914	10.153
17	33	15.729	16.173	13.638	15.964	13.402	12.518	11.619	13.170	13.470	12.557	11.677	13.217	13.491	12.569	11.696	13.237
18	33	8.982	8.612	7.782	8.890	8.670	7.980	7.512	8.396	8.697	7.995	7.535	8.415	8.705	8.000	7.542	8.423
19	33	9.704	9.274	8.408	9.632	9.162	8.316	7.938	8.809	9.192	8.332	7.963	8.836	9.200	8.337	7.971	8.842
20	33	10.300	10.076	8.924	10.285	9.509	8.768	8.239	9.222	9.543	8.786	8.268	9.247	9.552	8.792	8.277	9.256
21	33	19.174	19.824	16.626	19.617	15.459	14.132	13.403	15.051	15.609	14.213	13.532	15.153	15.659	14.241	13.575	15.198
22	33	18.390	19.047	15.944	18.812	15.017	13.840	13.019	14.703	15.180	13.931	13.160	14.814	15.236	13.962	13.208	14.865
23	33	8.775	8.505	7.602	8.717	8.506	7.956	7.370	8.321	8.578	7.997	7.432	8.368	8.604	8.012	7.454	8.391
24	33	12.112	11.882	10.493	12.199	11.100	10.187	9.618	10.835	11.386	10.343	9.864	11.009	11.499	10.406	9.964	11.108
25	33	9.623	10.043	8.334	9.970	7.738	7.230	6.704	7.895	8.604	7.682	7.452	8.375	9.045	7.917	7.844	8.740
26	33	8.634	10.558	7.472	10.353	4.292	3.544	3.717	4.340	5.670	4.031	4.909	5.264	6.690	4.374	5.838	6.278
27	33	10.579	11.251	9.165	10.955	8.625	8.355	7.474	9.005	9.581	8.892	8.300	9.591	10.023	9.146	8.694	9.968
28	132	5.741	5.273	4.983	5.588	5.454	5.110	4.736	5.319	5.515	5.145	4.787	5.398	5.548	5.165	4.817	5.430
29	33	5.474	5.641	4.740	5.636	4.408	3.991	3.818	4.385	4.906	4.242	4.248	4.678	5.147	4.363	4.464	4.875
30	33	9.982	11.934	8.640	11.621	5.278	4.250	4.571	5.228	6.937	4.827	6.006	6.356	8.004	5.167	6.974	7.388

Table D38: IEC Simulated Results for Case 1 at 85% penetration level and DG located at Bus 7

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.752	13.048	9.466	12.323	10.576	12.820	9.316	12.109	10.672	12.908	9.397	12.176	10.704	12.939	9.425	12.205
2	132	10.472	11.503	9.150	11.137	10.140	11.013	8.867	10.635	10.313	11.144	9.013	10.825	10.375	11.192	9.068	10.881
3	132	6.387	6.391	5.548	6.443	6.191	6.087	5.382	6.160	6.292	6.150	5.467	6.269	6.329	6.174	5.500	6.302
4	132	8.700	8.496	7.560	8.723	8.274	7.824	7.197	8.119	8.485	7.946	7.376	8.354	8.567	7.995	7.449	8.429
5	132	8.282	8.003	7.201	8.246	7.676	7.068	6.681	7.449	7.977	7.232	6.938	7.716	8.093	7.297	7.042	7.821
6	132	10.824	10.612	9.410	10.864	9.851	9.078	8.575	9.547	10.310	9.330	8.967	10.025	10.501	9.437	9.139	10.205
7	132	10.332	11.123	8.955	10.916	7.089	6.205	6.154	7.073	8.384	6.783	7.270	7.860	9.021	7.069	7.853	8.494
8	132	7.623	7.642	6.633	7.691	7.253	7.044	6.317	7.163	7.436	7.155	6.472	7.356	7.507	7.200	6.535	7.422
9	33	16.358	16.335	14.207	16.554	16.110	16.177	13.997	16.414	16.220	16.245	14.089	16.453	16.271	16.280	14.135	16.490
10	33	19.595	18.248	16.998	19.324	19.343	18.109	16.785	19.177	19.456	18.170	16.880	19.222	19.508	18.200	16.926	19.259
11	11	23.216	27.693	20.223	26.350	23.101	27.589	20.127	26.283	23.150	27.632	20.166	26.300	23.174	27.656	20.188	26.317
12	33	16.327	15.192	14.174	16.081	16.180	15.111	14.049	15.988	16.250	15.149	14.108	16.022	16.280	15.166	14.134	16.044
13	11	25.669	30.990	22.314	29.938	25.572	30.900	22.233	29.873	25.616	30.940	22.269	29.894	25.636	30.959	22.286	29.910
14	33	8.300	7.735	7.192	8.095	8.263	7.714	7.160	8.068	8.283	7.725	7.177	8.081	8.290	7.729	7.183	8.086
15	33	13.197	12.001	11.440	12.781	13.108	11.952	11.364	12.719	13.154	11.977	11.403	12.746	13.171	11.987	11.418	12.760
16	33	10.322	9.772	8.946	10.175	10.259	9.736	8.893	10.135	10.290	9.754	8.919	10.151	10.302	9.761	8.930	10.106
17	33	13.549	12.601	11.744	13.264	13.436	12.538	11.649	13.193	13.490	12.568	11.694	13.219	13.513	12.581	11.714	13.236
18	33	8.715	8.005	7.550	8.425	8.677	7.984	7.517	8.398	8.697	7.995	7.535	8.410	8.704	7.999	7.541	8.416
19	33	9.215	8.345	7.983	8.861	9.172	8.322	7.947	8.820	9.195	8.334	7.966	8.844	9.203	8.338	7.973	8.851
20	33	9.572	8.803	8.293	9.264	9.521	8.775	8.250	9.229	9.548	8.789	8.272	9.244	9.557	8.795	8.281	9.252
21	33	15.620	14.217	13.539	15.123	15.470	14.137	13.413	15.028	15.543	14.176	13.474	15.065	15.573	14.192	13.500	15.087
22	33	15.157	13.915	13.138	14.754	15.014	13.837	13.016	14.661	15.084	13.875	13.075	14.697	15.112	13.891	13.100	14.719
23	33	8.519	7.962	7.380	8.304	8.480	7.940	7.347	8.276	8.501	7.952	7.365	8.289	8.509	7.956	7.371	8.295
24	33	10.990	10.121	9.520	10.624	10.918	10.082	9.460	10.574	10.956	10.103	9.492	10.597	10.969	10.110	9.503	10.607
25	33	6.988	6.750	6.053	6.919	6.950	6.727	6.021	6.894	6.969	6.739	6.037	6.904	6.977	6.744	6.044	6.910
26	33	3.068	2.874	2.657	3.023	3.061	2.870	2.651	3.017	3.065	2.872	2.654	3.020	3.066	2.873	2.655	3.021
27	33	8.080	7.967	7.000	8.167	8.022	7.931	6.952	8.133	8.049	7.947	6.974	8.144	8.060	7.954	6.984	8.152
28	132	5.683	5.503	4.931	5.641	5.435	5.098	4.719	5.286	5.557	5.169	4.824	5.424	5.606	5.197	4.866	5.468
29	33	4.097	3.808	3.548	3.990	4.084	3.801	3.537	3.977	4.090	3.805	3.543	3.984	4.093	3.806	3.545	3.987
30	33	4.296	3.758	3.721	4.159	4.285	3.752	3.711	4.148	4.291	3.756	3.716	4.154	4.293	3.757	3.718	4.156

Table D39: IEC Simulated Results for Case 2 at 85% penetration level and DG located at Bus 26

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.568	12.810	9.307	12.094	10.560	12.803	9.300	12.085	10.565	12.807	9.304	12.091	10.566	12.809	9.305	12.093
2	132	10.093	10.976	8.823	10.657	10.081	10.966	8.813	10.644	10.088	10.972	8.819	10.653	10.091	10.974	8.821	10.655
3	132	6.174	6.075	5.365	6.179	6.163	6.068	5.356	6.167	6.169	6.072	5.361	6.175	6.172	6.074	5.364	6.177
4	132	8.219	7.792	7.147	8.144	8.195	7.777	7.127	8.119	8.208	7.785	7.137	8.135	8.214	7.789	7.142	8.140
5	132	7.509	6.973	6.533	7.356	7.504	6.970	6.529	7.352	7.507	6.972	6.531	7.355	7.508	6.973	6.532	7.356
6	132	9.667	8.975	8.411	9.508	9.624	8.950	8.374	9.460	9.643	8.961	8.391	9.489	9.656	8.969	8.402	9.500
7	132	6.165	5.684	5.350	6.018	6.156	5.679	5.342	6.008	6.161	5.682	5.346	6.015	6.163	5.683	5.348	6.016
8	132	7.212	7.018	6.279	7.182	7.191	7.004	6.260	7.158	7.201	7.010	6.269	7.173	7.207	7.014	6.274	7.178
9	33	16.128	16.232	14.012	16.387	16.078	16.154	13.968	16.367	16.105	16.171	13.992	16.377	16.118	16.180	14.003	16.389
10	33	19.513	18.341	16.931	19.279	19.396	18.140	16.830	19.246	19.468	18.181	16.892	19.285	19.494	18.196	16.914	19.310
11	11	23.107	27.594	20.131	26.273	23.083	27.571	20.110	26.257	23.095	27.583	20.121	26.262	23.102	27.589	20.126	26.268
12	33	16.229	15.184	14.090	15.997	16.182	15.112	14.050	15.991	16.212	15.128	14.076	16.008	16.222	15.134	14.084	16.018
13	11	25.606	30.932	22.261	29.900	25.574	30.902	22.234	29.876	25.593	30.919	22.250	29.887	25.600	30.926	22.256	29.894
14	33	8.283	7.740	7.178	8.073	8.268	7.717	7.165	8.076	8.279	7.723	7.174	8.083	8.281	7.724	7.176	8.086
15	33	13.209	12.078	11.451	12.791	13.160	11.981	11.408	12.777	13.191	11.998	11.435	12.795	13.201	12.004	11.444	12.805
16	33	10.287	9.776	8.916	10.141	10.264	9.739	8.897	10.141	10.279	9.748	8.910	10.150	10.284	9.750	8.914	10.155
17	33	13.499	12.626	11.702	13.220	13.451	12.547	11.661	13.215	13.482	12.564	11.688	13.233	13.492	12.570	11.696	13.243
18	33	8.708	8.028	7.545	8.414	8.689	7.991	7.528	8.414	8.702	7.998	7.540	8.422	8.706	8.000	7.543	8.426
19	33	9.203	8.365	7.973	8.877	9.183	8.327	7.956	8.823	9.197	8.335	7.968	8.838	9.201	8.337	7.971	8.840
20	33	9.556	8.823	8.280	9.244	9.532	8.781	8.260	9.244	9.549	8.790	8.273	9.254	9.553	8.792	8.277	9.259
21	33	15.697	14.409	13.608	15.203	15.587	14.203	13.514	15.167	15.656	14.239	13.573	15.204	15.680	14.253	13.593	15.227
22	33	15.284	14.156	13.249	14.882	15.162	13.922	13.144	14.835	15.237	13.963	13.209	14.875	15.264	13.978	13.232	14.901
23	33	8.635	8.123	7.481	8.416	8.580	7.998	7.433	8.386	8.612	8.016	7.461	8.401	8.625	8.024	7.472	8.413
24	33	11.679	10.911	10.118	11.370	11.444	10.377	9.915	11.134	11.567	10.442	10.021	11.181	11.629	10.476	10.075	11.236
25	33	10.060	10.115	8.714	10.093	9.088	7.967	7.873	9.079	9.497	8.141	8.226	9.172	9.790	8.284	8.484	9.424
26	33	25.137	31.544	21.751	30.793	9.253	5.211	8.014	9.111	13.304	5.540	11.515	11.867	17.425	5.970	15.253	15.769
27	33	9.145	9.171	7.924	9.268	8.791	8.431	7.617	8.972	8.971	8.531	7.773	9.038	9.066	8.589	7.856	9.124
28	132	5.493	5.132	4.769	5.377	5.463	5.114	4.742	5.341	5.474	5.121	4.752	5.361	5.484	5.127	4.761	5.370
29	33	4.259	3.998	3.689	4.181	4.193	3.864	3.632	4.069	4.233	3.886	3.667	4.090	4.248	3.894	3.679	4.104
30	33	4.435	3.921	3.841	4.324	4.376	3.797	3.791	4.191	4.413	3.816	3.822	4.232	4.426	3.822	3.833	4.241

Table D40: IEC Simulated Results for Case 3 at 85% penetration level and DG located at Bus 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.580	12.822	9.318	12.105	10.568	12.810	9.307	12.090	10.575	12.816	9.312	12.100	10.578	12.819	9.315	12.103
2	132	10.115	10.993	8.843	10.676	10.095	10.978	8.826	10.654	10.105	10.985	8.834	10.668	10.111	10.989	8.839	10.672
3	132	6.192	6.087	5.381	6.195	6.175	6.076	5.367	6.175	6.183	6.081	5.373	6.187	6.188	6.084	5.377	6.191
4	132	8.260	7.816	7.182	8.181	8.224	7.794	7.152	8.139	8.239	7.803	7.164	8.163	8.250	7.810	7.173	8.172
5	132	7.517	6.978	6.540	7.363	7.509	6.973	6.533	7.355	7.513	6.976	6.537	7.360	7.515	6.977	6.539	7.362
6	132	9.772	9.034	8.502	9.602	9.704	8.995	8.443	9.518	9.726	9.008	8.462	9.562	9.749	9.022	8.483	9.583
7	132	6.185	5.696	5.367	6.035	6.170	5.687	5.354	6.018	6.177	5.691	5.360	6.028	6.181	5.693	5.363	6.032
8	132	7.272	7.055	6.331	7.234	7.236	7.032	6.300	7.190	7.248	7.040	6.310	7.214	7.260	7.048	6.321	7.225
9	33	16.121	16.197	14.005	16.370	16.072	16.149	13.963	16.355	16.094	16.163	13.981	16.359	16.108	16.173	13.994	16.371
10	33	19.434	18.203	16.862	19.195	19.338	18.105	16.780	19.173	19.392	18.135	16.826	19.198	19.415	18.148	16.845	19.218
11	11	23.102	27.589	20.126	26.264	23.079	27.568	20.107	26.251	23.089	27.576	20.115	26.252	23.096	27.583	20.121	26.258
12	33	16.210	15.141	14.074	15.980	16.169	15.103	14.039	15.972	16.193	15.117	14.059	15.983	16.202	15.122	14.067	15.992
13	11	25.590	30.916	22.247	29.879	25.562	30.890	22.224	29.859	25.577	30.904	22.236	29.867	25.584	30.911	22.242	29.873
14	33	8.277	7.725	7.172	8.070	8.264	7.714	7.161	8.069	8.273	7.719	7.169	8.075	8.275	7.721	7.171	8.077
15	33	13.166	12.008	11.413	12.748	13.125	11.962	11.378	12.738	13.150	11.975	11.400	12.752	13.159	11.980	11.407	12.760
16	33	10.277	9.753	8.908	10.134	10.257	9.735	8.891	10.131	10.269	9.742	8.901	10.138	10.274	9.744	8.905	10.142
17	33	13.473	12.574	11.680	13.196	13.433	12.536	11.646	13.190	13.457	12.549	11.666	13.202	13.466	12.554	11.674	13.211
18	33	8.696	8.003	7.534	8.404	8.680	7.986	7.521	8.402	8.691	7.992	7.529	8.408	8.694	7.994	7.532	8.411
19	33	9.191	8.340	7.963	8.854	9.174	8.323	7.949	8.821	9.186	8.329	7.958	8.833	9.189	8.331	7.961	8.835
20	33	9.543	8.795	8.268	9.233	9.523	8.776	8.251	9.231	9.536	8.783	8.262	9.239	9.540	8.785	8.266	9.243
21	33	15.588	14.253	13.514	15.094	15.504	14.156	13.442	15.072	15.555	14.183	13.485	15.099	15.574	14.194	13.501	15.116
22	33	15.151	13.973	13.134	14.746	15.060	13.863	13.056	14.720	15.115	13.894	13.103	14.750	15.135	13.905	13.120	14.768
23	33	8.554	8.018	7.410	8.331	8.514	7.960	7.377	8.318	8.539	7.974	7.397	8.331	8.547	7.979	7.405	8.339
24	33	11.237	10.415	9.735	10.900	11.088	10.178	9.607	10.780	11.176	10.226	9.682	10.825	11.209	10.245	9.711	10.855
25	33	7.928	7.805	6.867	7.887	7.531	7.090	6.524	7.566	7.739	7.204	6.704	7.654	7.839	7.262	6.791	7.743
26	33	3.188	3.015	2.761	3.167	3.129	2.909	2.710	3.043	3.164	2.929	2.741	3.084	3.177	2.937	2.752	3.093
27	33	11.562	11.961	10.017	11.842	10.113	9.257	8.763	10.448	10.768	9.549	9.329	10.673	11.169	9.759	9.683	11.019
28	132	5.635	5.213	4.831	5.504	5.578	5.181	4.842	5.426	5.588	5.187	4.850	5.462	5.611	5.200	4.871	5.484
29	33	26.227	32.757	22.696	31.918	9.727	6.341	8.425	9.886	14.340	6.832	12.413	12.656	18.500	7.391	16.182	16.599
30	33	6.614	6.312	5.727	6.639	5.679	4.390	4.919	5.435	6.073	4.528	5.259	5.566	6.341	4.627	5.496	5.790

Table D41: IEC Simulated Results for Case 4 at 85% penetration level and DG located at Bus 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.574	12.816	9.312	12.100	10.563	12.805	9.302	12.087	10.569	12.811	9.308	12.095	10.572	12.814	9.310	12.098
2	132	10.105	10.985	8.833	10.667	10.086	10.971	8.818	10.647	10.096	10.978	8.826	10.660	10.101	10.982	8.830	10.664
3	132	6.183	6.081	5.373	6.187	6.167	6.071	5.360	6.169	6.175	6.076	5.366	6.180	6.179	6.078	5.370	6.184
4	132	8.238	7.803	7.163	8.162	8.206	7.783	7.136	8.125	8.220	7.792	7.148	8.147	8.229	7.798	7.156	8.155
5	132	7.513	6.975	6.537	7.360	7.506	6.972	6.531	7.353	7.510	6.974	6.534	7.357	7.512	6.975	6.536	7.359
6	132	9.725	9.008	8.461	9.561	9.662	8.972	8.408	9.486	9.685	8.985	8.427	9.526	9.705	8.997	8.445	9.545
7	132	6.177	5.691	5.359	6.028	6.163	5.683	5.348	6.012	6.169	5.687	5.353	6.021	6.173	5.689	5.356	6.025
8	132	7.248	7.040	6.309	7.213	7.214	7.019	6.281	7.173	7.227	7.027	6.292	7.195	7.238	7.033	6.301	7.205
9	33	16.093	16.176	13.981	16.347	16.048	16.133	13.943	16.333	16.069	16.147	13.960	16.338	16.082	16.155	13.971	16.349
10	33	19.390	18.173	16.824	19.158	19.305	18.086	16.751	19.139	19.354	18.113	16.793	19.163	19.374	18.125	16.810	19.181
11	11	23.088	27.576	20.114	26.252	23.067	27.557	20.097	26.240	23.077	27.565	20.104	26.242	23.083	27.571	20.110	26.247
12	33	16.192	15.128	14.058	15.964	16.155	15.095	14.026	15.957	16.177	15.107	14.045	15.968	16.185	15.112	14.052	15.976
13	11	25.577	30.903	22.236	29.866	25.552	30.880	22.214	29.848	25.566	30.893	22.226	29.855	25.572	30.898	22.231	29.861
14	33	8.272	7.722	7.169	8.066	8.261	7.712	7.159	8.065	8.269	7.717	7.166	8.071	8.271	7.718	7.167	8.073
15	33	13.149	11.996	11.399	12.734	13.113	11.955	11.368	12.726	13.136	11.968	11.388	12.739	13.144	11.972	11.394	12.746
16	33	10.269	9.747	8.901	10.127	10.251	9.731	8.886	10.125	10.263	9.738	8.895	10.131	10.266	9.740	8.898	10.135
17	33	13.457	12.563	11.666	13.182	13.421	12.529	11.635	13.177	13.443	12.541	11.654	13.189	13.450	12.545	11.660	13.196
18	33	8.690	7.999	7.529	8.399	8.676	7.984	7.517	8.398	8.686	7.989	7.525	8.404	8.688	7.991	7.527	8.406
19	33	9.185	8.336	7.958	8.848	9.170	8.320	7.945	8.819	9.180	8.326	7.954	8.829	9.183	8.328	7.956	8.831
20	33	9.536	8.790	8.262	9.227	9.518	8.773	8.247	9.226	9.530	8.779	8.257	9.233	9.533	8.781	8.260	9.236
21	33	15.554	14.228	13.484	15.064	15.479	14.142	13.420	15.045	15.526	14.167	13.460	15.071	15.541	14.176	13.473	15.086
22	33	15.114	13.945	13.102	14.714	15.033	13.848	13.032	14.691	15.083	13.876	13.075	14.720	15.100	13.885	13.090	14.736
23	33	8.538	8.005	7.397	8.317	8.503	7.953	7.367	8.306	8.525	7.966	7.386	8.318	8.532	7.970	7.392	8.325
24	33	11.173	10.362	9.680	10.839	11.041	10.152	9.566	10.732	11.121	10.196	9.635	10.774	11.149	10.212	9.659	10.800
25	33	7.733	7.626	6.698	7.694	7.392	7.005	6.404	7.425	7.577	7.109	6.563	7.508	7.659	7.158	6.636	7.582
26	33	3.163	2.993	2.740	3.143	3.111	2.899	2.695	3.033	3.143	2.917	2.722	3.068	3.154	2.924	2.732	3.076
27	33	10.746	11.151	9.310	11.048	9.603	8.954	8.321	9.931	10.142	9.213	8.787	10.128	10.449	9.382	9.058	10.394
28	132	5.587	5.186	4.850	5.461	5.534	5.156	4.805	5.391	5.547	5.163	4.815	5.425	5.567	5.175	4.833	5.443
29	33	6.270	6.329	5.430	6.366	5.363	4.487	4.645	5.308	5.747	4.634	4.977	5.427	6.005	4.746	5.205	5.641
30	33	26.456	32.965	22.894	32.078	9.765	5.901	8.458	9.733	14.540	6.373	12.586	12.838	18.718	6.849	16.370	16.780

Table D42: IEC Simulated Results for Case 5 at 85% penetration level and DG located at Bus 7 and 29

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	kV	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG	3-Ph	LG	LL	LLG
1	132	10.730	13.027	9.447	12.305	10.561	12.806	9.303	12.086	10.647	12.885	9.375	12.155	10.682	12.918	9.406	12.186
2	132	10.420	11.462	9.105	11.094	10.100	10.982	8.832	10.620	10.256	11.100	8.964	10.780	10.323	11.153	9.023	10.839
3	132	6.372	6.381	5.535	6.430	6.175	6.076	5.368	6.154	6.270	6.136	5.448	6.251	6.312	6.163	5.485	6.288
4	132	8.667	8.476	7.533	8.696	8.235	7.800	7.163	8.102	8.437	7.919	7.335	8.315	8.530	7.974	7.417	8.398
5	132	8.103	7.892	7.046	8.103	7.558	7.001	6.578	7.333	7.812	7.142	6.795	7.586	7.926	7.207	6.897	7.687
6	132	10.736	10.557	9.334	10.790	9.754	9.023	8.490	9.458	10.191	9.266	8.864	9.928	10.405	9.386	9.056	10.125
7	132	8.997	10.056	7.798	9.820	6.518	5.886	5.658	6.421	7.471	6.365	6.480	7.089	8.003	6.627	6.962	7.601
8	132	7.624	7.643	6.634	7.693	7.237	7.033	6.302	7.150	7.416	7.143	6.455	7.341	7.500	7.196	6.530	7.417
9	33	16.394	16.375	14.238	16.584	16.089	16.163	13.979	16.400	16.228	16.252	14.097	16.471	16.296	16.297	14.157	16.522
10	33	19.694	18.351	17.084	19.398	19.330	18.103	16.774	19.190	19.511	18.203	16.927	19.293	19.589	18.248	16.996	19.354
11	11	23.234	27.710	20.239	26.372	23.091	27.580	20.118	26.276	23.155	27.637	20.171	26.309	23.187	27.668	20.200	26.334
12	33	16.357	15.223	14.199	16.098	16.167	15.104	14.038	15.984	16.262	15.156	14.118	16.041	16.302	15.179	14.153	16.073
13	11	25.693	31.013	22.334	29.967	25.565	30.893	22.226	29.872	25.627	30.950	22.278	29.911	25.654	30.978	22.302	29.934
14	33	8.307	7.742	7.198	8.096	8.259	7.711	7.157	8.067	8.286	7.727	7.180	8.086	8.295	7.732	7.188	8.094
15	33	13.239	12.048	11.476	12.810	13.109	11.953	11.365	12.730	13.180	11.992	11.425	12.777	13.206	12.006	11.448	12.800
16	33	10.335	9.787	8.957	10.182	10.254	9.733	8.888	10.134	10.296	9.758	8.924	10.160	10.313	9.768	8.939	10.174
17	33	13.582	12.636	11.773	13.284	13.426	12.533	11.641	13.194	13.507	12.578	11.709	13.243	13.539	12.596	11.737	13.270
18	33	8.727	8.020	7.561	8.431	8.674	7.983	7.515	8.400	8.704	7.999	7.541	8.420	8.714	8.005	7.550	8.429
19	33	9.228	8.360	7.994	8.883	9.168	8.320	7.944	8.813	9.201	8.337	7.972	8.845	9.213	8.344	7.982	8.855
20	33	9.587	8.820	8.306	9.271	9.517	8.772	8.247	9.230	9.555	8.793	8.279	9.255	9.569	8.801	8.291	9.267
21	33	15.720	14.324	13.626	15.199	15.476	14.141	13.418	15.057	15.607	14.211	13.529	15.139	15.657	14.239	13.573	15.181
22	33	15.273	14.039	13.238	14.843	15.025	13.844	13.026	14.699	15.160	13.918	13.141	14.784	15.210	13.947	13.185	14.827
23	33	8.577	8.030	7.430	8.351	8.493	7.947	7.358	8.300	8.542	7.975	7.400	8.333	8.558	7.985	7.414	8.347
24	33	11.257	10.421	9.752	10.916	10.996	10.127	9.528	10.698	11.148	10.211	9.658	10.793	11.200	10.240	9.704	10.840
25	33	7.830	7.723	6.782	7.807	7.258	6.925	6.288	7.310	7.571	7.105	6.558	7.488	7.696	7.179	6.668	7.598
26	33	3.177	3.007	2.752	3.158	3.092	2.888	2.678	3.018	3.144	2.918	2.723	3.071	3.161	2.927	2.738	3.084
27	33	11.044	11.502	9.567	11.322	9.151	8.688	7.930	9.535	10.065	9.165	8.720	10.010	10.514	9.412	9.118	10.390
28	132	5.850	5.606	5.076	5.789	5.527	5.152	4.800	5.372	5.668	5.232	4.919	5.520	5.743	5.276	4.987	5.589
29	33	15.380	19.040	13.310	18.586	6.498	5.111	5.629	6.713	9.316	8.533	8.065	8.377	11.392	6.343	9.950	10.375
30	33	6.208	5.987	5.376	6.274	5.037	4.116	4.363	4.851	5.579	4.337	4.832	5.170	5.863	4.452	5.084	5.420

Table D43: IEC Simulated Results for Case 6 at 85% penetration level and DG located at Bus 26 and 30

Bus		Wind				PV				Hybrid				Diesel Hybrid			
No	**kV**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**	**3-Ph**	**LG**	**LL**	**LLG**
1	132	10.585	12.827	9.322	12.108	10.564	12.807	9.304	12.085	10.576	12.818	9.314	12.101	10.581	12.823	9.318	12.105
2	132	10.124	10.999	8.850	10.682	10.090	10.973	8.821	10.646	10.108	10.988	8.837	10.669	10.116	10.994	8.843	10.676
3	132	6.201	6.093	5.389	6.201	6.172	6.074	5.364	6.170	6.187	6.084	5.377	6.189	6.194	6.088	5.383	6.195
4	132	8.282	7.829	7.201	8.197	8.218	7.791	7.147	8.128	8.250	7.810	7.173	8.169	8.266	7.819	7.187	8.183
5	132	7.519	6.979	6.542	7.364	7.507	6.972	6.531	7.352	7.514	6.976	6.538	7.360	7.517	6.978	6.540	7.362
6	132	9.808	9.055	8.533	9.629	9.686	8.985	8.428	9.491	9.740	9.016	8.474	9.570	9.773	9.035	8.504	9.599
7	132	6.192	5.699	5.372	6.039	6.166	5.685	5.350	6.012	6.179	5.692	5.362	6.029	6.185	5.696	5.367	6.034
8	132	7.287	7.064	6.343	7.244	7.223	7.024	6.289	7.173	7.252	7.042	6.313	7.215	7.269	7.053	6.328	7.230
9	33	16.197	16.284	14.071	16.443	16.090	16.162	13.979	16.389	16.146	16.198	14.027	16.412	16.172	16.216	14.050	16.434
10	33	19.607	18.413	17.011	19.353	19.379	18.132	16.816	19.249	19.516	18.208	16.933	19.327	19.563	18.236	16.974	19.371
11	11	23.141	27.625	20.160	26.303	23.090	27.579	20.117	26.270	23.116	27.602	20.138	26.280	23.128	27.614	20.149	26.291
12	33	16.271	15.215	14.127	16.030	16.178	15.110	14.047	15.995	16.235	15.142	14.096	16.029	16.254	15.153	14.112	16.046
13	11	25.636	30.961	22.287	29.929	25.573	30.901	22.233	29.881	25.610	30.935	22.264	29.903	25.623	30.949	22.276	29.916
14	33	8.292	7.747	7.186	8.080	8.263	7.714	7.161	8.073	8.284	7.726	7.178	8.088	8.288	7.728	7.182	8.093
15	33	13.241	12.105	11.478	12.816	13.145	11.974	11.396	12.772	13.205	12.006	11.447	12.808	13.224	12.016	11.464	12.825
16	33	10.304	9.790	8.931	10.155	10.260	9.737	8.894	10.141	10.289	9.753	8.918	10.159	10.297	9.758	8.925	10.167
17	33	13.535	12.654	11.734	13.248	13.442	12.542	11.654	13.214	13.501	12.575	11.704	13.250	13.519	12.586	11.720	13.267
18	33	8.720	8.038	7.555	8.423	8.684	7.988	7.524	8.412	8.708	8.002	7.544	8.427	8.715	8.005	7.550	8.434
19	33	9.216	8.376	7.985	8.891	9.177	8.324	7.951	8.816	9.203	8.338	7.973	8.842	9.210	8.342	7.979	8.847
20	33	9.571	8.835	8.293	9.256	9.526	8.777	8.254	9.242	9.556	8.794	8.280	9.261	9.564	8.799	8.287	9.269
21	33	15.763	14.466	13.665	15.255	15.555	14.186	13.486	15.153	15.683	14.254	13.596	15.229	15.725	14.278	13.633	15.268
22	33	15.353	14.217	13.308	14.937	15.124	13.901	13.111	14.817	15.264	13.978	13.232	14.900	15.310	14.004	13.272	14.943
23	33	8.658	8.150	7.501	8.436	8.557	7.985	7.414	8.374	8.617	8.019	7.466	8.407	8.639	8.032	7.484	8.427
24	33	11.764	11.017	10.191	11.480	11.333	10.318	9.819	11.069	11.571	10.444	10.024	11.188	11.670	10.499	10.111	11.275
25	33	10.358	10.609	8.971	10.564	8.590	7.725	7.442	8.750	9.415	8.101	8.155	9.118	9.864	8.322	8.553	9.499
26	33	14.350	17.910	12.418	17.543	5.899	4.248	5.109	5.965	8.336	4.753	7.216	7.569	10.380	5.176	9.075	9.551
27	33	11.364	11.949	9.845	11.722	9.425	8.868	8.167	9.585	10.385	9.346	8.997	10.349	10.848	9.596	9.407	10.749
28	132	5.646	5.220	4.901	5.511	5.545	5.162	4.814	5.389	5.581	5.183	4.845	5.453	5.612	5.201	4.872	5.482
29	33	5.979	6.101	5.178	6.120	4.841	4.230	4.193	4.837	5.373	4.467	4.653	5.098	5.648	4.593	4.897	5.324
30	33	15.717	19.363	13.601	18.869	6.694	4.885	5.798	6.737	9.620	5.544	8.328	8.628	11.717	5.982	10.231	10.635