Power Electronics Considerations for Voltage Regulation and VAR Control Approaches in LV Distribution Networks - Hybrid Power Electronic Modules

By

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Abstract

The future substation depends on finding a way to mitigate the effects of the drawbacks of the conventional legacy by employing the efficiency of the solid state switches in light of changing the loading features by time such as Electrical Vehicles (EV) and Photo-voltaic (PV) cells. In distribution transformers the ratio between the primary voltage and the secondary voltage cannot be changed, and the use of the on-load taps changers are limited. Poor voltage regulation and reactive power transmission is a direct reason for losses and shortening the life of several devices. This research discusses the considerations of applying Power Electronics (PE) approaches and designs that provide additional functions in regulating the voltage and controlling the reactive power that is injected in the distribution network, using embedded fractional rated converters attached partially with the windings of the LV transformer. These approaches studies the possible considerations that have the potentials to enhance the unit with more flexibility in controlling the voltage and reactive power at the last mile of the network, in order to decrease the losses and meet the future expectations for low voltage networks modifications, and that by using a Power Electronic (PE) approach has less losses and more functionality depending on the reliability of transformer and intelligence of PE solutions.

The approach of a hybrid distribution transformer is introduced and its functionality in regulating the voltage and injecting reactive power is illustrated. A back-to-back converter is controlled according to the immediate need for voltage control and reactive power in Low Voltage (LV) networks, and for the purpose of controlling three unbalanced phases using two control strategies; resonant controller and vector control. The overall controller adds or decreases voltage (10%-20%) to/from the total output voltage in order to control the whole output voltage of the transformer. In addition, some loads need high amount of reactive power at last mile of the network, therefore the consideration of using switched capacitors technique is introduced to serve at the end-user side whereby its ability to provide automatic variable reactive power compensation in a closed loop system is illustrated. The considerations results indicate significant potentials for deploying PE in the last mile of the network by using innovative designs and suitable control functions with less losses and costs.

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To the people of Palestine, hopefully they will find peace and freedom one day.

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Declaration

I certify that the effort in this thesis has not previously been submitted for a degree or has it been submitted as part of requirements for a degree. I also certify that the work in this thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been duly acknowledged and referenced.

Signature of Student

Mohammed A. M. Radi

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List of Abbreviation

Abbreviation	Description
AC	Alternating Current
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DN	Distribution Network
DNO	Distribution Network Operator
DVR	Dynamic Voltage Restorer
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
HT	Hybrid Transformer
HV	High Voltage
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical And Electronic Engineers
LCNF	Low Carbon Network Fund
LV	Low Voltage
N	Neutral
NOP	Normally Open Point
OFGEM	Office of Gas and Electricity Markets
OLTC	On Load Tap Changer

PE	Power Electronics
PI	Proportional Integral
PV	Photo Voltaic
RES	Renewable Energy Sources
RIIO	Revenue = Incentives + Innovation + Outputs
RP	Reactive Power
SOP	Soft Open Point
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TSC	Thyristor Switched Capacitor
TCR	Thyristor Control Reactor
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner-Smaller Version of the UPFC
VCC	Voltage/VAR Control

1 Introduction

1.1 Background

Surveying the recent history of electrical power systems and the electrical industry reveals the rapidly increasing concern of power quality, and this term is becoming clearer and more important for both end users and electrical utilities stakeholders in terms of electricity generation, transmission and distribution [1]. The issues of the power quality, such as voltage levels and reactive power transmission, have many different solutions, which make optimum choices for the best quality complex, often necessitating creative combinations of several techniques by engineers. It is necessary to identify the problem type and characteristics in order to devise optimal solutions that provide power quality with cost efficiency, minimising the massive investment required for power infrastructure and maintenance [2].

Power Electronic (PE) intervention has several forms and impacts on the electrical network, especially in the transmission networks, wherein this technology has proved its efficiency in HVDC transmission, and studies are in progress to use it in other parts of the electrical network from generation down to LV distribution networks. However, there are several technical and business factors that need to be considered before applying PE approaches in novel areas of the network, such as making it commonplace in distribution networks. Therefore, more efforts are needed to prove that the cost and losses of deploying PE designs can be ignored comparison to the technical and long-term benefits, Also more characterisation is needed for novel designs that can meet the current and future network challenges with less losses and costs [3].

The anticipated increase in loads and demands is considered a great concern for the DNOs, as current networks lack capacity and space. The conventional approaches for meeting this concern are adding to existing network infrastructure, with more lines and equipment, but this becomes increasingly costly, and several queries have been made concerning the possibility of root solutions, thus an alternative approaches are being pursued nowadays in order to avoid the conventional approaches and reach an acceptable tender regarding costs and benefits. PE approaches and designs are being investigated in the context of network reinforcement, voltage regulation, reactive power transmission, line ratings, increasing demand and energy storage. Hence PE controllability and functionality is considered an important advantage for the network over conventional solutions, but the main acceptance standard is represented in the gained advantage factor over the cost factor. PE approaches have the potential of delaying any needed temporary adjustments in the network, which is considered helpful in deferring high cost network reinforcement, by releasing more capacity and relaxing limits such as voltage and thermal limits.

Albeit power electronics has been investigated and introduced for some years, it is still considered a new area of technology and there are several concerns regarding its practical abilities in network deployment. However, this technology is demonstrably acceptable in the transmission area, commonly in the form of HVDC, where it has a clear route from a business perspective. PE deployment in distribution networks started to gain attention recently due to the increased level of problems in the Low Voltage Level (LV) networks, whereby Distribution Network (DN) development level does not meet the level of updated load types and amounts, and extra efforts are needed to achieve a concept of balance between the supply networks improvements and the end-user updates.

It is noticed from Low Carbon Network Fund (LCNF) projects and proposals [4]-[8] that there is an indicator of taking the issue of deploying PE approaches into another phase of seriousness, indicating that there is a trend in starting to realise the advantages against costs for using PE in LV networks. However, one of the main power quality dimensions in PE is voltage limits, therefore several studies have been conducted on this issue at several places in the electrical networks, although its importance is high throughout the system. The components of distribution network are designed at specific ratings according to international standards regarding voltage and thermal limits, to ensure a minimum level of power quality and to avoid operation interruptions such as voltage collapse or blackout. Most of the conventional methods that deal with voltage problems are based on reinstalling high voltage power cables and inserting more stepping transformers beside the on load tap changers [9], [10].

Reactive power injection and transmission is also connected with voltage profile, as it is also constrained within the standard limitations, but it is noticed that installing a compensation device as close as possible to end-users is more efficient than insertion within networks, as it supports the capacity of the transferred power through transmission lines . Reactive power compensation of transmission happens mainly due to lines' reactive absorption and due to the phase angle between the voltage and the current at the load; this load is classified as inductive or capacitive load according to this angle. This difference in the angle contributes significantly in the concept of power quality.

1.2 Research motivation

Electricity is different from other commodities in that is difficult to store and it needs to be continuously available; the perfect supply would have the advantages of ubiquitous, any-time availability of supplying and the serenity of the voltage wave from noise within the standard limits of voltage and frequency. These properties are difficult to check before delivery to the production line in order to assay quality, and it is also necessary to find a concept for low power quality by computing how far we are from this perfect power supply service and quality [11]. This concept was developed during recent years according to the rapid development and increase and change of loads types in the electrical distribution system and facilities such as computers, UPS, faxes, printers, TVs, electric cars and PV cells. In general, their number has been on the rise recently in homes and offices, where the issue of power quality refers now in a large degree to end-user facilities and equipment rather than restricting and reducing the problem in the power supply intrinsically.

The future substation depends on finding a way to mitigate the effects of the drawbacks of the conventional legacy by employing the efficiency of the solid state switches in light of changing the loading features by time such as electrical vehicles (EV) [12] and PV cells [13]. In distribution transformers the ratio between the primary voltage and the secondary voltage cannot be changed, and the use of the on-load taps changers are limited. Poor voltage regulation and reactive power transmission is a direct reason for losses and shortening the life of several devices.

Conventional Low Voltage (LV) networks are operated according to strict voltage limits. The absence of tap-control at 11/0.4 kV substations makes localised voltage control difficult. Even when high voltage (HV) side taps are present, it may not be possible to resolve control for generation-rich and load-rich feeders on the same transformer. Power electronic (PE) converters offer the flexibility and controllability to better serve loads within existing voltage limits, or even to radically relax the power quality standard. The use of power electronics for last mile voltage control is not straightforward because retrofit is required to very tight space constraints in distribution sub-stations. The function of PE in the LV substation transformer is introduced in this thesis is to light on the voltage control considerations that are taken in controlling a proper hybrid solution with LV transformers, in order to provide additional abilities in regulating the voltage for unbalanced loading systems.

Also other consideration is taken by designing a hybrid solution that provides additional abilities in injecting reactive power at the last mile of the LV network. This topology aims to provide the LV substation unit with more flexibility in controlling the flow of reactive power in order to decrease the losses that are caused by transmitting reactive power through long transmission networks.

Alongside the voltage regulation and reactive power injection at the LV substation, an approach is needed beside the load in some cases to provide additional reactive power where there is standard limitation in transmitting reactive power through transmission lines. It has been found that local compensation is more efficient than transferring it through long journeys, as the latter are full of losses [10], whereby some inductive or capacitive loads need extra injection that cannot be supplied by fractional hybrid solutions, which causes a phase angle difference between the voltage and the current at the load [14]. This difference in the angle reaches its optimum value (excellent power factor) at 0 degrees, which is known as a pure resistive load; nonetheless this condition commonly does not exist in power system networks. Significant improvement in the power factor is required in the presence of such loads.

Proper voltage and VAR power regulation improves the quality of the delivered power and increases the expected life of LV network equipment, besides making a great step forward in improving power quality as an intrinsic characteristic.

1.3 Aim and objectives

This research aims to explore the feasibility of deploying power electronics in the last mile of the network, in order to address voltage regulation limits and reactive power compensation. Designs and topologies are to be conducted considering network conditions and solution sites, including scenarios based on the current and future expectations. The aim seeks choices for future hardware implementations of power electronics in distribution networks, by providing approaches on the trade-offs between control/flexibility function and cost. This aim is addressed through the following objectives:

1. To investigate the research area behind applying power electronics in electrical networks, especially LV networks.

2. To review the literature on conventional methods of voltage regulation and reactive power compensation in the last mile of the network, and the prospect of using PE converters for the previous purposes.
3. To address voltage regulation at LV substations through deploying low cost and low losses power converter design.
4. To provide the ability of supplying reactive power for high demand loads at the end-user according to the exact demand, depending on controlled switched capacitors.
5. To introduce innovative topology giving LV substations the ability to inject partial reactive power using PE approach, and depending on low rated solid state switches.
6. To apply new hybrid PE techniques at LV network from losses, cost and volume perspectives.
7. To scale-up the concept of power electronic transformer and PE LV substations according to the conditions of electrical networks.

1.4 Contributions to knowledge

This thesis discusses the considerations of designing and using PE equipment in distribution networks to provide additional functions in regulating the voltage and controlling the reactive power that is injected in the distribution network using hybrid solutions and fractional converters attached partially with the windings of the transformers. This approach aims mainly to enhance the unit with more flexibility in controlling the voltage during the last mile of the network, in order to decrease the losses and meet the future expectations for low voltage networks modifications, using PE approaches with less losses and more functionality (depending on the reliability of transformers and the intelligence of PE). The design of hybrid solution is a combination between the features of one of the most reliable network devices, the transformer, and the effect of flexible PE existence with less losses in both switching and conduction. Reduced ratings PE and controlled switches provides the load with immediate need for voltage and VAR control in Low Voltage (LV) networks.

Reactive power injection is also introduced at the beginning of the last mile of the network through a hybrid solution at the same point at which voltage regulation is introduced, offering to contribute in a specific percentage of reactive power that could be an important potential for current and future scenarios in LV networks, whereby flexibility in controlling the flow of reactive power percentage during the last mile of the network decrease the losses that are caused by transmitting.

The design of the PE modules is detailed and its functionality in compensating VAR power is discussed in the following chapters, but it is necessary to explain some components from the outset. Capacitance compensation circuits are designed after the substation and before the load as LV distribution network mid-feeder according to the switching capacitors technique, whereby the required value of the reactive power can be controlled according to the switching pattern associated with the semiconductor switches in the proposed compensator. This switching capacitors topology is controlled by modifying, adding and eliminating some components to reach a situation that achieves its optimum operation by providing the load with its exact need from VAR, without any reactive losses that incur extra PF problems.

If a voltage regulation limit of ±20% is taken into consideration by the regulator, the switches of the PE converter can be designed at fractional ratings (around 10-20%) of the total ratings of the LV transformer. The following functionalities for the hybrid transformer are considered:

- Voltage regulation of up to ±10% with no VAR control.
- Reactive power control of up to ±10% with no voltage control.
- A combination of both functionalities may be considered as long as the total rating of the PE module is not exceeded.

Conventional data and recent research regarding using PE in the last mile and transmission network is investigated on advanced equipment using conventional and non-conventional approaches. The results of these studies will inform the choice of future hardware implementations of substation power electronics by providing solid ground on the trade-offs between flexibility/control function, efficiency and cost. This study evaluates recent research and designs for the proper area regarding deploying PE in electrical networks in order to meet the challenges at that area that their solutions not carried out practically in the network. The introduced approach takes into consideration the losses and high costs that were introduced by several designs and approaches that meet various challenges currently and in future. The layout of the reached contribution to knowledge is shown in the following figure 1.1 for illustration

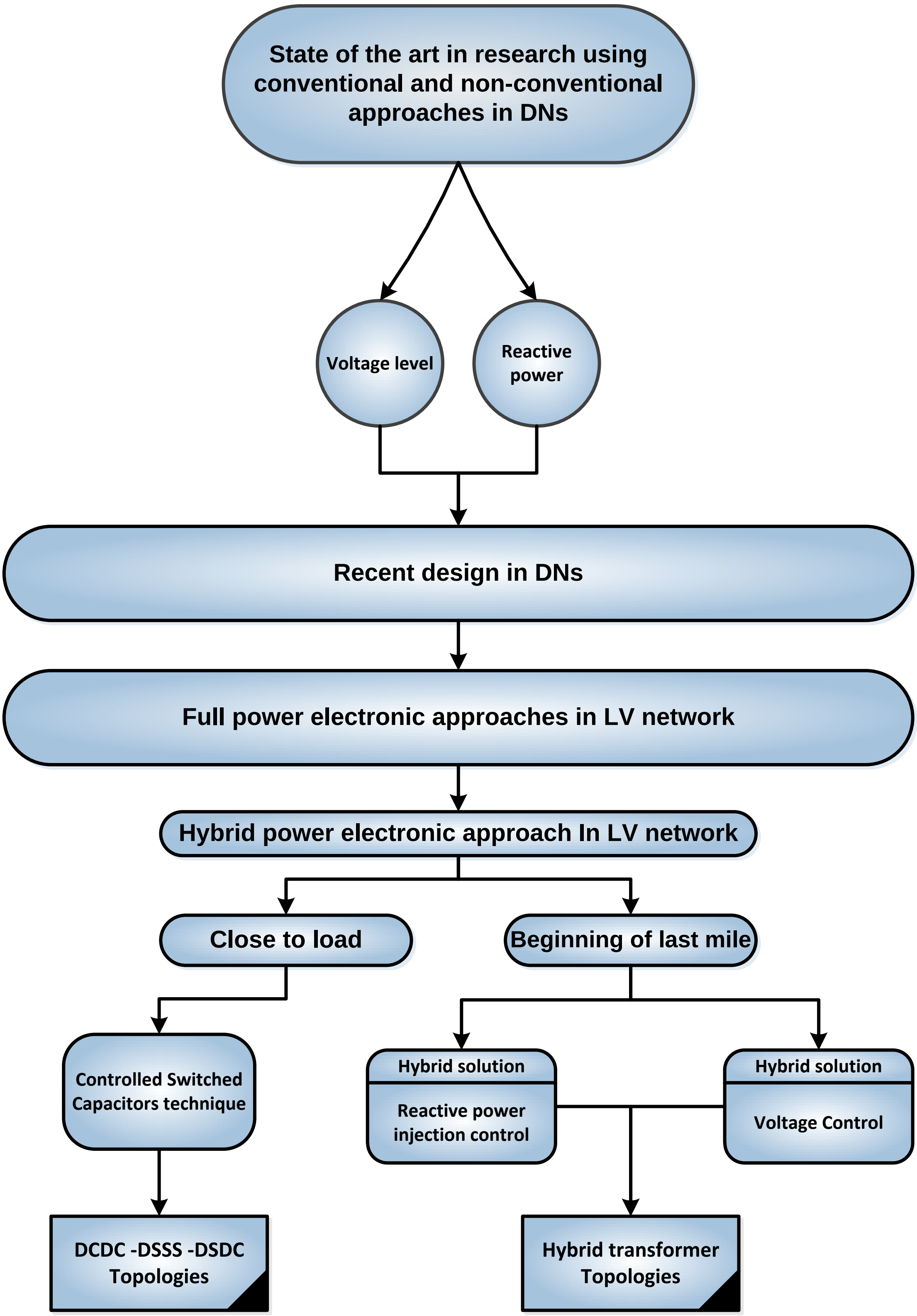


Figure 1.1: Thesis layout.

1.5 Thesis structure

The research is organised into seven chapters in order to meet the main aim of the thesis and mentioned objectives in section 1.3, as described below. Following the introduction chapter, the next six chapters include more details that enhance the theoretical background, operational techniques of using PE in LV networks, and more information regarding technical approaches that describes the concept of contribution to knowledge and thesis objectives.

Chapter two includes detailed background about the latest developments using PE approaches and projects in the whole network, especially in the last mile. It also represents the challenges that need to be met by power electronics devices in the LV network. Furthermore it explores several issues regarding power quality problems that could be solved using PE and conventional methods that are currently used by NGOs. The chapter also explores the cost-benefit analysis of using PE, and identifies obstacles that delay deploying PE approaches in the last mile of the network. Furthermore, it reviews the previous PE approaches used for voltage regulation and reactive power control purposes.

Chapter three introduces the background of power electronic technology and its fundamental importance in power conversion from different patterns, and it reviews the control strategies that are used to control the output of power semiconductor switches. Converter topologies are explored to explain their functions in transforming the forms of energy AC/DC/AC. PE switching patterns technique is also included in the third chapter related to the converter control topologies.

Chapter four discusses the problem of voltage regulation in the last mile of the network and the technical benefits of deploying a solution, besides showing the current and future need for such kind of potential in LV networks. Voltage drop scenarios are shown in the network by simulation according to different network condition in order to have a proper understanding of the problem in the last mile currently and in the near future. The behaviour of voltage profile and imbalances is demonstrated for different types of load before and after voltage regulation. Voltage regulation technique is applied through PE flexibility and control in order to address a solution, whereby partial fraction power electronics are used with less losses and cost, and without affecting the efficiency of performance.

Chapter five carries out the objective of providing an LV substation with the ability of supplying reactive power by controlling the injected reactive power at the beginning of the last mile network. The hybrid approach that is used is explained and different topologies and designs introduced for the purpose of injecting reactive power at the last mile of the network. This chapter explains the benefits behind providing the hybrid electronic substation with this property through design topologies and control techniques enabling the last mile of to provide part of the required reactive power. The hybrid solution is used depending on the object of minimising losses and cost in order to be amenable to projects of NGOs.

Chapter six discusses the application of switched capacitor circuits and their functionality in serving the need of load after the LV substation and close to the load. A comparison between two types of switched capacitor circuit is carried out in this chapter. The technique that is used is supported by automatic feedback for controlled Double Switch Double Capacitor (DSDC) circuit for reactive power compensation (a closed loop approach), and its control strategy is explained depending on the exact demand from load. Conclusions, explanations, and calculations are shown for each step of design.

Chapter seven summarises the main outcomes of the thesis and the achievement of the study aims. It also presents the conclusions of the tested techniques and objectives, highlighting the major contributions to knowledge and new routes for future research.

1.6 Publications

- M A. Radi, and M. Darwish. “Power electronics in Low voltage network - Voltage Regulation Consideration and Approaches.” *Research Conference (ResCon) 2012, Brunel University, 2012.*
- M. A. Radi, M. Darwish, and M. Alqarni. "Voltage regulation considerations for the design of hybrid distribution transformers." *Power Engineering Conference (UPEC), 2014 49th International Universities*. IEEE, 2014.
- M. A. Radi, and M. Darwish. "VAR control considerations for the design of hybrid distribution transformers." *AC and DC Power Transmission, 11th IET International Conference.* IET, 2015.
- M. A. Radi, M. F. Arman, and M. Darwish. “PSPICE Modelling of a Build-in Feedback Automatic –Reactive Power Compensation*” Abu Dhabi Research & Development Conference (ADRAC),* May 2015.

2 Literature Review

2.1 Introduction

Power Electronics (PE) has the potential of controlling and operating parts of the electrical systems at several points in electrical networks, producing novel thinking and approaches for replacing the electromechanical parts of the network, such as motorised tap changers, in order to reach a higher level of reliability and controllability in the overall performance. The usage of power electronics appears significantly nowadays in the transmission networks taking the form of HVDC, distributed generation, renewable energy sources and the control of maximising the usage of energy sources. However, the progress of utilisation the PE in LV networks known as Distribution Networks (DN) is not reasonable compared to the potential of this technology to add different flexible control functions to the last mile of the network, where it is needed nowadays and in the future, especially to meet the challenges of changing the features of the electrical systems and loading scenarios and types. However, there is a doubt that the current parts of the network are capable to handle the future expectations, such as charging a great number of electrical cars, or dealing with the DGs in the last mile of the network. Nonetheless, there is little deployment happening to retrofit the last mile of the network with PE.

The concept of using PE controllers in order to support the power networks operation gained some practical attention during the 1990s, which took the form of flexible AC transmission systems (FACTS) [15], several types of which have been accepted and deployed in reasonable ways to serve in the transmission network, such as SVCs, STATCOMs and Unified Power Flow Controller (UPFC), which has been used for the purpose of interfacing between the traditional part of the network and several applications such as DG and micro-grids, commonly based on renewable generation such as wind turbines and photovoltaics [3]. Also, High Voltage DC (HVDC) has been utilised in a significant number with higher ratings over time [16].

Several applications that can be used on DNs at the consumer side, such as voltage regulators, active power filter and some modified FACTS devices to be used at the consumer end (called D-FACTS) underpin much research on the use of power electronic transformer [17], [18]. However, there is a little evidence of using PE applications in the distribution network by the DNO (Distribution Network Operators) where power quality problems exist, and concurrently with appearance of Low Carbon Network Fund (LCNF) [19] established by OFGEM for the purpose of finding novel solutions to decrease carbon emissions, which led the DNO in the UK to start addressing PE applications as a solution for network problems.

The research in this area has been launched in several parts to address using the PE as a solution for the conventional electrical network. In the UK a lot of research has been conducted by Hubnet and top and tail projects [7], [8], [18], beside other individual researches in several research departments. However, it is obvious that the converters and PE devices are developing over time to meet several challenges regarding their criteria, functions and marketability, while on the other hand the network intervention by the PE applications is not supposed to be applied to solve immediate issues and problems, as it is intended to be inserted among conventional parts in power system networks. Interventions are thus limited for anticipated future trends in the power system industry, such as loads amount, loads type and specifically renewable energy interventions. However, meeting these expectations and requirements will make applying the PE in the network more reliable and likely to be adopted by the electrical infrastructure market.

This chapter explores the slow uptake of PE in the LV network (i.e. the DN) to highlight potential solutions for DNOs to adapt this view and attract their interest in the networks development process over the next two or three decades. It also includes the previous research and perspectives on the intervention of PE in both transmission and distribution networks to meet some of the main electrical networks challenges and functions. This chapter also shows the possibility of using the PE in last mile of the electrical network and removing a lot of the barriers between their functionality and the possibility of applying them in the network depending on their known flexibility in adapting the function of the conventional network parts.

2.2 Characteristics of LV distribution networks

In the UK transmission networks operate at 400V, 275KV and 132KV depending on the route of transmission and distance, while the LV network distribution network operates at 33KV, and 11KV, where it is transformed to 400V at the end users (e.g. domestic areas) or the last mile of the network. However, there is research debate about modifying and reviewing those voltage levels depending on several factors; furthermore, those rates are particular to the UK and other regions following British standards, and are not universal [7], [20]. Distribution networks are normally radial networks that use double line at the 33KV area and single line at the 11KV area, containing some connection points for protection purposes in order to cut off the line in case of planned outages and unplanned blackouts. DN are designed according to the assumptions that it serves loads at the last mile without any intervention for any kind of generation sources connected at the end users and depending on previous assumptions for the load amount required for the end-user.

The voltage regulation principle is applied in the LV network (normally 33KV to 11KV) by adjusting the voltage variations in this area using on/off tap changers that are equipped in the transformers that are connected at the beginning of the networks, where every tap is done by a specific planned strategy depending on the load variations that affect the voltage level. Although this method is used as a voltage regulation approach, some remote controllers are used to do switching actions in the meaning of upgraded tap changers in order to meet the voltage drops that are caused by the line drops compensation. Reference [15] contains a lot of network examples that are used in UK for power systems in general and reference [21] covers the scenarios that are applied in the case of distribution network in UK beside the issue of generation sources (embedded generation) at the last mile that is found in reference [22].

2.3 Challenges in distribution networks

Nowadays, with the recent development in the loads types and amount, several difficulties started to face distributing the energy to the last mile of the network (mainly 11KV/ 400V), such as:

- The increased intervention of Renewable Energy Sources (RES) within the borders of the distribution networks, raising issues regarding the voltage regulation and reactive power transmission through the network, both of which are related to each other, as clustering several DGs could lead to reversed power in some of the feeders, which affects the voltage level and the reactive power drawing in the DNs. This scenario could be noticed in rural areas due to the effect of wind turbines and farms, and in urban areas due to the effect of using the solar panels.
- The demand is increasing and the amount of load that conventional transformers and feeders were designed to feed is anachronistic, especially given likely future increases from usage of electrical vehicles (EV) and heat pumps [23]. This phenomena address voltage and capacity problems.
- The legacy system distribution network in the UK is antiquated and needs to be overhauled with new equipment, which is considered a great chance for

upgrading and not just replacing, in order to meet current requirements and future expectations.

- The amounts of harmonics and returning currents are increasing due to renewable energy penetration, and it is clear that the current feeders, transformers and tap changers are not capable of dealing with such problems [24].
- The difficulties will be increased in detecting the fault in the DNs in case of the existence of DGs.
- The reduced or increased power flow through the transformer due to increased demand or DGs existence respectively may affect the life cycle of transformers.
- The use of On/Off Load Tap changers (OLTC) is limited due to the expenses, and the transformer has a specific number of taping operations before reaching the end point of serving in the network, which means that it is not reliable to meet daily or hourly problems such as voltage variations caused by the previous factors [25].

In light of these challenges, modifications and upgrading are needed to address solutions for the current situation and expected future scenarios, but without causing undue disruption to the network and ensuring a high level of flexibility and reliability. Some of these challenges are technical issues resulting from the disability of control in the DN and the limitations of solid state switches. The following sub-sections address some of those technical issues in more details, as illustrated in the following diagram figure 2.1.

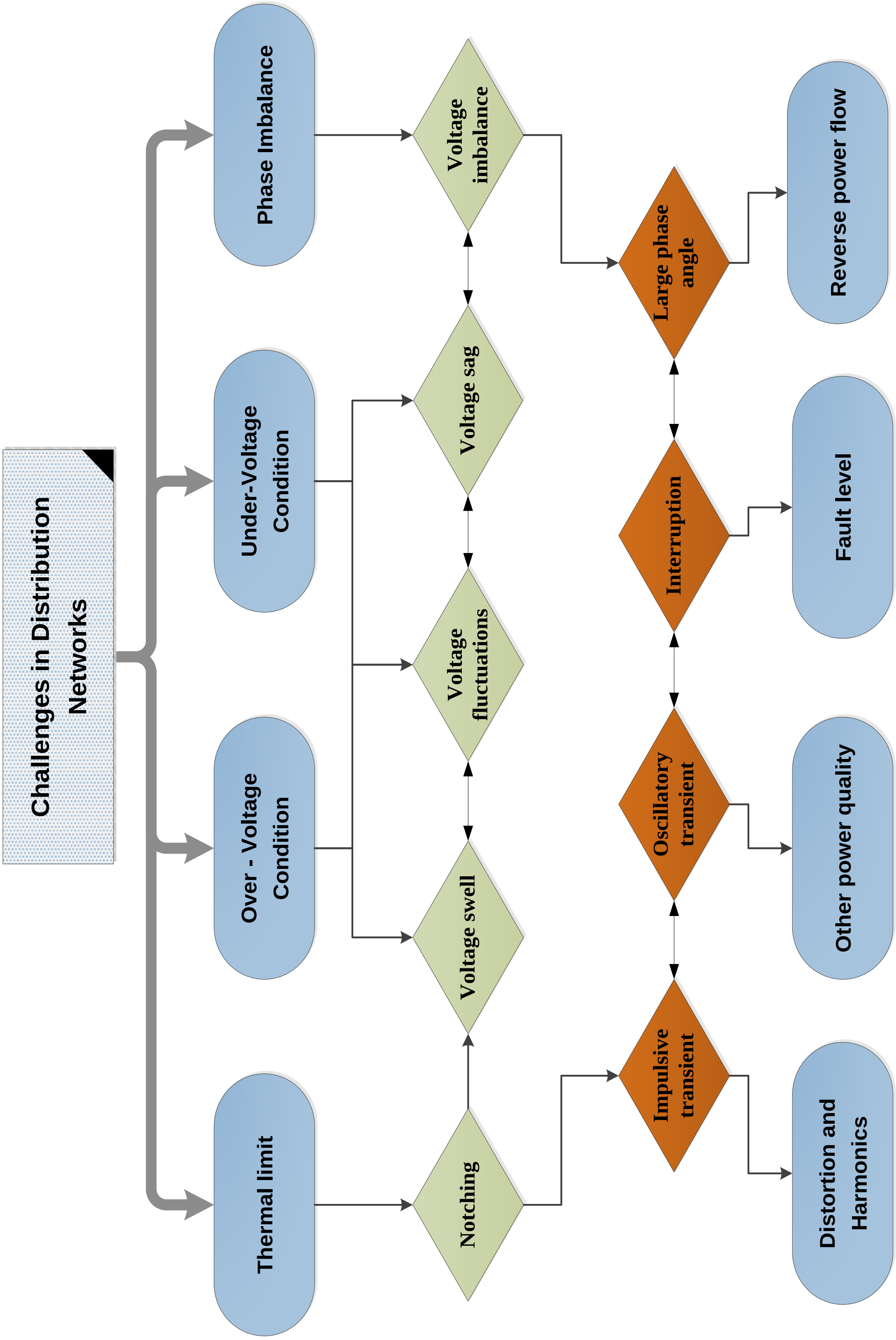


Figure 2.1: Challenges and problems in distribution networks.

2.3.1 Under-voltage condition

The voltage drops occurs along the feeders due to the differences voltages at the sending and receiving ends of the feeders, which is represented by:

$$\Delta V = |V_s| - |V_R| \approx \frac{RP_R + XQ_R}{|V_R|} \tag{2.1}$$

The distribution has a resistive nature more than the other types of networks, as the feeder lines have a relatively low X/R ratio equal to about 0.3 for the 400V cables, 1 for the 11KV lines and 3 in the 33KV area, which means that the flow of real power affects the voltage level more than the reactive power in the DN, whereas it is the opposite in the case of transmission networks. Heavy demand in the last mile of DNs causes high voltage drops, which could be treated by taping up the tap changers in order to compensate for the voltage difference at the primary side of the transformer, which action raises the voltage for all feeders, which are normally in three phases, causing high voltage for the other phases or feeders that do not face voltage drops, which sometimes could lead to exceed the voltage regulation limits, especially for loads close to the transformer.

Heavy loading future scenarios are expected to be caused by Electric Vehicles (EVs) and heat pumps operation, which could lead to one of the following two scenarios [26]:

- Long feeders are limited due to voltage drops across their long length; or
- Short feeders are thermally limited before reaching their voltage limits.

On the other hand, a recent study that investigated several lines in the UK networks stated that about 75% of lines in medium lengths are subject to voltage drops limitations rather than the thermal limitations under heavy loading [26]. Solutions have been investigated by the DNOs to overcome the voltage drop problem in traditional approaches, which means replacing the cables with larger capacity ones, shortening the lines by installing more substations, installing more transformers with more density and capacity, and installing manual tap changer at the secondary side of the last mile transformer 11KV/400V, which is rare or not logical in the case of the UK. Such approaches could contribute in solving the voltage drop issues, but they are considered impractical solutions due to the expenses and difficulties of inserting manual tap changers close to end users, although this could help in regulating the voltage for a specific number of times before reaching the end of life cycle.

2.3.2 Network X/R ratio

The X/R ratio specifies the difference between the distribution and transmission network as it describes the resistive or inductive nature of the network [27]-[29], which indicates the need of the network either for voltage or reactive power. In order to understand the nature of the network, it is important to identify the process of resistance/ reactance change [7], [30].

Two main effects cause the difference between the AC resistance and DC resistance: proximity y_p and skin effect y_s. The R_{AC} of a line can be calculated as shown in equation (2.2) by taking into account both effects (according to BS IEC 60287---1 standards):

$$R_{AC} = R_{DC}\,(1 + y_s + y_p) \tag{2.2}$$

For lines delivered under 5KV, the skin effect is calculated according to equation (2.3) [7], [27]-[29] :

$$y_s = \frac{x_s^4}{192 + 0.8.\,x_s^4} \tag{2.3}$$

$$\text{Where } x_s = \sqrt{\frac{8\pi.f}{R_{DC}}.\,10^{-7}\,K_s}$$

The proximity effect y_p is calculated according to the nearness of lines and cables beside each other, therefore the effect for single line delivers under 5KV is calculated by equation (2.4).

$$y_p = \frac{x_s^4}{192 + 0.8.\,x_s^4}\cdot\left(\frac{d_c}{l_s}\right)^2\left[0.3.\left(\frac{d_c}{l_s}\right)^2 + \frac{1.17}{\frac{x_p^4}{192 + 0.8.\,x_p^4} + 0.27}\right] \tag{2.4}$$

Whereby x_p is calculated as in equation (2.5):

$$x_p = \sqrt{\frac{8\pi . f}{R_{DC}} . 10^{-7} K_p} \quad (2.5)$$

Where:

d_c is the conductor diameter.

l_s is the mean geometric distance between the line centres.

K_p is the round conductor constant (which is very small).

K_s is the standard conductor constant (which is very small).

As long as the operation of the AC frequency is 50 Hz in the normal operation, then the skin and proximity effects change will have a minor effect on the difference between AC and DC resistance. This minor effect can be seen from figure 2.2, where the values change for the cable over the conductor area can be seen [7].

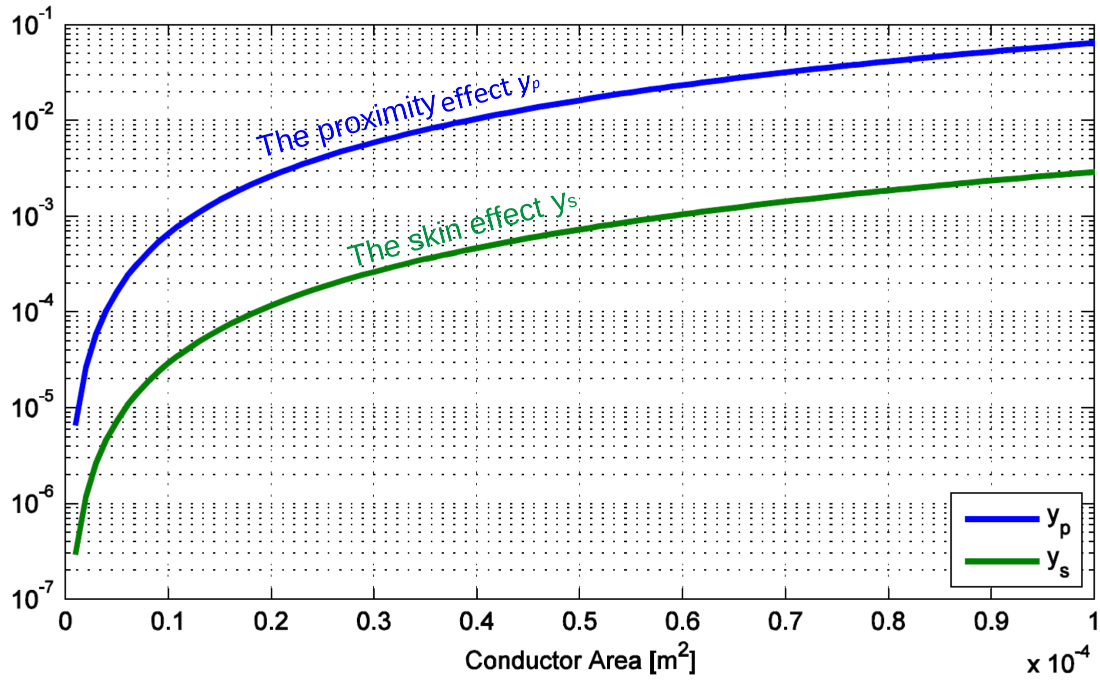


Figure 2.2: Skin and proximity effect in different conductor areas.

Where the following assumptions have been taken into consideration:

$$f = 50\ [Hz]$$

$$l_s = \frac{d_c}{2} \; [m]$$

$$R_{DC} = \frac{1.67\,E-8}{A_C} \; [\Omega m^{-1}]$$

$$d_c = 2.\sqrt{\frac{A_C}{\pi}} \; [m]$$

The reactance of a cable depends on two main factors, the internal and the external reactance. The internal reactance is produced due to the internal flux in the wire and its calculation could be done as in equation (2.6):

$$I_{internal} = \frac{\mu}{8\pi} \tag{2.6}$$

The external inductance is calculated for a single wire among there phase wires as:

$$I_{\,external} = \frac{\mu}{2\pi} \ln\left(\frac{D}{D'}\right) \tag{2.7}$$

Where:
D is the area between the centres of the three wires, assuming equal distances between them; and D’ is the self-distance of a stranded or solid wire, which is radius of the wire in another meaning.

The reactance equations indicate that the inductance could be decreased by decreasing the distance between the lines or by using conductors with increased radiuses, which is the same as increasing the cross sectional conductor area.

There is a difference in the X/R ratio between the LV network cables and transmission overhead lines. In LV network the three phase cables are sealed together in one single line. Nevertheless, the case in the transmission lines is that they are insulated and separated by air between them, which means there is a distance between the overhead cables more than would exist in underground cables.

It is clear from that difference that X/R ratio is lower for LV cables than for HV transmission lines. The self-distance could be increased by bundling lines together from the same phase by using separators between them, which makes the inductance lower, but the effect would not be significant as the air distance between lines is much more than the separators distances. Bundled cables are usually used in the urban public areas, which makes the idea of supplying reactive power in this area more interesting and attractive currently and in the near future.

2.3.3 Over voltage condition

The introduction of solar systems in the networks may lead to reversal of power flow in the networks, which would raise the voltage level, in contrast to the case of usual voltage drops. According to this phenomenon, the voltage limits may be exceeded to be over the allowed upper voltage limit. This issue has been started to be noticed in Germany according to several reports about areas that contain a high amount of PV cells [13], where voltage risings have occurred [31]. The Orkney Isles in north-eastern Scotland contain a large number of wind turbines feeding the electrical network, which sometimes causes over voltage conditions due to reversal power. This situation leads the operator management to install active controller management to cut off some wind turbine generators when needed, in order to avoid reaching the upper limit of voltage level [32].

2.3.4 Reverse power flow

Current network equipment such as cables and transformers are able to accommodate the flow of the reverse power subject to the voltage limits constraints, but in practice most of the protection devices and control equipment are designed according to the practical fact of unidirectional power flow. According to that practical fact, line drop compensators across the feeders (especially at the 33KV) and protection devices are designed to track the reverse current or power as a fault. So any power flow management equipment introduced should take into consideration the principle fact beside the practical fact and adapt the management of reverse power flow [33], [34].

2.3.5 Phase imbalance

Most of the domestic and commercial loads in the UK and EU are single phase loads that take their supply from a three phase feeder, which means that imbalances are expected due to uneven loading, whereby each load has its own demand, and each load has its own time varying pattern. The imbalances loading issue could address several problems such as:

- Higher conduction losses in imbalance feeders more than the balanced lines.
- More complex difficulties in dealing with the over/under voltage cases.
- More return currents in the neutral line of the three phase system.

- Imbalances problems reduce the capacity and utilisation of the network

However, the lack of monitoring for each phase in the DN (due to technical difficulties) deepens the problem, whereby depending on the expectations and recording the line connections do not yield a solution. A novel strategy is needed to accommodate this issue in the network. In terms of Low Carbon Network Fund (LCNF), imbalances incidences are considered a major issue that affect the capacity limit of the transmission and distribution network [35].

2.3.6 Fault level and thermal limit

Networks are normally designed to operate continuously without interruption; on the other hand they are designed to face any fault by interruptions. A lot of distribution lines and feeders have a high level of faults which cannot be higher for the whole safety of the network and the problem is faced by only circuit breakers as a protection strategy [36], [37]. A recent study showed that most faults occur due to the distributed generators (DG) having induction or synchronous machines, such as wind turbines, whereas the percentage of faults is less in case of PV cells, as the solar systems normally have their own control strategies that prevent output in case of faults conditions [38]. DNOs take into consideration the existence of DGs and their associated PE equipment, which could lead to interrupting supplying due to cluster DGs. Currently, faults are treated by splitting fault area or the connected transformer and supply the loads by another transformer or substation, which means less safety and more congestion on some feeders and transformers [36], [37].

Furthermore, demand increases and the type of demands changes over time, the power flow increases in the network through the feeders and electrical equipment, such as transformers. Eventually the thermal limit of the lines and transformers will be increased, regardless of the voltage limits, whereas sometimes the thermal limit exceeds the allowed limit before reaching the voltage limit. The absence of the ability to control the power flow directions by operators causes congestions in the feeders and transformers at the peak times, which pushes the operators to introduce a solution by preventing and limiting the transmission of power through specific lines at times of peak demand.

The thermal limit is subject to seasonal reasons, times, weather temperature and equipment designs. Some equipment takes into consideration a cooling time overnight, which is considered dynamic and flexible, and several factors can be used in this way to benefit the release of network capacity.

2.3.7 Distortion and harmonics

The existence of PE converters and the process of conversion from AC/DC/AC contribute in generating waveform distortion, which is represented in low order harmonics caused by high frequency switching or pulse width modulation (PWM). Harmonics means more losses in the networks that take usually the form of heat in the cables and equipment, and contributes in shortening the life cycle of the devices, posing serious risks [39].

2.4 Power electronics role in distribution networks

It is clear for DNOs and investors that the intervention of PE solutions in the network is an important issue that needs to be updated. However, reinforcement and replacement could take time before being fully applied on the required scale, but some current problems need an immediate mediation [40].

In the previous sections, it was mentioned that the DNOs acknowledged the serious need for novel solutions rather than traditional solutions that are not able to deliver the required capacity for near-future evolving loads and DGs. It was also mentioned in the previous sections that DNOs deal with some technical issues such as over/ under voltage by replacing the cables with wider cross section ones, or by splitting the substations to prevent relying only on one feeder in order to reduce the voltage drop over length. Several DNOs address these solutions to meet those technical problems right now.

However, applying those traditional approaches right now takes time, incurs more costs, and results in significant delays and distortions in network supply due to the replacement process. Additionally, this new installation will provide large capacity that is available in a wide range before it is fully needed and utilised. Thus investment should be directed towards providing what is needed step by step, subject to the need of the networks and depending on a flexible control strategy that releases the latent functionality and capacity in the current traditional networks when needed. This case could be reached by giving a taste of PE to the network by gradually deploying the functionality of solid state switches and control strategies.

Furthermore, in some situations, traditional reinforcement in the legacy network is not feasible due to crowded spaces with high density population and loads, wherein applying the replacement process would require more space, legal approvals and long waiting times for administrative hurdles. PE approaches have the potential in this case to provide feasible solutions that allow some system tolerance, especially regarding the space issue. Some of those applications have been introduced by the research community recently, such as full/ partially electronic tap changer and PE LV adapter for points of soft opening [41]. Some of those PE applications have made a further step to be considered by one of the DNOs, such as the PE fault current limiter, expected to be adopted in 2016 [35].

The Carbon Trust has been provided with a range of PE applications that were investigated by Parsons Brinckerhoff Company [42]; their investigations tested several PE technologies for the purpose of cutting carbon emissions and costs, such as fully electronic transformer (electronic substations), and PE fault current limiter. Most of the provided applications that have been considered by Carbon Trust rely on PE approaches and solid state switches solutions that contributes towards providing the network with extra capacity and releasing constrains [35], [42].

The current possible power electronics approaches that could intervene in LV networks to accommodate feasible solutions are discussed in the following sub-sections, whereby PE role is presented from a functional perspective as illustrated in figure 2.3.

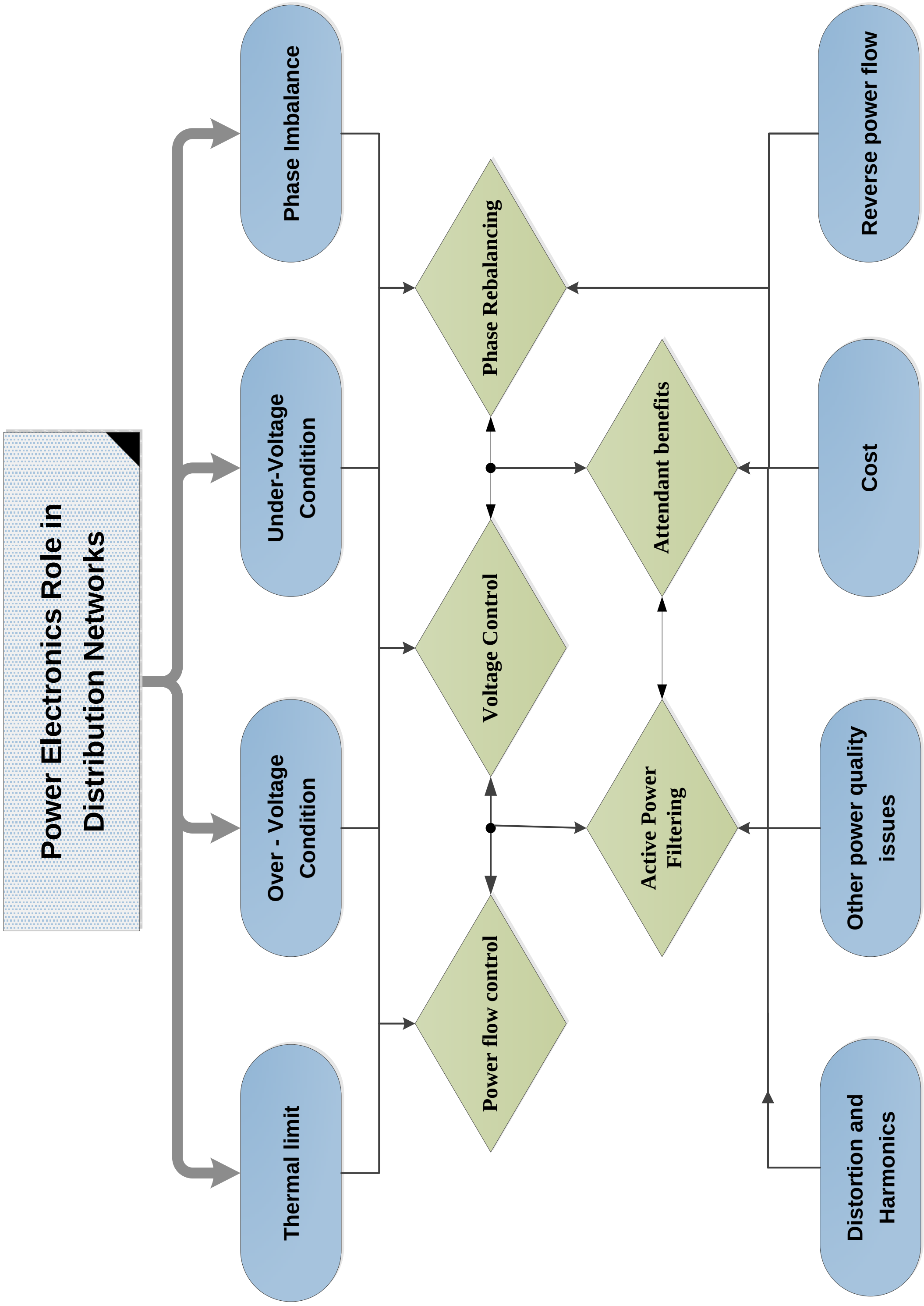


Figure 2.3: Power electronics prospective role in distribution networks.

2.4.1 Voltage control

Voltage variations whether drop or rise could be detected at the substation transformer, along the feeder, and at the end user. In the LV network, the only strategy used to deal with voltage variations is the On-Load Tap Changer (OLTC), but it is rarely used in UK substations in the last mile 11KV/400V, especially at the secondary side, due to several technical issues such as:

- Arch and safety, as changing the tap changers beside the load could affect the voltage instantly in a serious way due to the lack of smoothness in tapping.
- Beside the inaccuracy in detecting the exact required voltage level, the tapping process contains specific number of tapping levels.
- Traditional installed tap changers are constrained at the primary side of the transformer.
- Traditional tap changers regulate the voltage for the whole feeder (all three phases).
- Additionally, the space issues remain pertinent obstacles, especially as last mile transformers are usually installed in small places near the end users.

The concept of electronic transformer or hybrid electronic tap changer could contribute in treating voltage variations. Although also subject to space limitations [25], [43], practically it could be installed at one of the three places for detecting voltage variations. Electronic transformers have the potential to regulate the voltage separately for each line or phase according to the variation level for each phase, where every phase or line is controlled separately.

Voltage control strategy adopts other techniques such as Unified Power Quality Controllers (UPQC), which could be installed at the mid feeder as a link in the urban areas; hence it deals only with a small amount of load. However, more optimum solutions are needed to deal with 50Hz transformers by using high frequency PE [44].

Reactive power compensation is not common in the distribution network due the resistive nature as mentioned before, but one of the DNOs [35] studied the possibility of applying this concept in the last mile of the network. Initially they investigated the possibility of providing the reactive power using a STATCOM connected to the 11KV and 33KV networks. On the other hand, the efficiency of injecting reactive power in a network relies on the nature of the network and load consumption. LV networks tend to use underground cables more than using overhead lines, as it serves normally with urban areas, and underground cables have smaller X/R ratio than the ones used in the transmission network. Hence, providing reactive power at the distribution level may have little value, but on the other hand the existence of such a primary need at the last mile may add a great value in some cases depending on the future expectations and loading behaviour changes.

Accurate voltage control at the last mile is a primary need nowadays in order to meet voltage regulation standards. Voltage variations are expected to be more frequent than before due to the change of loads types and amount, such as using electrical cars, where effects are obvious in terms of voltage variation intervals (e.g. while charging some cars and discharging others in the same network). Hence an instant and frequent voltage control is needed to chase the frequent variations, which is impossible in case of using traditional OLTC, as it lacks the ability to track the voltage changes accurately, instantly and frequently.

2.4.1.1 *Voltage control in radial networks*

The biggest challenge is to maintain the voltage level within the allowed level or within the “voltage regulation” term in radial networks, such as in rural and urban areas in the UK. Therefor there is a significant need for voltage regulation in the radial networks as they operate in one direction, without any enforcement by other networks or applications, beside the challenges in treating the voltage in case of DGs existence. [31] Stated that PE approaches for voltage regulation issue take the 7th rank besides other solutions such as network reinforcement or reinstallation. The DNOs decision in Germany seems to consider PE solutions as non-feasible despite the high costs that result from traditional reinforcement of the network.

2.4.2 Power flow control

The increase of the power flowing in the network is to meet the demand of the new loads (such as electrical cars). This gradual increase causes stress on some feeders, which is treated by what is known as meshing the flow. This meshing occurs by changing the connection of the network to use the low congested feeders to carry the extra power flow. This strategy is known and common in the design plans for the DNOs [25], [40] and is applied by closing Normally Open Points (NOPs) in the case of post-fault restoration. However, by closing these points, the fault current will be heavily increased and wrong assumptions will be made for protection of grading design. The challenges that exist in closing the NOP could be overcome by using the

Soft Open Points (SOP) represented by back to back converter [31]. Back to back converter has the ability to control the direction of power flow, real power flow, return currents, and reactive power processing, beside the ability of controlling and limiting fault current. Meshing in network could take several scenarios and strategies [31].

Traditional DNs in the UK are divided into two types; radial networks and meshed networks. Traditional radial networks are expanding due to the developing increase of loads in the network, where radial networks are considered the essential tool to deliver power to the end-user gradually, from generation through to transmission, ending with radial DNs. In some cases the DNs are designed to be an interconnected network such as the ones that are designed by ASPEN [40].

Meshed networks are more complex and have better ability of dealing with fault conditions, but they are not straightforward in operating and controlling beside their higher cost in building. [31] investigated the ability of interconnected or meshed DNs in dealing with distributed generation (DG), and found that meshed networks in Germany are more efficient in dealing with large number of DGs than radial networks.

2.4.3 Reactive power compensation

Loads that are installed in industrial and home power networks normally have an inductive-ohmic nature [45] which causes a lagging reactive power in the network treated by leading reactive power at some nodes to correct this lagging in the power factor that forces the generator to produce and inject more reactive power into the network. This leading reactive power is produced by a capacitor compensation system feeding the inductive-ohmic load, which is placed close to the load to decrease the lagging reactive energy that is injected into the grid. Thus the capacitor acts as a reactive power generator, as shown below [46]

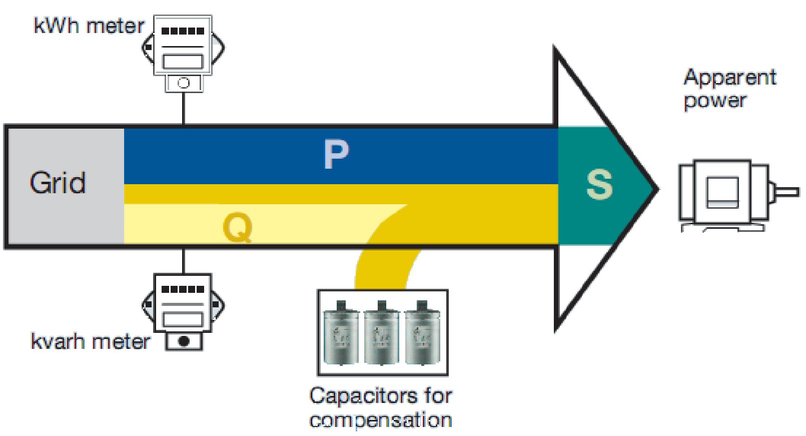


Figure 2.4: Capacitance compensation system diagram for a normal network.

By changing the load conditions and characteristics, the required reactive energy changes, which can be altered by increasing or decreasing the amount of capacitance compensation in switched PF corrections, as explained in later chapters. There are several economic, security and stability benefits that can be gained from this technique [46]:

- Getting better voltage quality.
- Decrease the voltage drops events.
- Decreasing the transmission losses and the cross-sectional area of the cables (because the value of the current that is carried through the network equipment is smaller).
- Increasing the efficiency of the operations of the installed electrical equipment.
- All the above benefits contribute to better economic investments and profits where the generated reactive power decreases.

2.4.3.1 *Power factor correction in nonlinear loads*

The power factor correction in nonlinear loads is divided into two parts:

1. Improving the displacement power factor.
2. Reducing the total distortions (distortion factor).

So the nonlinear PF = displacement power factor × total harmonic distortion factor [47]

The displacement power factor problems can be treated by the leading or lagging reactive power compensation, and the total harmonics distortions can be reduced by using filters (passive or active), but even that is not enough to improve the power factor in nonlinear loads, where the power quality of PF issue needs an integrated group of solutions to reach the optimum solution [47].

2.4.3.2 *Reactive power compensation techniques (Q and V injections)*

The most well-known method to handle the problem of the presence of reactive power during the last mile of the network is based on power capacitors. These compensating passive elements are attractive primarily because of economic reasons; they are relatively cheap and simple in operation compared to other compensation means such as active filters [48].

2.4.3.3 *Convectional power capacitors compensators*

Traditional PFC, sometimes called fixed PFC , is implemented by connecting power capacitor in parallel with the source system directly to terminals of a load that has to be compensated, as shown in figure 2.5 This method is normally used at the end user in case of large loads, such as factories and reactive power machines consumers, and it is not provided for normal loads such as houses at the current time; it seems to be efficient for now, but not for the case of future scenarios as mentioned in the introduction. This connection has the merit of reducing electric grid load, since Reactive Power (RP) is generated at the consumer's load terminals. In order to find out the value of capacitance to improve the PF to unity, a series of calculation steps is required. An inductive load in series with a resistor (R) is assumed as in figure 2.5.

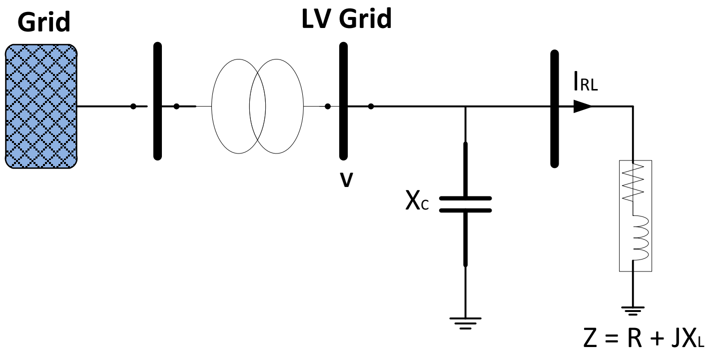


Figure 2.5: Traditional reactive power compensator beside loads.

A proposed algorithm for linear loads is presented as follows.

1. The load inductive reactance (X_L) is determined, where f is the source system operating frequency in hertz (Hz), and L is the inductance in Henries (H).

$$Z = \sqrt{R^2 + {X_L}^2} \tag{2.8}$$

2. The load's inductive current is calculated, where I_{RL} is the load current and V is the supplied voltage.

$$I_{RL} = \frac{V}{Z} \tag{2.9}$$

Determine the angle θ_1 between X_L and R.

$$\theta_1 = \tan^{-1}\frac{X_L}{R} \tag{2.10}$$

3. Since the aim is improving the PF to unity, θ_1 is zero, the desired capacitive current can be calculated as:

$$\sin\theta_1 = \frac{I_c}{I_{RL}} \tag{2.11}$$

$$I_c = \sin\theta_1 \times I_{RL} \tag{2.12}$$

4. Finally, the compensated capacitance can be determined as:

$$X_c = \frac{V}{I_c} \tag{2.13}$$

Where X_c represents the capacitive reactance, and the required capacitance is calculated as:

$$C = \frac{1}{2\pi f X_c} \tag{2.14}$$

2.4.3.4 *Switched capacitors*

There are many types of switched capacitor that can be used for reactive compensation that use different techniques, such as Mechanically-Switched Capacitor (MSC) and Thyristor-Switched Capacitor (TSC) [49]. The following chapters discuss the double switched capacitor introduced in 1982 by Marouchos [50], and used as an active filter by Darwish [51]. It can be used for different power electronics applications. Circuit types regarding their construction introduced by Darwish in 1985 and in the following chapter are the Double Switches Double Capacitors (DSDC) and the Double Switches Single Capacitor (DSSC) [49].

The switched capacitor circuit contains at least one capacitor whose operation depends on voltage pulse controlled switches [50], as seen in figure 2.6. The total effect of this figured circuit is the same effect of variable capacitor that provides the reactive compensation either in leading or lagging mode.

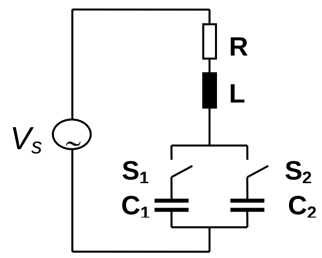


Figure 2.6: The DSDC circuit.

2.4.3.5 ***Static VAR compensator (SVC)***

The main benefit of the SVC for stability enhancement is direct through a shunt connection of one of the FACTS devices family by using a solid state switches converter in order to control the flow of the power and enhance the transmission grid with more transient stability. SVC functionality depends on regulating the voltage at its terminals by controlling the flow and amount of Reactive Power (RP) injected in the transmission lines, or absorbed as demanded from the grid. In case of low voltage, the SVC injects RP into the grid and takes the mode of being capacitive, while on the other hand, when voltage is high the shunt device absorbs RP and takes the mode of being inductive [52]. This variation between the inductive and capacitive modes is achieved through switching between the capacitors and inductors banks, which are connected at the secondary side of a shunt transformer with the network, as seen in figure 2.

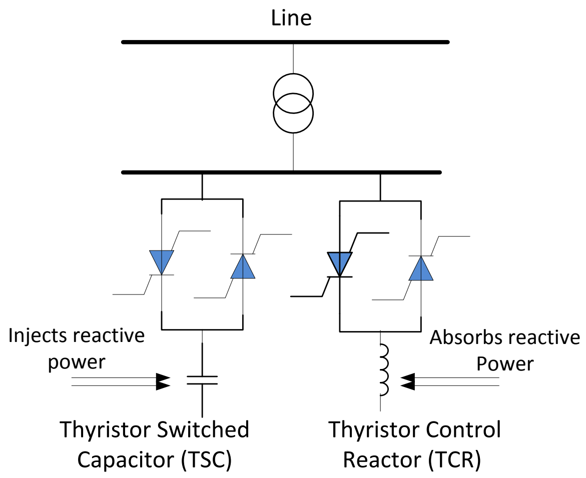


Figure 2.7: SVC static VAR compensator structure.

SVC will make sure to boost the capacity of the transmission lines and prevent voltage sags even when it is loaded heavily, which means more transferable power under stable conditions and within acceptable voltage limits. Thus the benefits of using this FACTs family include that it enables one to [53], [54]:

- Keep a stable voltage interval for the transmission grid.
- Minimise the transmission losses.
- Maximise the transmission capacity, obviating installation of more cables.
- Achieve more transient stability.
- Achieve proper voltage control for the transmission grid.
- Dampen power variation.

Using SVC for voltage stability is more common in transmission networks than in distribution networks, and it is not known to have been used in the last mile of the network due to the resistive nature of most end-user of the networks. SVC devices are employed on a very large scale worldwide, mainly to achieve voltage stability for the transmission system. The following table indicates its utilisation around the world for operational purposes, not for experimental and research aims [54].

Table 2.1: SVC devices employment around the world [54].

Place	Ratings	Utilisation
Maryland, USA	500Kv -145 /+575 MVar	Control line voltage
Saudi Arabia	110 kV, -60/ +600 Mvar	Voltage stability under hot climate conditions
Bretagne, France	225Kv, -100/ +200 MVar	Two SVCs in operation to add flexibility to voltage control of huge transmission system
Mining complex, Peru	220Kv, -40 /+90 MVar	Stabilise voltage for most restrictive operation of mining substation to be within ±5% for a huge mining machines
Western Texas, USA	69Kv and 34.5Kv -40/+50 MVar	Dynamic support for RP due to the existence of large number of wind power turbines (three SVCs installed at different networks ratings)

The SVC was employed at a very large scale in 2007 at key substation near Maryland in the USA where it provided a reliability at 500KV (-145/+575 Mvar) for the most congested interconnection area in the region to enable more power to be transferred on the existing cables. The Saudi Electricity Company is also using this technique to support a large transmission system that feeds almost 80% of air conditioners from the total load due to the special high temperature climate in KSA, which causes a slow voltage recovery and extra heat in the transmission cables, which restricts their normal transmitting ability. To overcome this obstacle, three large SVC devices were installed in 2008 at the transmission line 110 kV, -60/+600 MVar basically for the purpose of keeping the voltage stable during the operation of a huge number of air conditioners [54].

2.4.3.6 *STATCOM*

Recently, the progression of STACOM technology and development has been growing beside the concern of developing control methods and strategies for it, and for other FACTs such as Unified Power Flow Controller (UPFC) and Static Synchronous Series Compensator (SSSC) [54]. The deregulation of power networks and systems beside the extra restrictions in the transmission network has led to a situation where power compensation devices can improve the system and decrease transmission limitations. STATCOM uses storage devices to produce and absorbs Reactive Power (RP); it uses solid state switches of a converter to produce Var [55]. The STACOM is connected in shunt, as seen in figure 2.8, where it normally uses a large voltage source converter to inject the RP in the grid in order to improve the stability of the transmission grid and increase the amount of transferred power through the same number of lines. Shunt STATCOM injects RP at capacitive mode when V_{DC} is above its nominal value and it absorbs power at inductive mode when V_{DC} is below its nominal value [55].

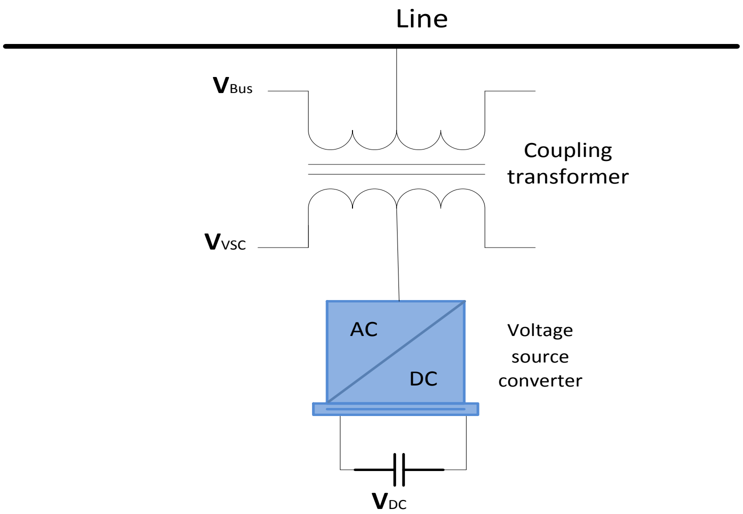


Figure 2.8: STATCOM Static Synchronous Compensator.

It is common to use STATCOM technology in transmission grids, and it is not used commonly in distribution networks due to the fact that it is more needed to stabilise the long way of transferred power in the transmission networks and not in the short way of distribution lines compared to the transmission lines; it also provides the transmission parts such as cables and transformers with its own needs from RP, to be taken from the compensation device along the way and from the generation source. It is believed that this compensation contributes positively also at the last mile of the network as seen in [56] , as well as at the transmission grid, depending on the current situation and future expectations of requiring more capacity in DNs to match the continuous development and changes in end user devices.

2.4.3.7 *Static synchronous series compensator (SSSC)*

The SSSC is used in the transmission line to inject the power as voltage in series with the transmission lines, and it is also considered as member from the FACTs family that provides for the system by injecting voltage with more stability by damping the power oscillation. The construction of the SSSC is close to the STATCOM constructions but differs in connection as it is connected in series with the transmission grid (as seen in figure 2.9). The injected voltage should be controlled to be in quadrature with the current of the grid, which is controlled normally by using *dq* controller in order control the V_q of the injected voltage, to be in quadrature and in phase with grid as V_q and V_d represent the converter voltage. The control strategy is performed through a voltage source converter (VSC) attached with the secondary side of the series transformer [57].

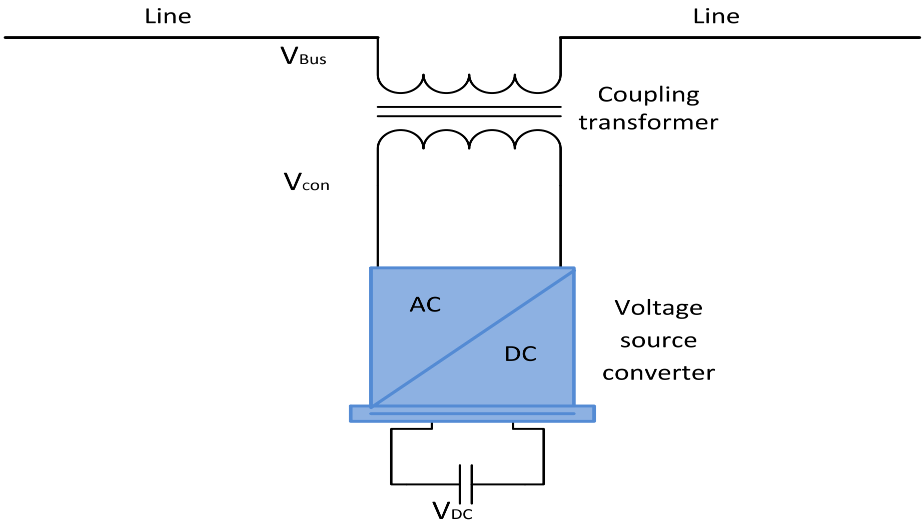


Figure 2.9: SSSC connected in series with a transmission line.

2.4.3.8 *Unified power flow controller (UPFC)*

STATCOM structure could be combined with SSSC structure, with both of them connected together, to form the UPFC device, which combines between the abilities of the shunt connection and series connections, in order to exhibit the ability of injecting current in shunt (STATCOM characteristic) and injecting series voltage (SSSC characteristic) [55], [58]. Thus it increases the flexibility of operational options. Its construction is shown in figure 2.10, where a line converter (AC/DC) is connected in parallel with the feeder, and a load converter (DC/AC) is connected in series with other side of the line. The parallel converter function is to assure providing the second series converter with its demand from active power through the DC link. The parallel converter is also used either to absorb or provide reactive power [59], [60]. The device has three operational options that could be performed to [55], [58]:

- Control the flow of the RP at the series and shunt connection.
- Control the flow of the real power through the DC link at both of the shunt and series connections points.
- To regulate the voltage in a technique similar to STATCOM.

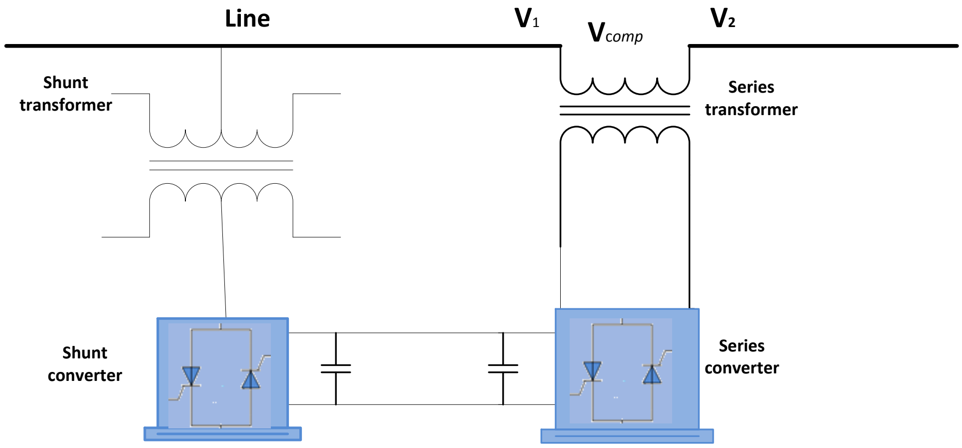


Figure 2.10: Unified power flow controller (UPFC).

UPFC performs both of the STATCOM and SSSC functions beside the ability to add extra features such as real power injection. Four freedoms of control options are available in the device, as shown and explained by the phasor vectors in Figure 2.11. UPFC performs the control options by injecting voltage (V_{pq}) to the terminal voltage *(V_o)* with the suitable amplitude and phase angle. The control options are as the followings [58]:

- Terminal voltage control; which similar the voltage obtained by taps changers in transformers where V_{pq} is injected with V_o as ΔV as shown in figure 2.11a.
- Line impedance control (Z_{line}) or series compensation; which injects $V_{pq} = V_C$ with Line current as shown in figure 2.11 b.

- Phase angle regulation, where the injected Voltage V_{pq} is represented as V_{σ} which is injected in an angular perspective in order to reach the required phase shit σ without affecting the magnitude as shown in figure 2.11 c.
- Multifunctional control is performed by applying the three previous control options simultaneously; voltage regulation ΔV, series compensation V_C, and Phase angle regulation V_{σ}, whereby $V_{pq} = \Delta V + V_{\sigma} + V_C$ as shown in figure 2.11 d.

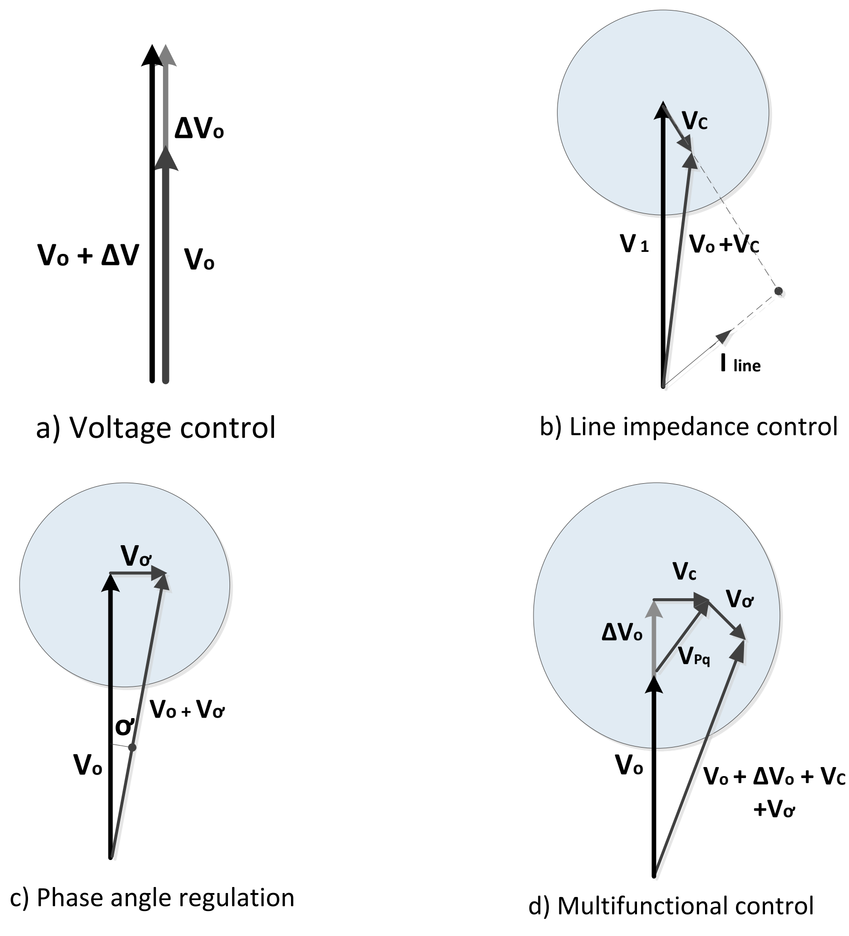


Figure 2.11: Control options for UPFC [58].

2.4.4 Phase rebalancing

The DC bus concept exists in most mid-feeder compensators, such as STATCOM, SVC and dynamic voltage restores (DVR), which gives the potential of power exchanging between phases. This power exchanging allows the DNOs to perform balancing strategy in one feeder of three phases. This advantage of PE could be included in the potentials that PE could introduce for the DN in order to guarantee a balanced feeder in the 11KV and 400V networks. Balancing the feeder at the 11KV/400V networks contributes in reducing the losses and releases the network capacity. Notwithstanding the lack of PE experience, DNOs have started to consider the approach of PE or hybrid PE in order to mitigate this issue [31].

2.4.5 Active power filtering

Active Power filtering is represented in many applications and there is an abundance of literature concerning it [61]-[63]. It is applied on some areas close to the load, such as consumers' buildings and hospitals, but not within the distribution network itself. However, there are great benefits from applying filtering process at group of loads connected within the same network in the distribution network. The filtering of low order harmonics existence at the same phase angle [24] seems a beneficial idea within the distribution network in order to synchronise to the fundamental voltage.

DNOs started to recognise the value behind filtering in the DNs, and analyses have started to investigate the areas where there are PV cells and wind turbines. However, it is believed that there is a need for filtering at the network, even though the entire end-user loads are meeting the required product standards, such as IEC 61000-3-3:2013 standards; the total effect of the loads could cause a harmonic problem at the network. Mostly, these harmonic problems are not planned for in the design of the traditional DNs. The DNOs in this case are responsible to reduce the resistance of the network by replacing the current cables with ones that have less impedance, or adding PE to handle the filtering process.

2.4.6 Attendant benefits

The intervention of PE applications in the electrical networks, especially distribution works, could revolutionise the dynamic control of the network in several ways besides the main contributions mentioned above. PE can give the network the taste of monitoring, communication and flexible reactions towards the poor network infrastructure without digging every pavement in the last mile to upgrade and develop the current systems, which saves immense time and resources that could be wasted in the upgrading process. It can offset losses in functionality, flexibility and cost depending on the need of every single DN in the whole electrical system, from generation until end users [35].

Furthermore, the main advantage introduced by PE is represented in dynamic control of the systems, which need real tracking for the local network behaviour; this could be done by a common network communication control panel that provides this information in a wide range. This PE strategy could meet the exact control requirements and provide what is needed accurately, without extra costs in equipment and infrastructure replacement [42].

2.5 Power quality

Power quality usually means money, economy, safety and savings, which are the main objectives of achieving high power quality. Unfortunately, the recent generations from engineers turned their research, concern, analysis and diagnosis towards the PQ issues, trying to find a solution for a complex problem that covers varying complex topics [2]. The solutions that were applied were focused on utility networks, but the new solution applications and concepts are being applied to end users' devices and equipment now [2].

The issues of the power quality have many different solutions which complicate the choice, and to devise optimal solutions engineers have to mix between several solutions and techniques and identify the problem type and characteristics that would be helpful in finding this optimal solution. This optimal choice plays a vital role in the economic side, whereby some choices or solutions need high investments [2].

According to the reason above, an informational program was established by some academies in the European Commission in 2000 focused on the PQ issues related not only to power suppliers but also to end users in the electrical network. This project achieved great success with 100 affiliated global partners, and after seven years many sub-projects had been launched related to the PQ issue [2].

By discussing the PQ problems here and their classifications, in non-linear loads there are two general solutions could take the engineers to their aim in reaching a reasonable level of power quality: improving the power factor and decreasing the distortion factor. the power factor could be improved by capacitor compensation with an intelligent technique having the ability to act as a suitable capacitor for the inductive load, and the distortion factor could be improved by an efficient passive or reactive filter to achieve a reasonable result by deleting a reasonable amount of the harmonics and noise [2].

As mentioned previously, increasing the non-linear loads in the facilities spurred research into two ways to achieve the optimum solution in PF corrections in these non-linear loads where the power factor is affected by two factors: the displacement factor and the distortion factor. Both these factors could be improved as seen in Figure 2.12 to reach the proper sine wave, which is clear from noise and phase angle difference [2].

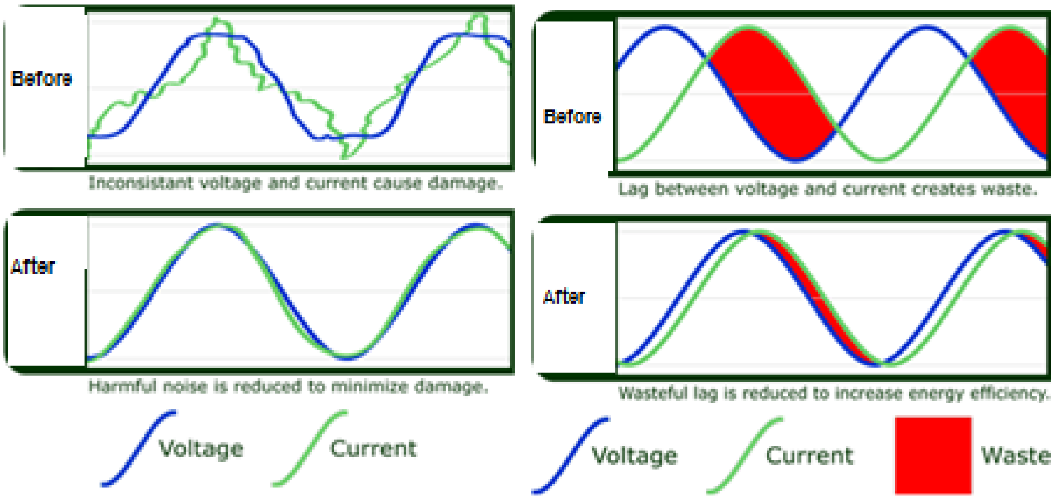


Figure 2.12: Improving the distortion power (left) and displacement factor (right).

2.5.1 The definition of power quality

There are several definitions of power quality reflecting the aims of those defining it; it means reliability for utility owners and supply efficiency for load owners, among many other criteria. One prominent definition is the following [64]

> *"Any power problem manifested in voltage, current, or frequency deviations that result in failure or disoperation of customer equipment".*

The IEEE defined power quality in terms of the study of powering and grounding, as in the *IEEE 100 Authoritative Dictionary IEEE Standard Terms* [65]:

> *"The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment" [65].*

However, such a functional definition faces the problem that what was traditionally considered good power quality for devices such as washing machine motors is considered poor power quality for modern electrical devices such as laptops and electronics devices, where a shortage in voltage could damage these devices while not affecting the work of motors, so the PQ issue is discussed generally in this chapter regarding the normal sensitive devices that any facility contains nowadays [65].

2.5.2 Events represent poor power quality

For the purpose of clarity, the figures in the table 2.2 are either a result of calculations or observations or generated from electrical test equipment.

Table 2.2: Definitions of power quality events [65].

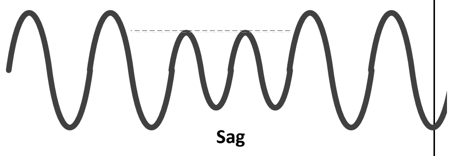
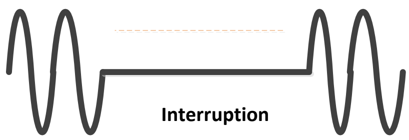
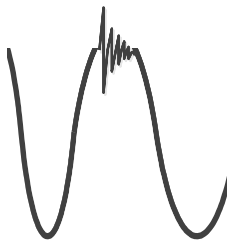
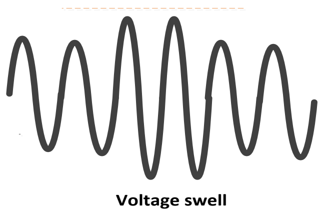
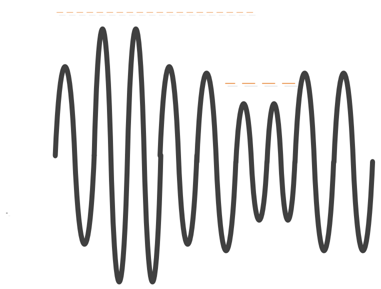
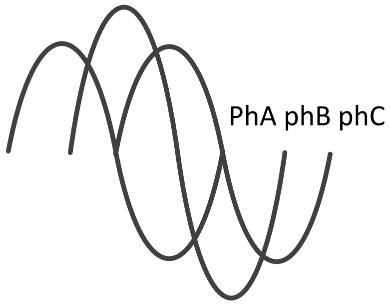
Voltage sag	An event happens as a result of utility faults and at the beginning work of a motor, which lasts from 5 cycles to 1 minute, and causes a short reduction in the effective value of the voltage, normally reaching 10-90% of the voltage [65].	
Interruption	An event lasting for a maximum of 60 seconds causing a reduction in the line voltage, which acts as an interruption in the process of the power flow. Its percentage reaches a maximum of 10% [65].	
Oscillatory transient	An alteration in voltage and current that acts as an alteration in the power line in two directions because of the oscillation that comes from the switching process of the capacitors' compensation circuits and in general [65].	
Impulsive transient	It is similar to the oscillatory transient with the difference that the impulsive transient is unidirectional, which means the variation happens in one direction, and it happens generally because of the switching process in the electrical power networks and through operation of some electronics components such as Zener diode and MOVs. It can cause total damage at the end users' devices if the transient voltage of the fault is too high [65].	

Table 2.2 cont. [65].

Voltage swell	The opposite operation of the voltage sag, defined as the increment in the effective value of the line voltage (Rms) for a short time, from 0-5 cycles to 1 minute. Normally this increment is between 110-180%. The reason behind this action is normal faults in the wires of a transmission network due to wrong tap stinging in some transformers [65].	
Voltage fluctuations	It takes the shape in the figure as an event smaller than 5%, defined as an alteration in the effective value of the line voltage caused by electrical systems whose consume ampere does not match the synchronization of the common frequency 50Hz, as in Arc furnaces. In addition, it has a viable effect on the lights sharpness and intensity [65].	
Voltage imbalance	It is an event which happens when one of the three phase voltages varies compared to the others [65]. Large phase angle between voltage and current happens in the inductive and capacitive loads. The current in this case either leads or lags the voltage in the wave form to create a wasted energy or reactive power that contributes to decreasing the power quality level at the electrical networks.	

2.5.3 The cost of poor power quality

Like any other commodity, quality in power has a price, and there are penalties for disappointing levels of quality (i.e. absence of power). There is a cost for every power quality defect, no matter the causes and reasons, and as a sign of necessity for achieving high level of PQ in the electrical systems and networks, the problems of poor PQ are estimated to cost EU countries more than €10 billion annually in the electrical industry field, while it is estimated that installing preventative equipment would cost less than 5% of this. Although the obvious good sense of installing such equipment is therefore manifest, achieving this requires complicated efforts, as mentioned previously, and several steps in an efficient plan, where the first step is to reach a level of understanding of the problem type from a business point of view and display a comparison between the cost of the PQ problem and the cost of its solution [45], [66] .The harmonic distortion represents a serious problem of PQ from its economic effects side and from a business view.

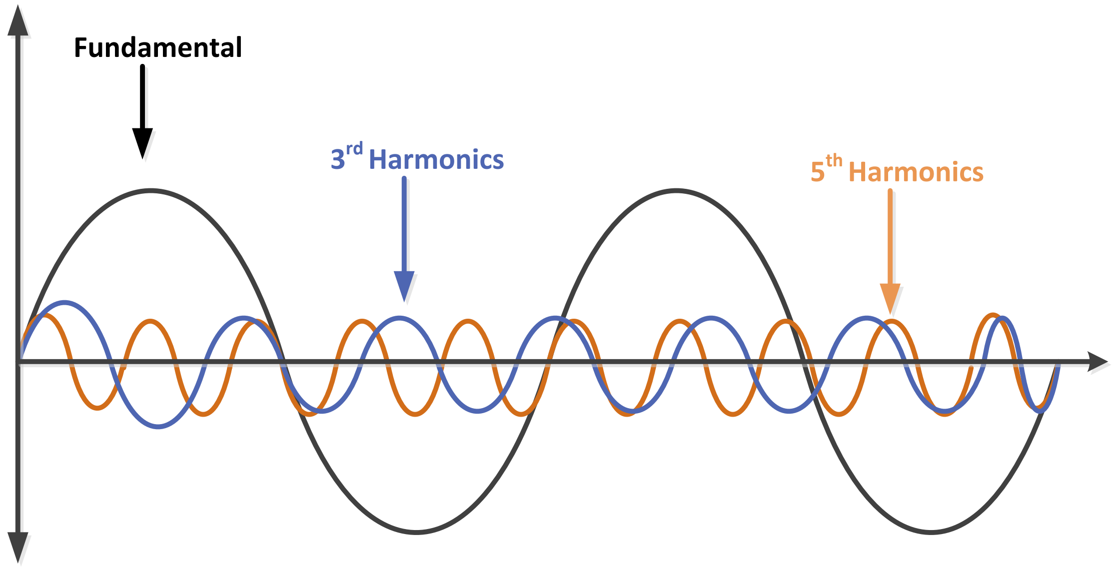


Figure 2.13: Harmonics components in an AC signal.

From economic side, the main effects of the harmonics are

- The reduction in the life time of the equipment.
- The reduction in the delivered and transferred energy.
- Undesired, annoying sounds.

There is no single solution for PQ problems, rather every problem has its own solution; however, these solutions should be compatible with each other and with respect to the load type and problem, so the designers can reach the optimum solutions by a mix of compatible solutions [67]. In the field of power quality, it is always clear that prevention is cheaper than cure, so engineers are expected to be more experienced in finding solutions for the several complex PQ problems.

2.6 Power electronics from a business case perspective

The previous sections discussed the technical challenges that PE applications could face in application. Several approaches have been suggested and tested by previous studies to meet these challenges and to decrease the cost of upgrading or delaying the long-term modification of networks from a mainly technical perspective, but it is necessary to consider the business perspective of investors and DNOs, who must be convinced of the technology through meetings, workshops, and research studies if PE is to be applied.

One of the most important priorities for DNOs is to minimise costs. The financial risks stem from the novelty of applying the concept of PE in the DN for the first time, whereby there is a lack of record for PE applications in this area of the network, which doubles the risk from the DNO perspective and increases concern. There is consent among previous research studies that the business case for PE solutions is more perplexing than the related technical challenges [68].

2.6.1 Power electronics costs

DNOs instinctively evaluate PE by a cost-benefit analysis. This evaluation entails balancing the cost of PE applications themselves and the cost of traditional enforcement solutions, which are inflated by infrastructure replacement and upgrade considerations. The result of comparison will tell the investors or the DNOs to deploy PE or traditional solutions, and sometimes maintain the status quo.

The annual cost can be calculated by equation (2.15), which is the summation of capital investment, operational costs and maintenance costs [68]:

$$C_{annual} = \frac{K_{inv}}{A_{Tl\,R}} + (E_L C_e + C_m) \qquad (2.15)$$

Where:

C_{annual} : is the annual cost

K_{inv} : is the investment cost

$A_{Tl\,R}$: is the annual constant factor for life time

Tl : is the life time of the application in years

R : is the capital cost rate

E_L : is the electrical loss per time

C_e : is cost for electrical losses unit

C_m : is the mechanical cost

The annual factor can be calculated by:

$$A_{Tl\,R} = \frac{1 - \frac{1}{(R+1)^{Tl}}}{R} \tag{2.16}$$

Each part of the equation is investigated deeply by investors, as discussed below.

2.6.2 Investment cost ($\mathbf{K_{inv}}$)

It is clear for the investors that the cost of the semiconductors compared to the electromechanical approaches parts is relatively high, but there are other considerations that should be taken into account. One of these important considerations is the ratings of the PE compared to the required effect on the network. One of the good examples for this pattern is double fed induction generator (DFIG), which is a wind turbine whose induction generators are attached partially with two PE converters (around 30% of the generator rating). The PE controls the power flow, which gives variable generator speed. In this case the DFIG is considered more effective from a cost perspective as it uses partially rated PE converters for the control aspect according to need [68]. The UPFC has a similar strategy relatively by applying it in series with mid feeder with lower ratings. This hybrid or thin PE strategy improves efficiency and affordability compared to full PE solutions.

The investment cost includes also the space cost, and housing PE equipment is considered a major challenge for investors, especially in the distribution network area where the space is limited among the urban areas, and extra ancillary renting services and arrangements are needed. The cost of renting a space or purchasing is an essential case and is taken seriously by investors. However, there are several routes that could be taken to reduce the volume of the PE and increase power density through [68]:

- New designs for circuits (circuit innovation).
- Providing high frequency PE devices that reduce the amount of magnetic and passive parts.
- Using newly researched materials that can handle more temperatures, thus the cooling equipment size is reduced.

Equation (2.15) does not take into consideration other life cycle costs of the PE device, known as disposable costs, which it thus assumes to be zero. Such costs are supposed to be added to equation 2.15 for accuracy purposes, but first an accurate knowledge of disposing is required for each single PE device, as every application has its own criteria. However, it is obvious that the value of recycling the metal in an old transformer is higher than the value of PE applications during the whole life cycle.

2.6.3 Lifetime ($\mathbf{Tl}$)

One of the most important factors in a business case decision is the lifetime factor. The expected lifetime of the device could contribute seriously to the annual capital costs. This factor effect is shown practically in the frequent replacing for the short time devices with long lifetime ones. However, it is stated that the average lifetime for traditional assets in DN is about 50 years [25], which is much more than the expected lifetime for PE applications such as converters, which vary between 20-25 years [35]. Consequently, the decision of investors to adopt PE assets neglects any facts of temporary or permanent installation for the applications, as the lifetime will be key factor for the decision. Risk option appears in case of improbability of lifetime for a device, where the assets that are used in the DN are known and their lifetime factor is understood as a matter of certainty. On the other hand, DNOs look to the lifetime of PE devices as a non-transparent term, where it is considered a new technology for them and there are some doubts about the lifetime that a PE converter can give. This uncertainty adds more risks and doubts among DNOs, inhibiting adoption of new technology using PE in distribution networks [35].

2.6.4 Electrical power losses $\mathbf{E_L}$

Electrical losses are categorised under operational costs, as they occur during operation. DNOs take these losses very seriously in their consideration of the potentials and functional abilities of PE. Practically, there are some examples of including electrical losses within the system cost, such as in the transmission network, where the losses of HVDC for example are added to the total cost of the device over the period of the life cycle, thus giving a clear and accurate idea about cost efficiency.

A practical, fair comparison between the losses of PE and traditional assets in DN can be seen by representing a PE converter that is rated to operate within the DN (230 KVA) and a traditional distribution transformer at the same ratings. The PE converter shows 95.9% [69] of full load efficiency against 98.9% [70] for the distribution transformer. The efficiency figure for the PE includes also the other attached devices such as PWM, and it is not trapped within the semiconductor losses. This simple practical example demonstrates the competitive advantages of PE (despite being marginally less efficient), where the transformer is considered one of the most reliable devices in the network. The higher losses in PE applications could tolerated by DNOs given the extra functions and benefits that they provide, where losses occur in PE itself, but on the other hand it saves a lot of losses when it provides functions for the networks such as voltage regulation and better power flow control. Thus the overall system losses are supposed to be taken into account and not just the device itself.

Some projects such as the LCFN project talk about PE applications within their provided solutions, which means that the high PE losses could be exceeded comparing them with the high flexibility and advantages that PE provides, and what is seriously required by the current and future networks. In addition, the reduction of losses is possible over time as the development of new low loss semiconductors is growing gradually.

2.6.5 Maintenance and mechanical cost

Customer minutes lost (CML) and customer interruptions (CI) are considered two of the most important pointers of performance by the DNOs [71] . This means that every single device performance is important to uplift the quality of delivered energy to end users. Thus inspecting and testing the PE devices as a strategy is considered a cost issue for DNOs, whereby some components need frequent replacements and maintenance, such as DC capacitors links, which normally show a risk possibility in the network operation. Therefore, the maintenance cost of PE faces a serious challenge in front of the maintenance cost of traditional equipment in the LV network (11KV/400V), where maintenance takes the shape of annual inspections and replacing simple peripheral components.

Depending on the fact that PE is a new technology, the uncertainty of dealing with failures in the PE systems is considered a concern that may lead to high costs, thus conservative PE approaches are considered in most of the systems planned by DNOs in order to avoid the nightmare of unplanned outages and complex repairs [36], [71], [72].

2.7 Ancillary challenges for power electronic approaches

Besides meeting the cost, technical and business challenges for PE intervention, the operation of PE devices in LV networks needs other ancillary requirements that contribute in providing a soft operation for the new introduced system.

2.7.1 Guidelines and training (logistical support)

Distribution network engineers are not used to dealing with the new operation of PE, such as PE converters and their control strategies. Thus training programs are suggested by DNOs to introduce new technology for the technicians and engineers as a matter of necessity. Furthermore, additional tools are required by the planners to deal between the human and PE applications. The current DN code and guide in UK does not include any information about PE, nor does BSI documentation state any guides for dealing with it. Thus a training issue is raised also by the DNOs beside the other addressed issues, which also represents a cost concern [32], [71].

2.7.2 Promotion challenges

There is a common impression among network planners that they can solve current and future issues without the intervention of PE depending on the old reputation of high losses semiconductors. Somehow the DNOs experienced the ability of PE in the transmission line according to the necessary need for it in that area of the network, but they still do not value the potentials of PE in the DN. However, the LCNF project is considered a good opportunity for PE designers and researchers to promote the ability of PE and provide solid empirical evidence to persuade DNOs of the efficacy of PE systems [71], [72]. Several project proposals have been accepted, such as one of the four proposals submitted to LCNF containing the intervention of PE in the DNs [73].

2.8 Power electronics design properties and goals

According to the mentioned challenges for applying PE approaches, the design of PE devices is supposed to be well established and have a solid design that can face any technical or cost issue. Therefore, the focus in designing an approach is believed to be achieved by three routes:

- Design methods and strategies.
- Circuit design topologies.
- Control phases and schemes.

However, the design is supposed to be limited according to what was mentioned in the previous section of cost limits, whereby the business prospective is necessary. Figure 2.14 shows the design aims and properties for the required PE intervention in order to show PE devices as feasible solutions in the DNs [3], [7]. Figure 2.14 labels are discussed and presented in the following subsections.

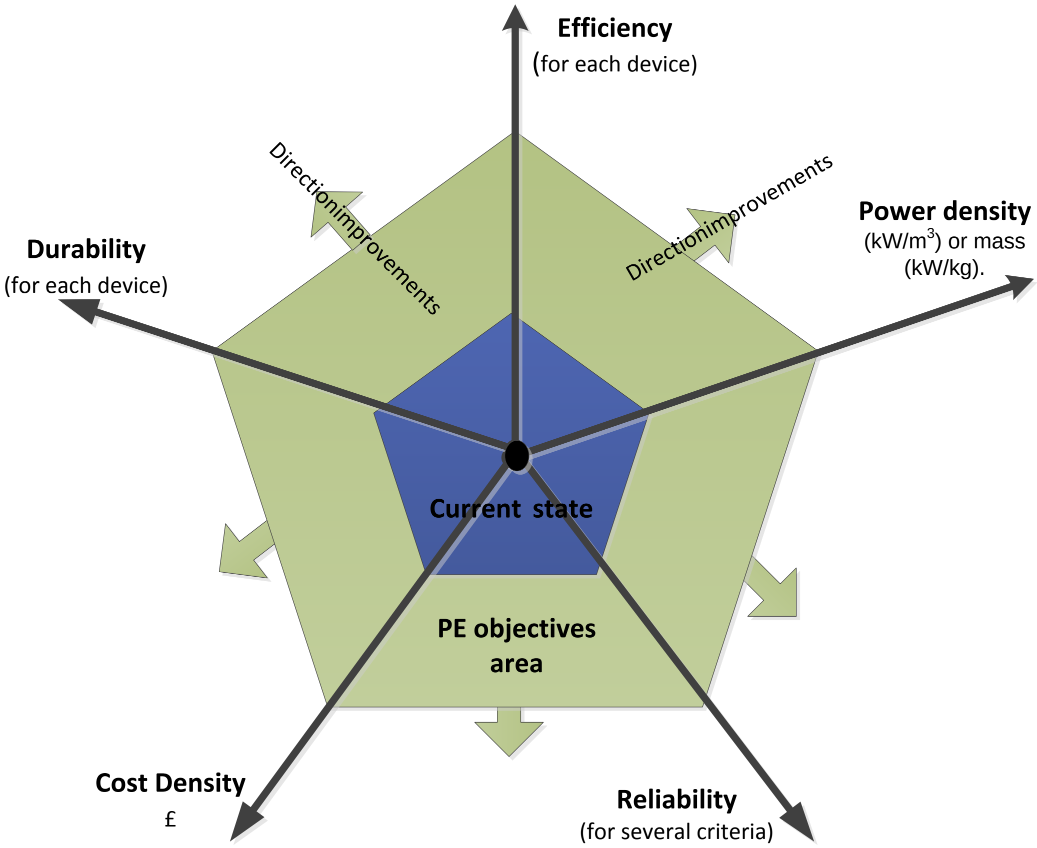


Figure 2.14: Approach required properties and development area [7].

2.8.1 Power density

There is a physical property for each device in the network determined according to its ability to provide power compared to its size (kW/m^3) or mass (kW/kg). In networks, a device could be installed either in pavement or on a pole in a transformer, where it is considered a key factor for the device density in the network. In transmission network, PE devices tend to have low power density due to the existence of the long distance factor in the network, and a low density rate is also found in industrial drives where cooling systems are attached, giving more weight and volume to the drivers. High density is noticed in aerospace technology, where it is supported by high cost budgets for the provided solutions. One of the main supporters for the density issue is the gradual development of an industry of electric vehicles [12], [74] , as power density is a necessary factor in the design of EV and could contribute in making high density available with reasonable cost [70].

The compared transformer in the previous section of electrical losses reaches 194 kVA/m^3 of power density beside an overall 98.9% efficiency [70], where the density of the compared converter is about 388 kVA/m^3 and 95.9% efficiency [69]. It seems that there is a kind of competitive trade-off between properties here and a decision is needed to be made to choose between both of them. In some cases, power density is chosen over other benefits, especially if it limits the burden of extra attachments such as bulky cooling systems. Thus a better understanding for the requirements of a specific DN would help in designing a suitable PE approach.

2.8.2 Power density thermal effect

By increasing power density, concern increases about heat and thermal issues, where cooling a high density converter represents a challenge that should be met in front of the limited space at the DN. However, research is going on regarding designing a new technology for cooling down the equipment, with the possible minimum space in order to allow the devices to operate at higher power density.

Dissipating the heat from converters is just part of the solution, because practically cooling down the devices means wasting heat energy and dissipating it for nothing. Thus heat disposal is another research area that is taken into consideration by researchers [75]. This research point could be very useful for current transformers' cooling cycles, as the cooling off periods get some interruptions by unexpected power flows through substation transformers.

2.8.3 Durability

The lifetime of a device is considered an important issue and was discussed in the section of PE in business case, where it is assessed as an important factor to determine the feasibility of a device. The objection is often made that traditional transformers and devices have longer lifetimes than new converters, but as with any emerging or new technology researchers are continually developing PE components with longer lifespans, thus applications will become more durable in the near future.

2.8.4 Efficiency

A significant component of the annual cost of PE is attributable to semiconductors, and new designs are supposed to have strategies to deal with issues in order to minimise such losses. Moreover, reducing the losses of the converter will contribute to reducing the amount of cooling attached equipment, which will help in increasing the power density by decreasing the space in the distribution network. This kind of efficiency could be reached in parallel with developing research on new semiconductor materials and components, such as SiC and GaN. Furthermore, decreasing the amount of losses could be achieved using low-loss magnetic material, such as that used in some transformers or in AC links between PE converter.

Currently, based on existing research results on semiconductors, strategies and new topologies in design are supposed to be used to compensate higher losses in the PE converter, therefore a new design is supposed to give a taste of PE for the network gradually by using hybrid or thin PE applications. A combination of the advantages of both the traditional reliable equipment and the new technology flexibility is believed to support the network requirements with the lowest cost and highest efficiency.

2.8.5 Reliability

Reliability is determined by several criteria. PE designs' reliability is specified according to the following points:

- High reliability is tackled through the high reliability of every single device used in the system, where the failure of one component the meet the criteria would affect the all reliability seriously.
- Operation system and strategy is considered reliable by having the criterion of redundancy, such as that in the multi-level converter.
- The trade-off is considered reliable by reaching a balanced point between power density and cost.
- Reliability is not just a matter of cost, where reliability is expensive sometimes.
- The PE converter is supposed to have a high level of protection and safety in the last mile of the network, as it is going to be installed close to end users, in contrast to the transmission network.

2.8.6 Operation monitoring

As mentioned previously, reliability means the reliability of each component in the network, and monitoring those components guarantees a high level of reliability and gives a better idea about the degradation of PE converters over time. This data can be helpful in protecting PE from failures. Continuous monitoring enables DNOs to get the highest value from their investment and gives them a clear idea about the economic issues involved. Further (future) study is needed to explain the new devices and their relation with time as an aging factor.

2.8.7 Network protection

Network protection is needed in several ways for monitoring PE behaviour and to avoid any failures, especially in the case of PE in DN, as it is placed near the public user and could cause real danger. New protection systems need to be installed with the new PE converter to adapt the new the operational strategy in the distribution network. Relying only on circuit breakers will not be efficient in case of PE converters, as it needs a more complex protection strategy.

2.8.8 Cost analysis and efficacy

As mentioned previously, it is important in several dimensions to conduct a proper cost and efficacy analysis (conventionally called a cost-benefit analysis in a purely business perspective), and it is important to understand all cost issues in any introduced design and introduce benefits from a monetary prospective beside other aspects in order to convince DNOs, given that there are competitive solutions other than PE. However, although economic and commercial issues are important drivers of any technology adoption, it is not the overriding concern with regard to PE and electricity generation and delivery generally due to the ubiquitous requirement for this service and its absolutely essential importance to modern life. Nevertheless, apart from its technical benefits, a reasonably priced PE solution will add more value and novelty to the design. There is a lack of research providing feasible PE solutions from a practical (i.e. economic) point of view that DNOs could consider, so there is a research challenge in providing analytical cost study that quantifies PE advantages [73].

One of the most important roles of PE is the delay or avoidance of expensive investment in the reinforcement of traditional networks. However, DNOs have stated that their intention is to replace the current cables and transformers with higher capacity ones, in order to meet the expansion in the loading amount and types [25], [73]. The additional cost of replacing an existing current transformer with an uprated one is 6% higher than replacing it with one of the same ratings [73]. Since the replacement process is an integral and regular part of network maintenance anyway, in order to upgrade the capacity, PE cost analysis should be introduced through models that show the future network benefits with and without PE approaches. This comparison will show and quantify the values of PE intervention in the DN.

2.9 Conclusions

It is clearly noticed from the LCNF project and their aim of reducing carbon emissions that networks will be facing capacity shortages and technical issues if they cling to the same traditional infrastructure in the face of rising and changing demand, which in turn will affect DNs. There is great concern among DNOs regarding the change of loads quantity and types, such as in the clusters of renewable energy intervention and increased EV chargers. The specific main constraints that would be faced in the distribution network is the situation of under/over voltage and thermal limitations due to the increased power flow in the lines. Those constraints could be exacerbated by events in single phase, which cause an unbalanced situation regarding voltage and thermal limit. Furthermore, treating such incidents is complex as it is not feasible to apply voltage limits on one phase without the other phases. However, PE projects have been introduced to overcome those problems by several approaches, as in pure PE solution. The overall question is whether the research is taking into account the difference between applying PE in distribution and transmission networks, beside the cost and losses issues.

PE applications, especially STATCOM, are applied efficiently in the transmission networks in order to control voltage and compensate reactive power, although they are often prohibitively expensive. This kind of PE is capable of being applied in the high voltage side of the distribution network (33KV). On the other hand, it is challenging to apply this kind of PE that depends on reactive power to compensate voltage in the LV side of the distribution network (400V), due to the resistive mode of the LV network according to the low X/R ratio, which makes reactive power injection less effective. Some approaches use DN series voltage compensators by injecting voltage as real power, which is the case of (UPQC). The DC links of PE are efficient in treating the imbalances between voltage and current, in addition to other benefits. From previous researches, it is obvious that increasing the amount of transferred power is possible through PE approaches in distribution networks.

Releasing power capacity and constraints in the network necessitates re-routing the power flow in the feeders, which is not possible in the radial distribution networks. However, inserting power electronics at certain points in the network or creating extra points for PE intervention can increase the limitation in networks and give more meshes for power flow. This flexibility could be reached in the last mile of the networks without digging each pavement to replace the traditional assets. Additional controllability can facilitate additional power through constrained lines.

PE intervention could be a feasible temporary solution that can delay expensive and extensive enforcement, and sometimes it could represent a long-term approach under monitored maintenance. PE projects are being researched and introduced, and some have been successful under LCNF. However, the research in this area and the designs introduced demonstrate a technical opportunity for DNs. The technical challenges in deploying these approaches are represented in proving the advantages practically and experimentally in trial fields to motivate some project such as LCNF to take a part and adopt those advantages.

The business case is at least as important as the technical issues in any engineering project, and generally there is some kind of trade-off between costs and benefits. However, the current snapshot of PE and its related cost dimensions reflects the nadir of its cost efficiency; it will become increasingly cost competitive with progress in the semiconductor industry and other technologies and ancillary business acumen (e.g. the familiarity of maintenance personnel with the new components), and more research is required over the coming years to decrease the cost level while maintaining and improving the technical advantages of PE.

A number of previous studies aimed to increase power flexibility and quality, some of them concentrating on controllability and functionality while others paid attention to cost, without providing a reasonable business solution. Furthermore, other studies consider cost in terms of equipment, capital, installation, maintenance, life cycle and operational cost, all of which are losses. These issues are subject to refinement by researches and engineering projects to reach a higher level of lifetime efficiency, and the relative efficiency of PE in future will improve compared to traditional systems due to issues of space constraints and locales in the DN pertaining to the need for increasing power density. Researches for solutions and approaches to this field should elaborate subjects such as materials of PE, semiconductors operation, circuit designs, topologies and control.

Several challenges and problems have been introduced in DNs, which could be met by PE approaches, addressing two main problems preventing DN feasibility in future loading scenarios:

- Voltage level problems such as under/over voltage and voltage fluctuations.
- Reactive power compensation for some loads in the last mile that operates on reactive power beside real power.

Therefore, PE intervention could take part in providing solutions for those two main problems in economic manners regarding cost and losses, without affecting the quality and functionality level. During recent years, the research in PE for distribution networks purposes have been developed and more knowledge has been gained by researchers, whereby both operators and PE research communities are aware of the challenges and advantages that PE could provide at the distribution level. This mutual understanding by both of them enhances the opportunities of radical change in DNs through PE approaches.

3 Power Electronic Technology

3.1 Power electronic technology

PE devices and technology is used in several applications, including PE blocks and conversions, in power semiconductor switches and converter design circuits that operate on several conversions between DC and AC levels, besides operating at different frequencies [76].

3.2 Background, history and trends

Power electronics underwent great growth after General Electric introduced the first solid state switch called Silicon Controlled Rectifier (SCR) in [77]. PE is increasingly used in the power conversion process from one or more AC/DC levels to another or more DC/AC levels, beside the control issue. Each conversion process contains two stages, the power conversion stage and the control stage as illustrated in figure 3.1 [77]. The converter of PE constitutes of several solid state switches that are controlled to transfer the power from one side to another according to a control topology, which controls the output depending on specific quantities, normally voltage, current and frequency. The control topology depends on a specific algorithm setup according to what is required from the system [77].

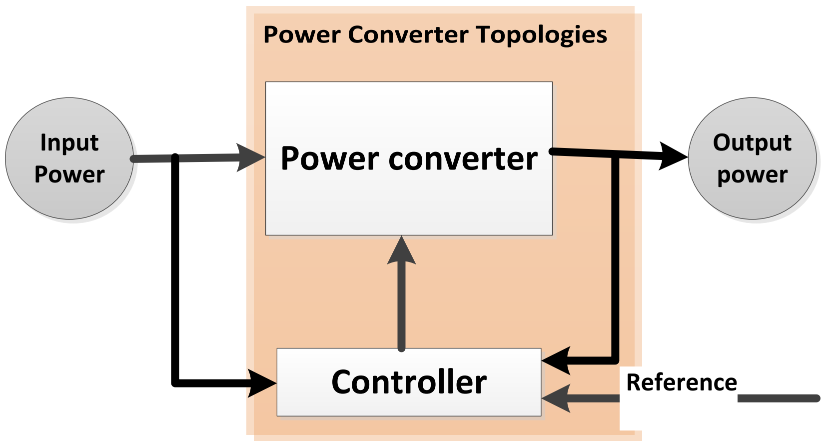


Figure 3.1: Power converter topologies.

The SCR introduction replaced the mercury arc rectifiers (introduced in 1902), Thyraton (1923), and Ignitron (1931), and was also used in several industrial circuit designs such as Chopper (1940), Cycloconverter (1920) and Graetz Bridge (1897) [76]-[78]. The SCR was the only used available PE device for more than 25 years and it remains efficient in high power applications. However, due to its difficulty in forcing turn-off condition, faster technology has appeared with higher voltage and current ratings, and more controllability was introduced with these applications. The new faster technology introduced bipolar junction transistor (BJT) in 1970. The BJT was used in several applications until the appearance of MOSFET (metal oxide semiconductor field effect transistor), introduced in 1978. MOSFET switches are applied in high frequency and low power applications, and the GTO is applied in high power and medium frequencies. IGBT was introduced in 1983 and is used in low-to-medium frequency and power [76]. The IGCT introduced in 1997 operates within low-to-medium frequency and medium-to-high power. These voltages, frequencies and current ratings operation for PE switches are shown in figure 3.2 [76], [77].

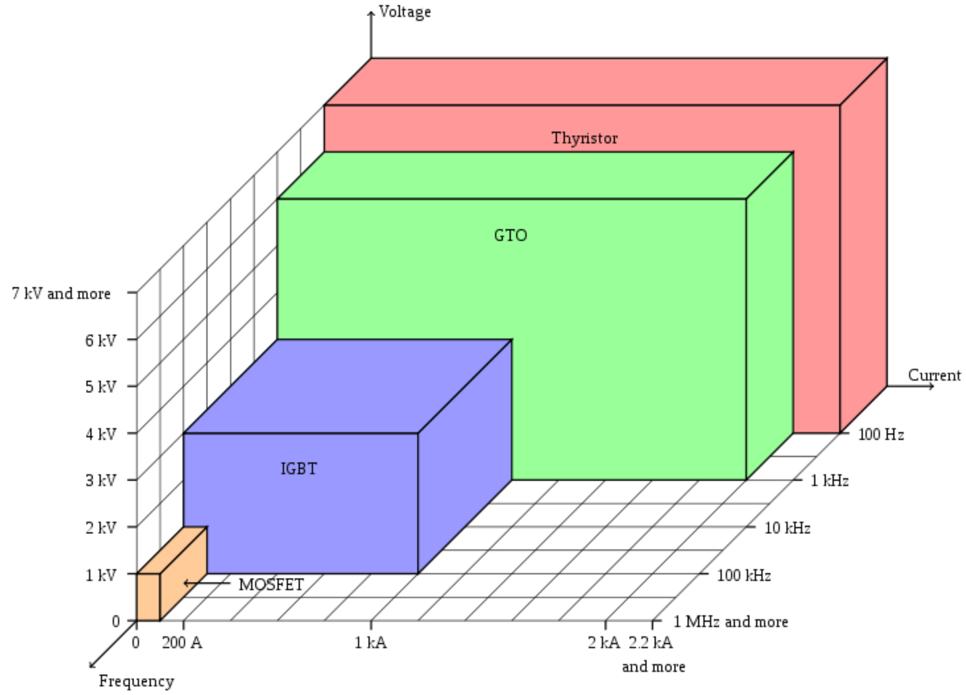


Figure 3.2: Domain of operation for PE switches (frequency, voltage and current)[77].

3.3 Topologies of PE converter

PE converters represent a switch mode that transfers power through the switching process of semiconductor devices. The power systems are either AC or DC, thus there are four kinds of converters: AC/AC, AC/DC, DC/DC and DC/AC [77].

3.3.1 DC/DC converter

It is considered as a circuit for switching regulation, as the topology modifies (bucks or boosts) the voltage level that comes from a DC source, such as solar cell, fuel cell and batteries. The purpose of changing the voltage level is to be suitable for either a

DC load or for control as an intermediate stage between PE converters such as AC/DC/DC/AC conversions. DC/DC converter usage is common nowadays in HVDC transmission lines [79].

3.3.2 DC/AC converter (inverter)

This is a topology that transfers the power from the DC form to a sinusoidal AC form to feed AC loads, or convert the DC power from DC sources such as fuel cells and PV cells to AC form connected to the AC grid. It is used sometimes to control motors also, but it is common as stage comes after the intermediate stages such as DC/DC converters [78], [80].

3.3.3 AC/DC converter (rectifier)

This kind of topology is used to rectify the sinusoidal AC voltage sources to a constant DC level. It is common in converting power from a voltage source that operates at 120V/60Hz or 230V/50Hz, which are the same ratings that are used in distribution networks. The converted unidirectional voltage is used to feed DC pure resistive loads or to control DC motors. The DC output voltage is controlled sometimes by using a further stage of DC/DC converter or DC/AC converter. Rectifiers are used normally after several electrical applications and it is supposed to be installed and designed properly, otherwise it would cause harmonics and low power factor due to the switching and conducting losses [80].

3.3.4 AC/AC converter

Conversion from AC to AC requires more complex topologies than the other converters as it requires changing the voltage magnitude, frequency, and capabilities of bipolar voltage blocking. Converters that have the same ratings for input and outputs regarding voltage and frequency are known as AC controllers. Other AC/AC coveters are used to convert Constant Voltage and Constant Frequency (CVCF) to Variable Voltage Constant Frequency (VVCF), which are used in controlling AC motors. Cycloconveter is known as the topology of converting from CVCF to variable frequency and voltage, and when the switches are completely controlled, the topology is known as matrix converter [77].

The aim of AC/AC conversion could be reached by connecting two of the converts together (AC/DC to DC/AC). This type of converter passes through an intermediate area for the DC link. Complex control topologies are required for this kind of converter as its instant regulating and rectifying processes are required together at the same time, whereby it can control the amount of injected power and the direction of power flow [79], [80] .

3.4 Advanced converter topologies

A combination of several power conversion topologies with advanced power converters techniques can form an advanced converter topology with extra benefits for complex requirements [77].

3.4.1 Matrix converter

A matrix converter operates using several inputs and outputs switches that represent multiple conditions or operational moods. It can be shown that controlled bidirectional switches (i.e. with four quadrants) that operate at high frequency have X inputs and Y outputs, as shown in figure 3.3 below, representing a case of equal inputs and outputs (x=y=3), which is considered a three phase AC/AC converter [77].

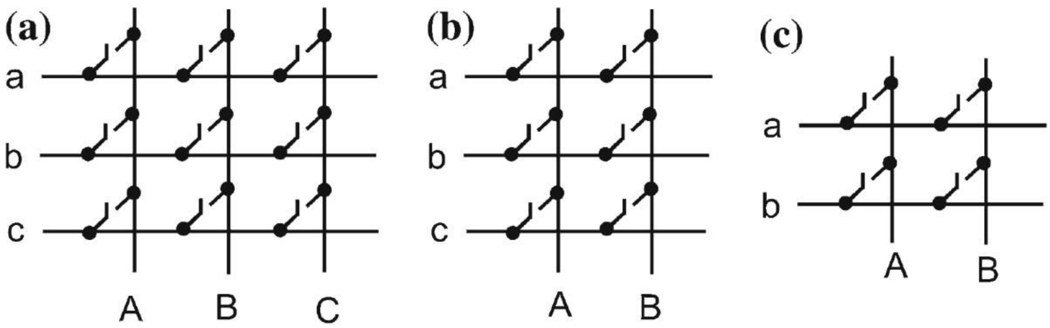


Figure 3.3: Examples of matrix converter cases,

a) AC/AC b) AC/DC c) AC/DC, DC/DC and DC/AC.

Figure 3.3b represents the case for x = 3 and y = 1; in this case it operates to convert from three phase AC to DC, or conversely from DC to three phase AC. Figure 3.3c represents the case for x = y = 1; in this case the converter could take three converting forms (AC/DC, DC/DC and DC/AC) [76]-[78]. The switches used in this type of converters are fully controlled switches with diodes, as shown in figure 3.4 below [77].

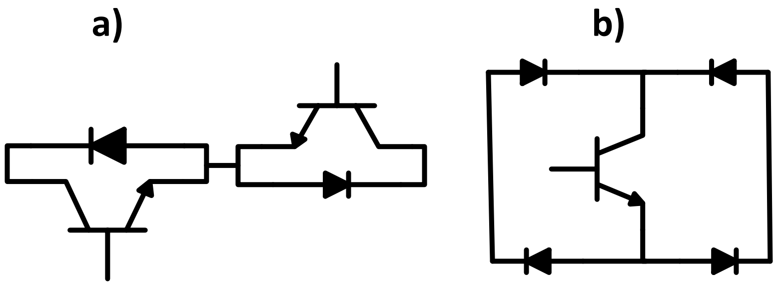


Figure 3.4: Fully controlled and bidirectional switches [77].

The matric converter gained interest in several applications since its appearance due to recent improvements in the area of PE switches and converter topologies [77].

3.4.2 Multilevel converters

Multilevel converters consist of series converters that are connected together with splitting capacitors for high voltage approaches. Figure 3.5 shows a multi-level converter in the form of modulated series converters with a staircase waveform [77].

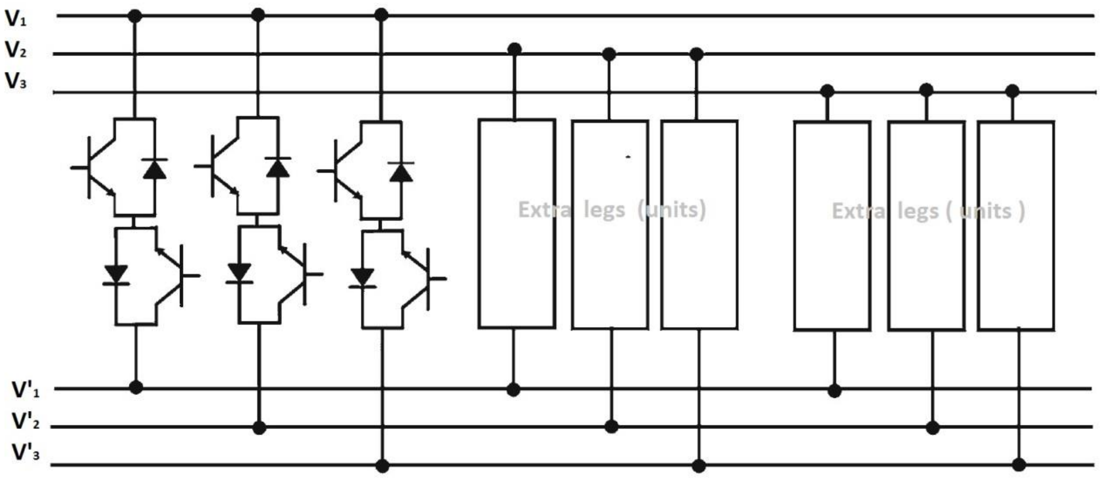


Figure 3.5: Chart of three-phase multilevel converter (AC/AC) [77].

A three-level converter consists of two converter units connected in series and two capacitors connected with the neutral, where each leg or unit consists of a pair of PE switches, as seen in figure 3.6a, [77]. The output waveform is synthesized to add more degrees or steps to the waveform, whereby the number of steps is increasing with the number of converter levels to form a more refined waveform, as seen in figure 3.6b [77], [81].

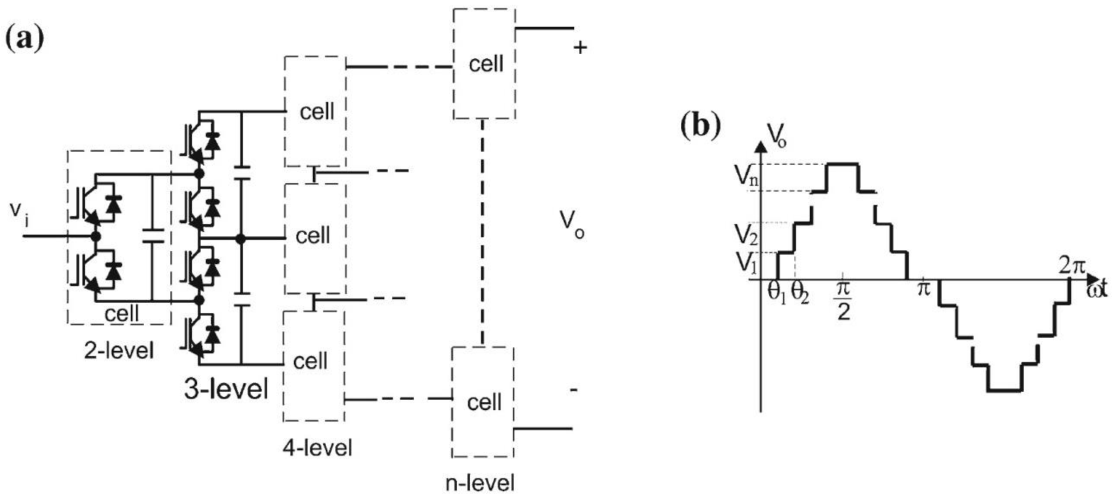


Figure 3.6: a) Multi-level inverter, b) output waveform.

Another configuration for the multi-level converter could be performed using cascaded H-bridge with cascaded topology. DC sources are used in this topology separately, connected with each unit from two levels to several (i.e. five) levels, as shown in figure 3.7. The output form is controlled normally using PWM technique [77].

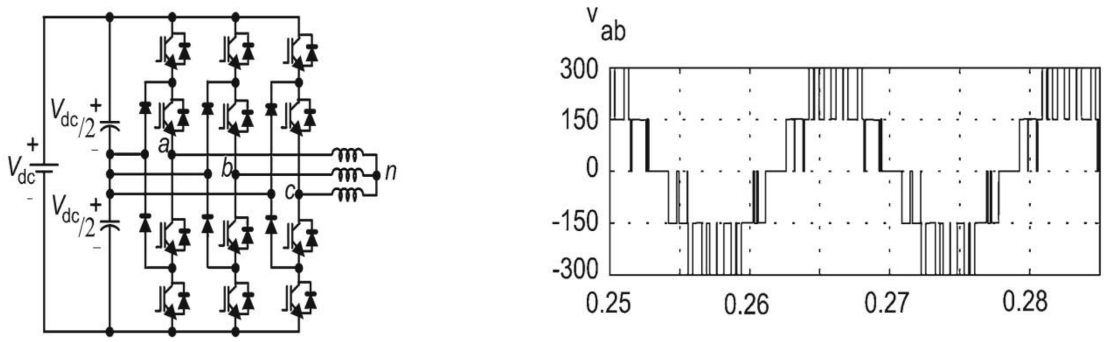


Figure 3.7: Natural point clamp (NPC) multilevel inverter bridge converter (left), NPC output waveform (right).

3.4.3 Back to back converter

Back to back converter consists of two converters, one for AC/DC rectifier conversion and the other for DC/AC (inverter) conversion. It is considered to comprise two bridges whereby the front end of the first converter is connected to the back end of the second converter, as seen in figure 3.8. One of the advantages of back to back converter is the ability of imposing fast control on the power flow, where the DC link is fixed at constant voltage level in order to control the power flow for the output [82]. Thus a fast response controller guarantees a smaller size for the DC capacitor without affecting the operation of the inverter or its response performance [83].

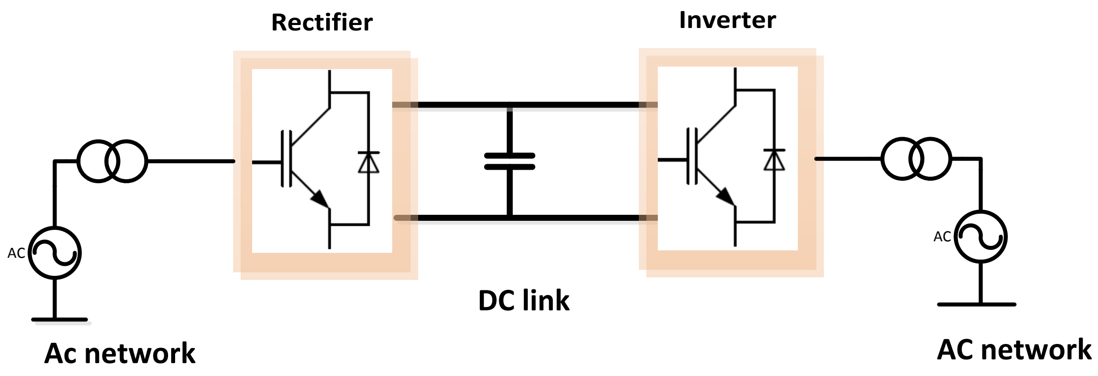


Figure 3.8: Single line diagram of back to back converter structure.

The converters in this type of converter are known as line converter (AC/DC) and load converter (DC/AC). Both of the units are normally voltage source converters that deal with three phase systems [59]. Back to back converter has the potential to be used in several applications due to its control performance. For instance, it could be used in the transmission line, such as in UPFC, as shown in the figure 2.10.

3.5 Control of power converters

The control purpose for PE converters depends on what is required from the converter in the power grid. Control purposes include voltage control, current control, DC link voltage or current control, harmonics elimination, machine speed control and so on. The control strategy normally consists of two loops that control two variables, the inner fast loop and the outer slow loop, the latter of which takes action depending on the outcomes of the former. For example, the control of a rectifier consists of two loops, one of which (the inner) is fast for the current and the other of which (the outer) is slower for voltage [77], [84] .

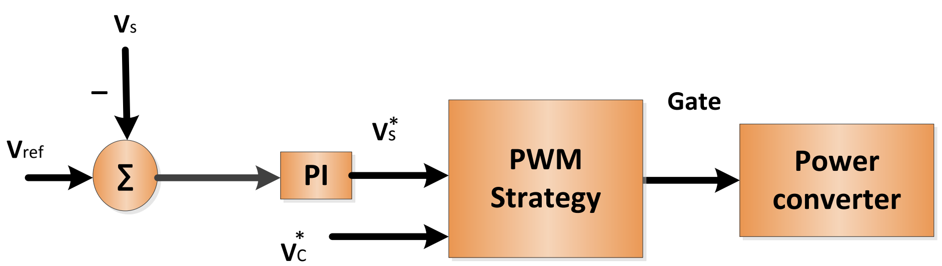


Figure 3.9: General variable controller strategy [77].

By considering the control of voltage, as seen in figure 3.9, PMW technique is used, where V_s is the controlled voltage that is compared with a reference voltage V_{ref}. The resultant error is modified by slow control regulator such as proportional Integrative controller (PI), where this regulator is modified according to the control variables requirements. Voltage control is done normally for converters such as VSI, where the reference between the measured voltage and reference voltage (V_s- V_{ref}) is called error and it is fed into a controller (proportional integrative, PI), the output of the controller or the controlled voltage V_S^* is used to produce a PWM signal by comparing it with a carrier signal V_C. This comparison produces a duty cycle used to operate the switching process of the converter [77], [85].

The control approach for voltage could be applied also by using tow loops as seen in figure 3.10, one of which (the inner) is fast for the current and the other of which (the outer) is slower for voltage. The output signal of the slow loop is used as reference for the internal fast loop. This kind of control is more accurate than the slow one as it has two separate variables to control, but both of them are dependent on each other. The output signal of the controller or regulator (PI1) is compared with template signal in order to produce the reference for the internal loop, thus the process ensures fast control operation, as seen in figure 3.10 [77], [86]. The inner loop includes another regulator or controller (PI2), where the inner error (I_{ref} - I_s) is controlled after a comparison with a reference I_{ref}. The output of the inner controller I_S^* is used to feed modulation of the PWM technique, as shown in figure 3.10 [77].

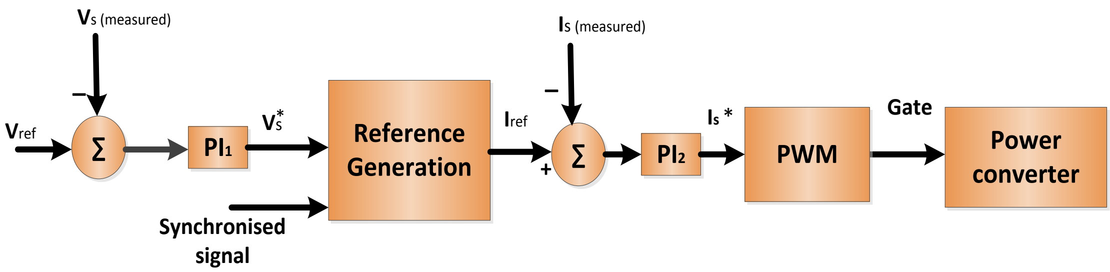


Figure 3.10: General control strategy for converters [77].

Applying the last scheme on a Voltage Source Rectifier (VSR), as shown in the figure 3.11 controls the PWM by fast and slow controllers' loops. In this control, the voltage and current are controlled as they are the objectives of the controller. I_s is the measured current of the grid and Vs is the measured voltage of the DC link capacitor. The regulator or the controller could be any of P, PI, PID, and fuzzy controllers. The inner loop (current loop) reference (I_{ref}) is supposed to be a sinusoidal signal, which is taken from the output of the outer loop control (voltage loop). The output of the outer loop is multiplied by a reference signal that has the same frequency and phase-shift of the main grid waveform. The final outcome of the outer and inner loops is used by a PWM stage to produce a switching pattern that is able to impose the current to behave as the required reference I_{ref}. The controller stability could be reached by application of a suitable gain adequate with the circuit parameters [87].

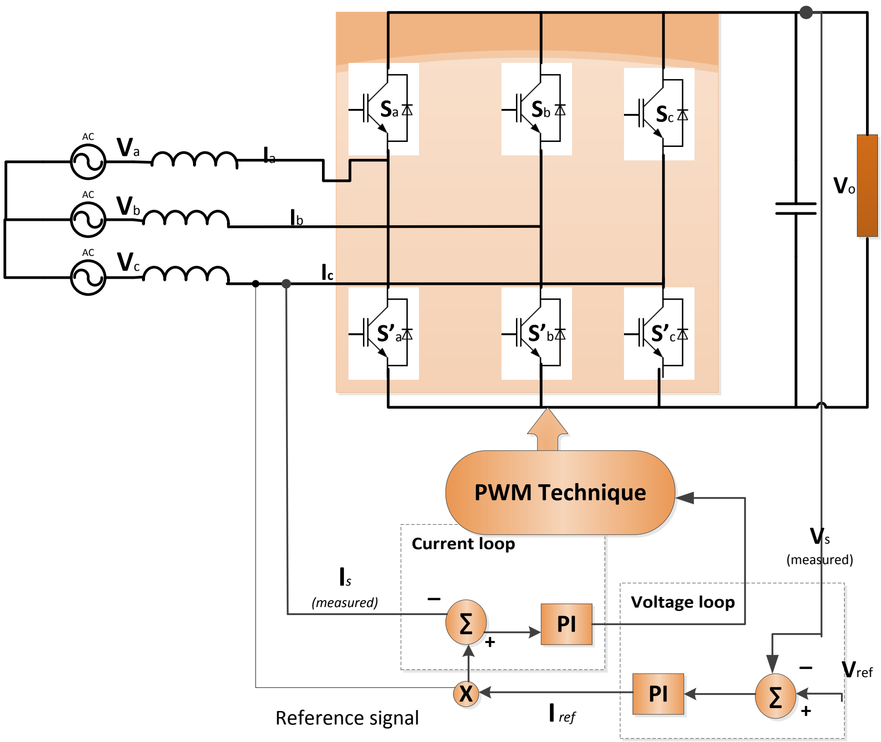


Figure 3.11: Voltage current controller for three phase converter [77].

Advanced control strategies could be used to control the output voltage and current of a converter, such as space vector controller seen in figure 3.12. In this controller, the three phase system is transformed to two components according to the value of *dq* coordination; the references and controller inputs are processed into *dq* components [77].

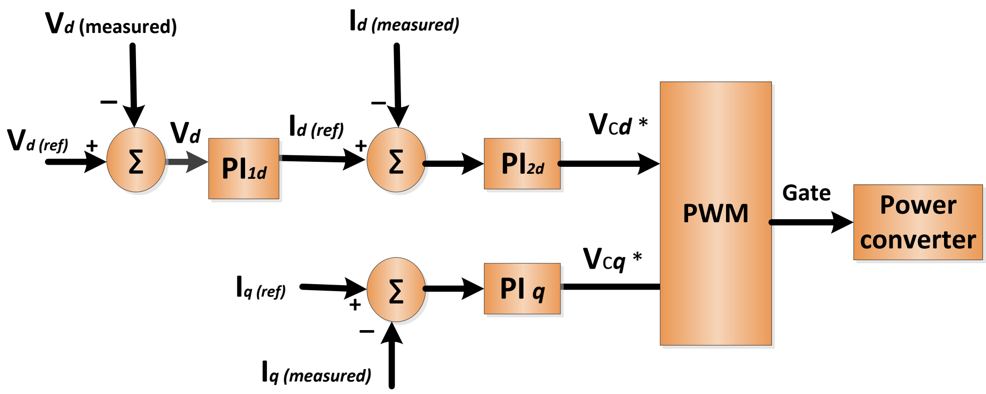


Figure 3.12: Space vector control strategy [77].

As seen in figure 3.12, a current controller is divided into two parts I_d that represents the real current, and I_q which represents the reactive part of the current. I_q is fixed at zero to perform unity power factor. The controlled values of V_{cd}* and V_{cq}* are given after applying to PI controllers, driven into inverse transformation to obtain *abc* form, which is used to get the gate pulses through the PWM comparisons. A space vector controller could be used to fix the voltage at the DC capacitor link side in a back-to back converter [77].

3.6 Pulse width modulation (PWM)

Any previous discussed control scheme needs a PWM technique in order to produce a pattern for switches operation. There are several strategies that are used to control switches that vary from simple to advanced techniques. Specific techniques are used to control each type of converters according to function (AC/DC or DC/DC or DC/AC). The pattern of generated pulses by PWM is modulated depending on the variation of either the slope of carrier signal or its amplitude, as seen in figure 3.13 [77].

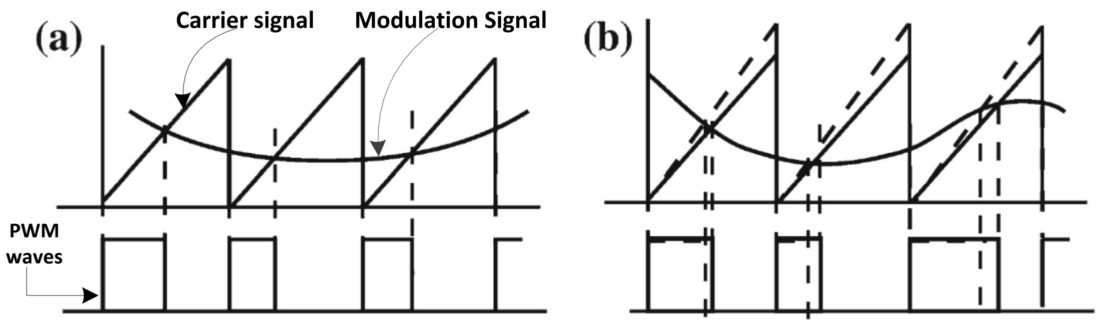


Figure 3.13: (a) PWM by varying control voltage wave over carrier wave (b) PWM by varying the carrier wave.

PWM is commonly used in controlling the output voltage of VSC and a lot of research efforts have been made in this area by researchers and designers, with several major techniques being discussed [86], [88] that deal with several functions such as those used in harmonic elimination [77], [89]. The most common technique of PWM is the Sinusoidal Pulse Width Modulation (SPWM), Space Vector Width Modulation (SVPWM), and some Hybrid techniques that use both methods (HPWM) [77], [89].

The PWM strategy used in VSI is the almost same as that used in VSR, but the function of the controlled PWM in VSR is keeping the DC voltage link at a specific constant level. Therefore, the PWM in VSR is required to change its index according to the DC voltage level variations beside its function reducing the harmonics at the converter input by choosing also the right modulation index for the input PF [85].

3.7 Carrier modulation

The normal PWM is done as a comparison result between the triangular wave with carrier frequency and sine wave with modulating frequency, as seen from figure 3.13. This kind of modulation is known as SPWM, as it includes sinusoidal wave [76]. The SPWM is applied (as shown in figure 3.14) on a half bridge inverter. The out voltage depends on the comparison between the modulating signal and the carrier signal. If the sinusoidal signal is higher than the carrier signal, the output voltage will be positive and equal to $\frac{V_{dc}}{2}$; on the other hand, if the carrier signal is higher than the sinusoidal modulating signal, the lower switch will be one and the output voltage will equal - $\frac{V_{dc}}{2}$. This ration between carrier and modulating signals amplitude is called the ration of amplitude modulation (m_a), and the ratio between both of the signals' frequencies is called frequency modulation (m_f) [77].

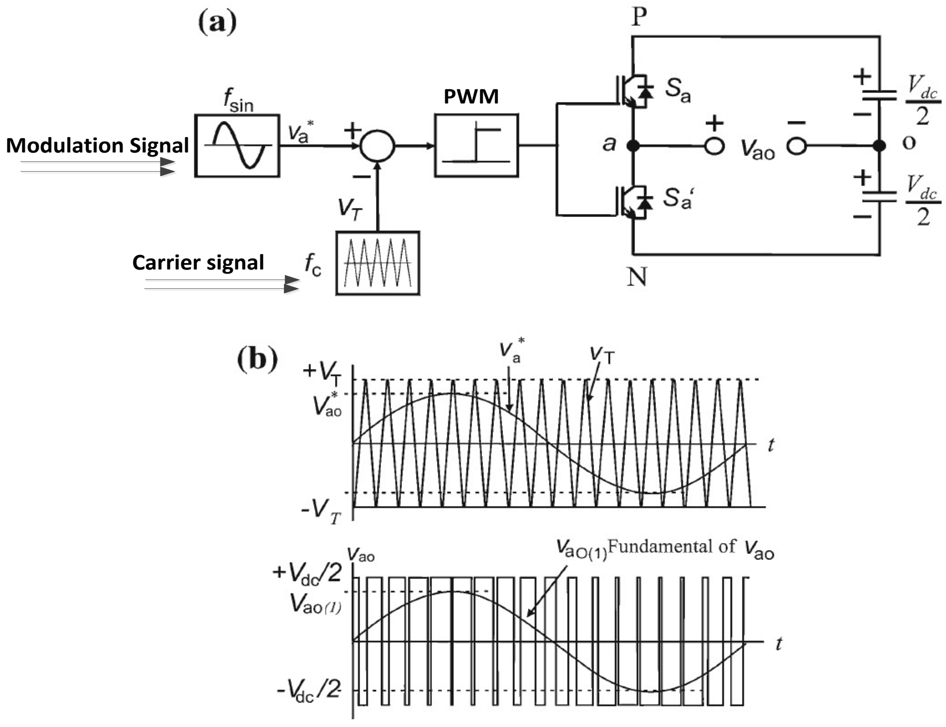


Figure 3.14: (a) Sinusoidal Pulse Width Modulation for half leg inverter (b) input control signal (upper) and output voltage (lower).

The fundamental frequency voltage V_{ao} is linear and its component is calculated as in equation (3.1) when the frequency amplitude is high [77]:

$$V_{\text{ao}} = m_a \frac{V_{dc}}{2} \tag{3.1}$$

An SPWM is shown in the figure 3.15 for a three-phase inverter, where three modulating signals are compared with one carrier signal to produce a three gate driving pluses; figure 3.15 (c) and (d) shows the output voltage for the inverter as line-to-line voltage and phase voltage [77].

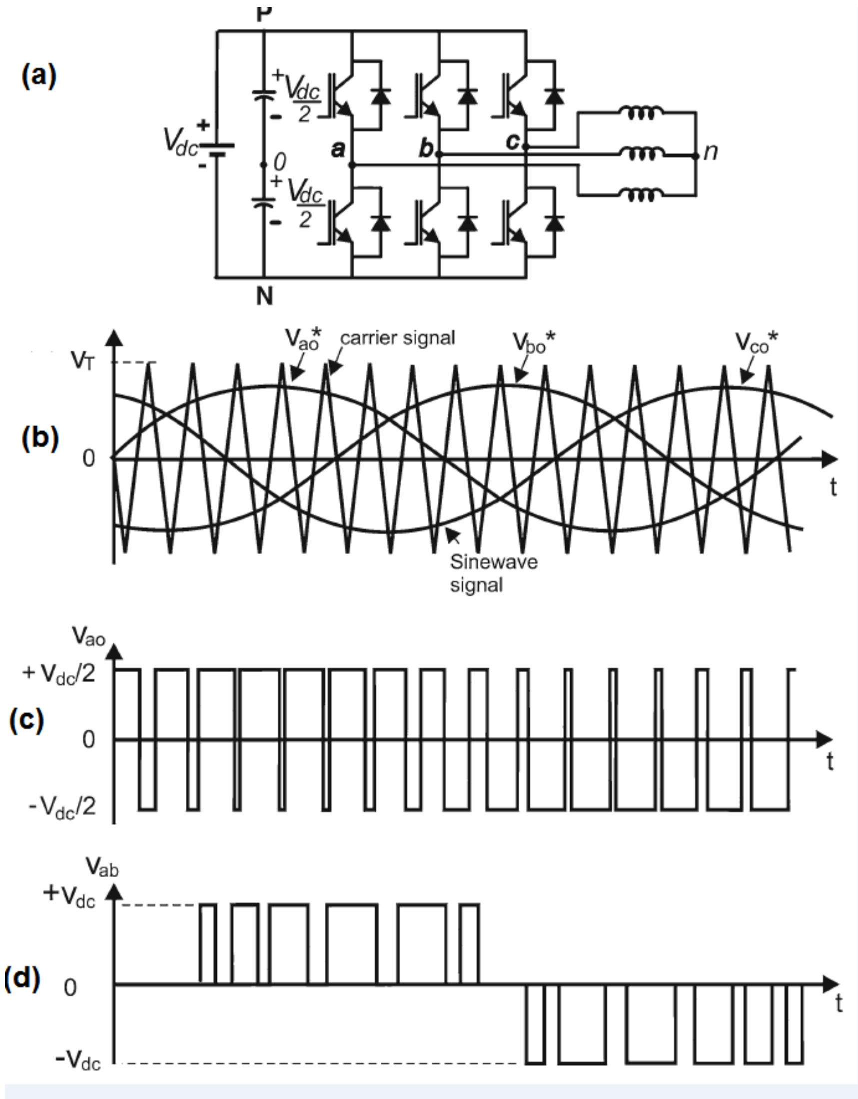


Figure 3.15: Three phase SPWM: a) Full inverter 3ph circuit, b) SPWM control signal and converter output voltage.

The combination of switches of the three phase inverter above gives eight output conditions for the three legs of the inverter according to the following table, where “P” represents the upper switches and positive conduction, and “N” is for the negative conduction [77]:

Table 3.1: Eight output conditions for the three legs inverter

Combination 2	PPN	Combination 6	NPN
Combination 3	PNN	Combination 7	NPP
Combination 4	PPN	Combination 8	NNN
Combination 2	PPN	Combination 6	NPN

3.8 Conclusion

The chapter included an overview of the main principles and technology used in power conversion and the functional role of the converter in its operation, such as AC/DC, DC/DC, DC/AC and AC/AC. It also included the common control techniques used to control the switching operation of converters through PWM. Other advanced techniques could be found in previous studies [90]-[92] such as soft switching for less switching losses and several control designs depending on the purpose of using PE. As mentioned in the previous chapter, more conversions means more losses, which should be taken into consideration before building any PE module, as there is a great challenge in convincing NGOs in the trade-off between the losses of PE and the gained benefits. The next chapters demonstrate the use of converters and PE technology in general in distribution networks in order to raise the functionality of last mile equipment regarding voltage regulation and reactive power compensation control techniques. A proper control for PE switches means increasing the level of functionality and flexibility for those devices, besides decreasing the amount of losses that stand as a barrier between applying PE in LV networks and its high functionality.

4 Voltage regulation in LV networks

4.1 Introduction

One of the main utility's core responsibilities is to deliver voltage to loads within a suitable and acceptable range which requires a voltage regulation process from the utility. On LV network, voltage drop occurs due to the resistive natural of the cables beside the impedance of the transformers; this chapter represents and tests the feeders and phases in LV network in several conditions in order to allocate and assign an optimal voltage regulation for the LV substation such that Providing the best voltage profile on the feeder or the phase leading to efficient performance for voltage and Improving the system operation, power factor and reducing system losses.

Voltage profile control, losses minimisation, voltage balance and power factor correction were considered and carried out in the light of exploring the ability of power electronics to achieve them. Owing to the future expectations of load growth, the design of the LV substation lies under critical requirements and improvements due to the increase of voltage drop and losses in the LV network by the time [93].

Several voltage profiles and conditions are carried out using MATLAB to investigate the behaviour of the voltage, losses and PF at the secondary side of the transformer in order to determine; the suitable voltage control strategy for each individual phase, the voltage limits to be applied, and the suitable power electronic solution that could have a wider impact on the voltage at the terminal of LV substation.

Several topologies are being considered and discussed in order to reach the aim of this chapter in order to achieve the followings:

- Provide the best voltage control on the feeder or the phase according to several scenarios that are tested and investigated.
- Lead to an efficient performance for voltage (constant voltage).
- Achieve voltage balance at the transformer sides and between feeder phases.
- Construct new approaches to voltage regulation at the substation
- Introduce the suitable control strategy used in PE for the purpose of achieving the above aims

Low voltage (LV) circuits are quite different than the High Voltage (HV) circuits, where they have a resistive nature more than the inductive nature, which means that these circuits are capacity constrained on voltage regulation and not current flow [93].

Owing to the expectations of increased load growth in future, the design of the LV substations entails specific requirements and improvements depending on the flexibility of PE in order to decrease the voltage variations and losses in LV network. The absence of tap control in 11/0.4 kV transformer addresses a voltage regulation problem: the existence of High Voltage (HV) tap changers cannot help in case of load rich feeders in the last mile of the network. Voltage regulation could be feasible in the LV network by using PE functionality attached with the last point in the network.

The Hybrid distribution transformer is introduced as an approach that has the potential to upgrade the operation of the new LV substation to a new level that has the ability to meet the demand of the future distribution grid from an efficiency, controllability and volume perspective. Hybrid Transformer HT is used in this chapter to address a solution for the problem of voltage regulation by using its partial ratings solid state switches. Several schematic and topologies for the hybrid design are introduced in this chapter besides two control approaches that were used to control the partially attached back- to –back converter with the transformer.

4.2 Power Distribution Systems

The electric utility system usually consists of generation, transmission and distribution. The last mile of the network consists of substations where the voltage is stepped down so it can be distributed to the users. There is a large number of factors accounted for when building a substation like load intensity, capacity, reliability equipment's, load growth, voltage drops, cost and losses, therefore the design of substations is supposed to take into consideration the previous factors.

Commonly, there are two types of distribution networks, one for the country and one for the city. The density of these networks is much larger than the transmission systems feeding them. Differences between these networks depend on devices, and widely varying types of loads. The proportion of the usage of distribution networks has significantly changed, especially in rural areas where distributed generation percentage is increasing by the time such as photovoltaic, wind and micro turbines and combined generation. The installed generation power is installed sometimes without taking into consideration that it could be significantly higher than the consumption. DG causes altered power flow direction where the conventional power network considers a unidirectional load flow. Thus, the power flow may even become bidirectional. This temporary reversal of the power flow can affect voltage rises, especially at feeder ends far away from the substation.

There are several loads types that are considered in the investigation of the behaviour of the voltage at the LV network where these load categories are affected differently by voltage Variations:

- Constant current load: The current stays constant as the voltage varies, but the power changes proportionally with voltage. As voltage decreases, the current draw stays constant, so the voltage drop is not affected [94].
- Constant impedance load: The impedance stays constant as the voltage varies; the power is proportional to square voltage. As voltage decreases, the current draw decreases lineally which decreases the voltage drop. This type of load is used normally to simulate resistive loads and incandescent lights [94].
- Constant power load: The apparent power (*S)* (real and reactive power) stays constant as the voltage varies. As voltage decreases, the load draws more current which increases the voltage drop in the cable. A constant power model is normally used in the simulation of the induction motors [94].

The voltage tolerance that is allowed is usually a tolerance of 10% [94], [95]. If the voltage exceeds these limits, other devices and equipment might be damaged.

To better understand why the regulation of voltage makes power systems more efficient, an investigating has been done in:

- Voltage Drop Scenarios in LV network.
- Voltage Behaviour in LV Network at different PF values.
- Voltage Versus distances and demand (future expectations).
- Losses and their relations with voltage regulation.
- Voltage imbalances at the sides of the transformer.

4.3 Voltage Regulation Problem

Conventional design of the substation considers delivering the power from the transformer to the several loads along each feeder, where the impedance of this feeder causes voltage drop besides the impedance of the transformer. Therefore the designers keep the voltage up the nominal voltage at the secondary side of the transformer to compensate this voltage drop that is caused by the transformer and the impedance of the feeder.

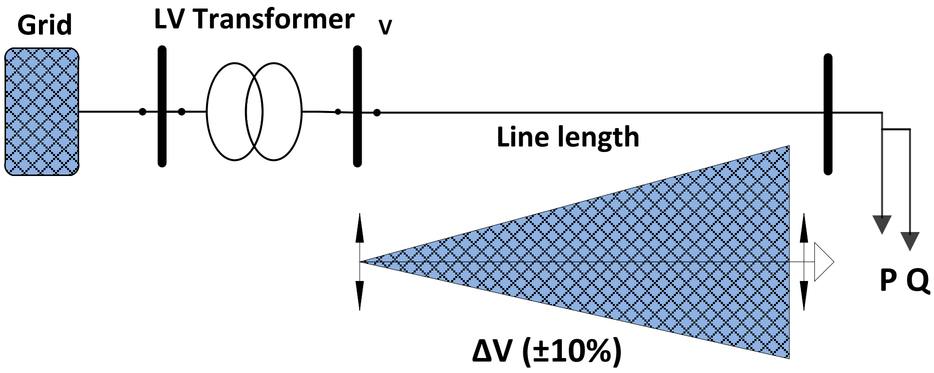


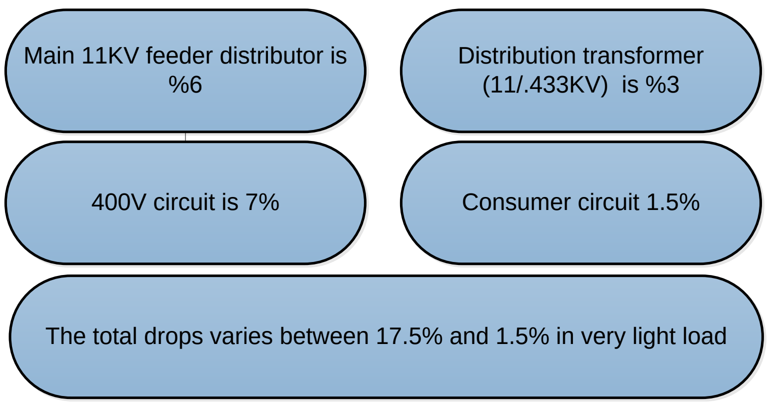
Figure 4.1: Voltage drop through feeders.

In the distribution transformers, the ratio between the primary voltage and the secondary voltage cannot be changed, where use of the on load taps changers -that in used in transformers- are limited especially in UK [95] . Poor voltage regulation is a direct reason for losses and shortening the life of several devices, a proper voltage regulation improves the quality of the delivered power. In low voltage conditions, the equipment work at lower power factor and draw more current with constant power consumption, which means more losses in the feeders due to the relation $P = I^2\mathrm{R}$ [94].

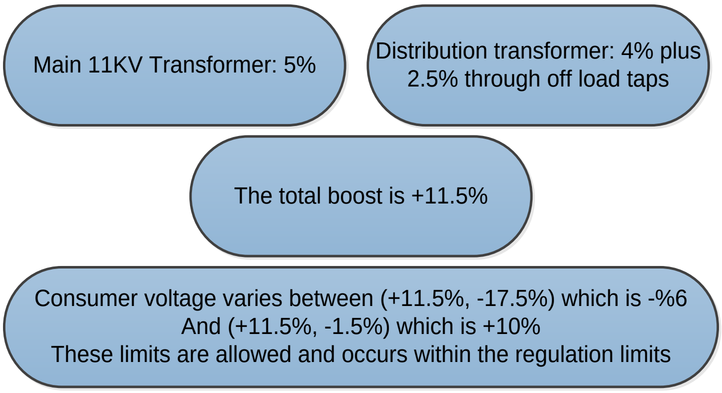
How is voltage regulation term understood and applied in the British LV network?

The older specifications recommends "240V -10, +6%", this means the voltage has a limit of 216, 254.4V. The newer spec (EN50160) recommends "230V -6 +10%" and translates into 216.2, 253V [96], [97]

- The typical voltage drops in the distribution in UK



- To compensate this drop, several voltage boosts are applied in different areas of the network



The voltage level at the substation should be installed high enough to compensate the voltage drop in the line under maximum load conditions

4.3.1 Voltage drop scenarios

The LV system is tested under several conditions to investigate the voltage behaviour at the substation during the current and future scenarios. The used initial system is a balanced three-phase system as an initial state to investigate the voltage behaviour in a radial network. The distribution network data and configurations were modified in the later subsections to include more investigated conditions. Loads and line sections data are as shown in table 4.1.

Table4.1: System data.

Frequency	50Hz
Input power in the radial system	750 KW /1.5MW
Primary side	11Kv
Voltage of the secondary side	430 (3pH) 230v (single phase)
Each feeder (minimum load)	250 KVA
Number of loads connected to each feeder	15
Type of loads	$R+(X_L-X_c)$
Transformer voltage drop at full load	4%
line Drop	6% for 1KM

The following circuit in figure 4.2 has been simulated using MATALB in order to do the forthcoming tests in the followings sub-sections. The network data in table 4.1 have been used as an initial state for the simulation in order to extract and investigate the results, the measurements for the V_{rms} values have been taken basically at the secondary side of the transformer for each phase (at the beginning of each feeder) in order to study the behaviour of the voltage in the LV network. However, the research in this chapter focuses on the situation of the transformer (11/.43KV) and its ability to deal with voltage variations at the secondary side. The locations of the main measurements for voltage are shown in figure 4.2. The detailed MATALB circuit is illustrated in Appendix A.

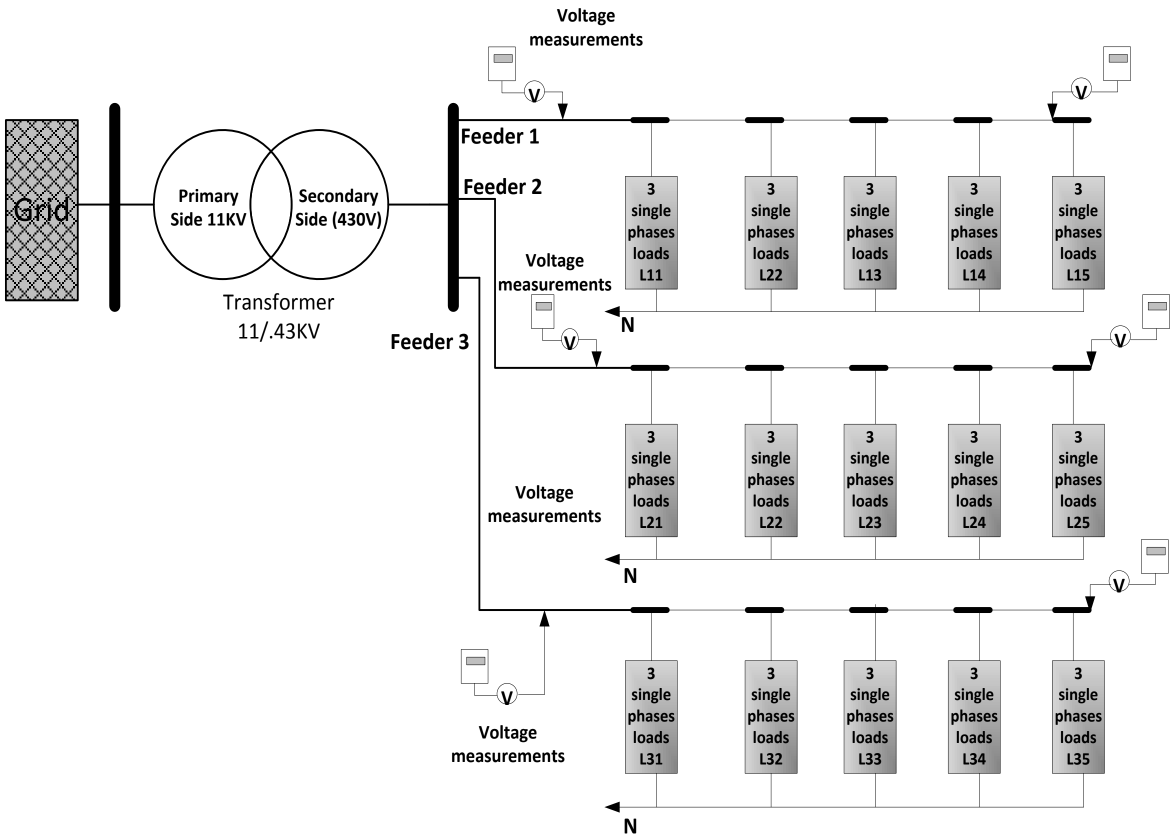


Figure 4.2: A single line diagram for the simulated and tested LV network.

The following subsections represent the simulations and tests that have been done using the network in figure 4.2 and depending on several conditions for the current and some of the future scenarios of voltage behaviour and network situations. The condition of the network has been changed using a MATLAB programing code (attached in Appendix B) in order to reflect the practical networks.

4.3.1.1 *Equal loadings for phases and feeders*

The ideal case for a distribution network could be reached by applying balanced system and loads, the behaviour of the voltage is tested and investigated at:

- Fixed demand and variable distances.
- Fixed distances and variable demand.

The results of the simulation are shown in table 4.2 for a fixed demand **and** different distances between loads (remote loads). And the voltage measurements for fixed distances and variable demand are shown in table 4.3.

Table 4.2: Voltage versus distance.

Distance (m)	V_{rms}	per unit
200	244.34	1.06
400	240.97	1.05
600	237.80	1.03
800	234.81	1.02
1000	231.99	1.01

Table 4.3: Voltage versus demand.

Equal loadings for 1Km distance		
Demand for each phase KVA	V_{rms} (each phase)	Per unit
250	247.93	1.08
350	247.69	1.08
450	247.40	1.08
650	246.66	1.07
750	246.20	1.07
850	245.68	1.07
950	245.11	1.07

The voltage is decreased by increasing the demand due to increasing the current that flows from the transformer to the load. The load draws more current which increases the voltage drop in the cable.

As the distance increases, the voltage drop increases in the cable, this condition appears clearly at the end of the feeder where the remote load receives the power at low voltage, and sometimes it goes below the regulation range. The behaviour of the voltage is illustrated in figure 4.3 for both of the conditions; fixed demand and variable distances, and for fixed distances and variable demand.

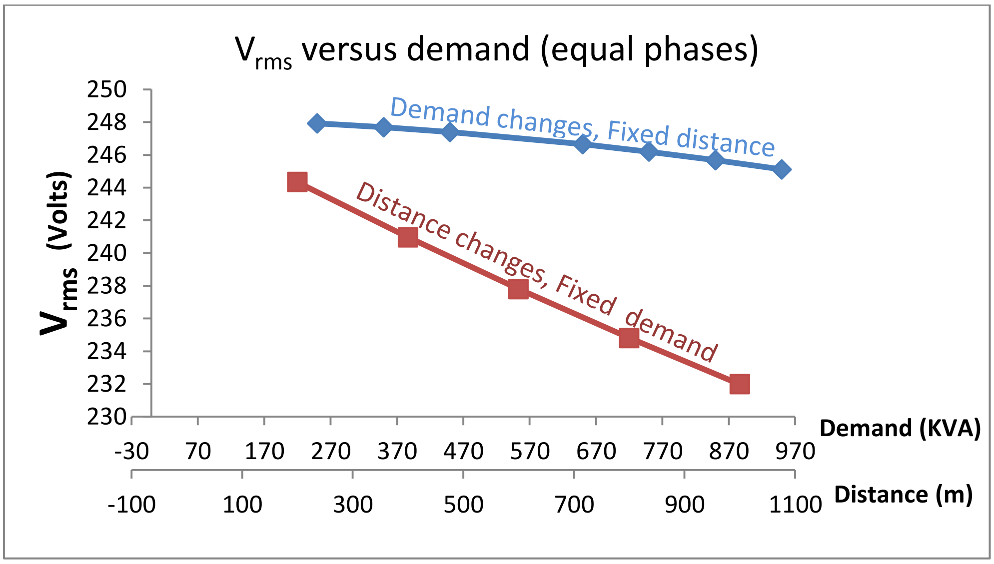


Figure 4.3: Voltage versus demand and distance.

4.3.1.2 *Unequal Phases*

The voltage is measured at specific nodes to allocate the state of the LV network feeders; the most important node that could control the range of the voltage for the other loads along each feeder is the first node after the substation transformer on the 0.43Kv side a seen in figure 4.2. Therefore, the voltage measurements are taken for each phase, where each feeder consists of three phases. This is normally set up according to the data that is provided regarding the cables and the amount of demands.

The scale of loading is shown in table 4.4, where it was being changed periodically by the MATLAB code. It represents unequal loadings for phases and feeders retroactively.

$S_{Load} = S_L$ = 16.67 KVA starts to increase gradually.

$S_{Feeder} = S_F$ = 16.67 KVA x 15 (number of loads in each feeder) = 250KVA.

Table 4.4: Loadings data for unequal phases.

	PhA=2SL	PhB=1/4SL	PhC=3/4SL
F1=2Sf	4SL	1/2SL	3/2Sl
F2=1/4Sf	1/2SL	1/16SL	3/16Sl
F3=3/4Sf	3/2SL	3/16Sl	9/16SL

4.3.1.2.1 *Voltage Imbalance*

The results of voltage measurements for each phase, and the percentages of voltage imbalances between phases are taken at the secondary terminal of the transformer (LV substation) and before the first load, the Rms voltages are illustrated in table 4.5. The voltage differences between phases are shown in figure 4.4 for different loading values where the demand was increased in steps of 10KVA.

Table 4.5: Load Imbalance and Voltage Imbalance.

Demand S_L (KVA) 10KVA increment	**PhA (v)**	**PhB (v)**	**PhC (v)**	**Average voltage (v)**	**Maximum Deviation (%)** from 230 V rms	**Voltage imbalance (%)**
16.67	247.23	248.16	248.09	247.83	0.34	**0.14**
26.67	246.15	248.06	247.91	247.37	0.69	0.28
36.67	244.88	247.95	247.65	246.82	1.12	0.45
46.67	243.48	247.81	247.31	246.20	1.61	0.65
56.67	242.01	247.67	246.89	245.53	2.15	0.87
66.67	240.50	247.53	246.41	244.81	2.71	1.11
76.67	238.97	247.37	245.86	244.07	3.30	1.35
86.67	237.44	247.22	245.26	243.31	3.91	1.61
96.67	235.91	247.06	244.62	242.53	4.53	1.87
106.67	232.90	246.73	243.22	240.95	5.78	**2.40**

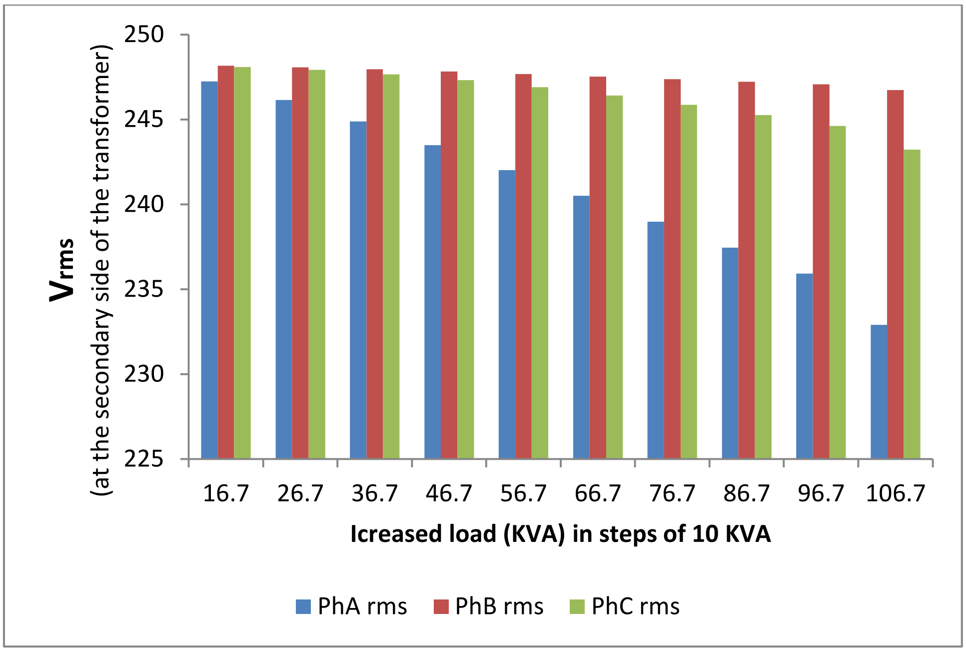


Figure 4. 4: Over/Under voltage for each phase.

The percentages of voltage imbalances (at the secondary side of the transformer) are calculated according to equation 4.1 [98], and shown in figure 4.5, whereby the maximum deviation is calculated according to the nominal voltage value which is 230V.

$$V\ imbalace = 100\ \frac{(\,maximum\ deviation\ from\ average\ voltage}{average\ voltage}\ \% \qquad (4.1)$$

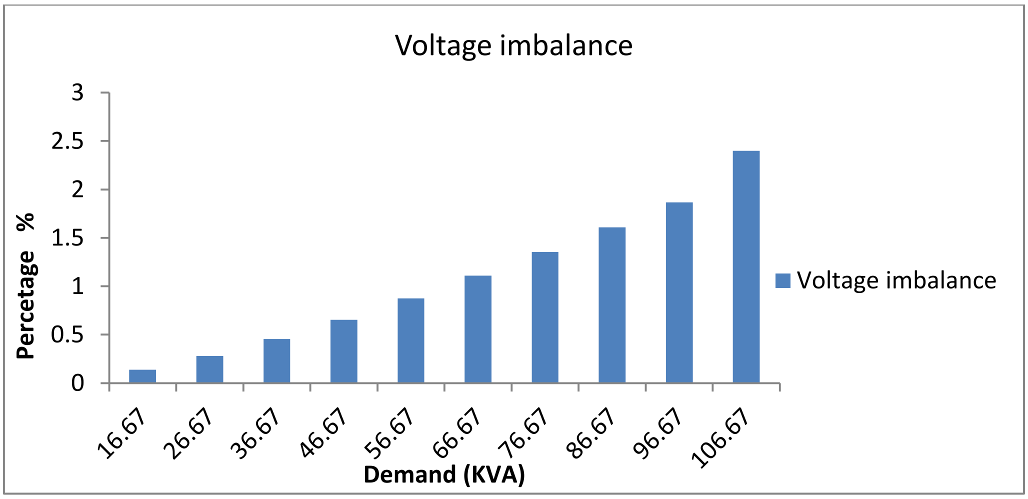


Figure 4.5: Percentage of voltage imbalance at different demands.

The voltage imbalances are increasing by increasing the demand as seen in figure 4.5, where it recorded an imbalances interval between (014% and 2.4%). The simulation takes into consideration the nature and reasons of imbalance problem in LV networks which is presented practically as the followings [98]:

- Over time distribution feeders trend to increase in load imbalance
- Loads are increasing gradually by the time on single phase lines
- Single phase lines arbitrarily get switched to other phases
- Lack of planning for the network.
- Inequality in distribution of single phase loads on three-phase line.

Voltage imbalances have serious negative effects on the network such as increased return current, voltage shifts and physical ramifications [98], the physical ramifications and losses are illustrated in table 4.6 [98]. The measured percentages of voltage imbalances show a variation between 0.14% and 2.4%, which means that the tested transformer is exposed to heat raise in its winding to more than 140^{c} .Also the efficiency of the simulated transformer would be decreased by 1- 2.5% according to the study results in table 4.6. These physical implications would decrease the expected life of the transformer from 20 years (in case of 0% imbalances) to less than 5 years in case of 2.4% imbalances [98].

Table 4.6: Voltage imbalance effects.

voltage unbalance %	Winding temp. (C°)	Efficiency reduction	Expected winding life (years)
0	120	—	20 years
1	130	Up to 1/2%	10
2	140	1-2%	5
3	150	2-3%	2.5
4	160	3-4%	1.25
5	180	5% or more	Less than 1

4.3.1.3 *Voltage measurements art different power factor values*

The case of different loadings for each phase (unequal phases) is used beside the case of equal phases in this subsection, in order address the voltage behaviour in the last mile of the network. The measurements of the voltages (Rms values) have been taken for each phase of the transformer at the secondary side, where the control is to be applied in the forthcoming chapters. Different values of PF (leading and lagging) have been applied by using power loads that consumes both of active and reactive power beside the condition of producing reactive power such as in capacitive loads, by using the network that is illustrated figure 4.2 and detailed MATLAB circuit in Appendix A. The percentage of consumed reactive power by loads and cables has been changed gradually by using a MATLAB programing Code that used modify the consumption of refractive power over time. By doing so, the Pf values have been changed to give different Pf conditions for the whole network. The measurements of voltages have been taken at each PF value.

The results of voltages measurements are shown in figure 4.6 for the case of lagging power factor, where the voltage is decreasing by decreasing the PF, also the voltage imbalance is increasing by supplying loads or network with low lagging PF value.

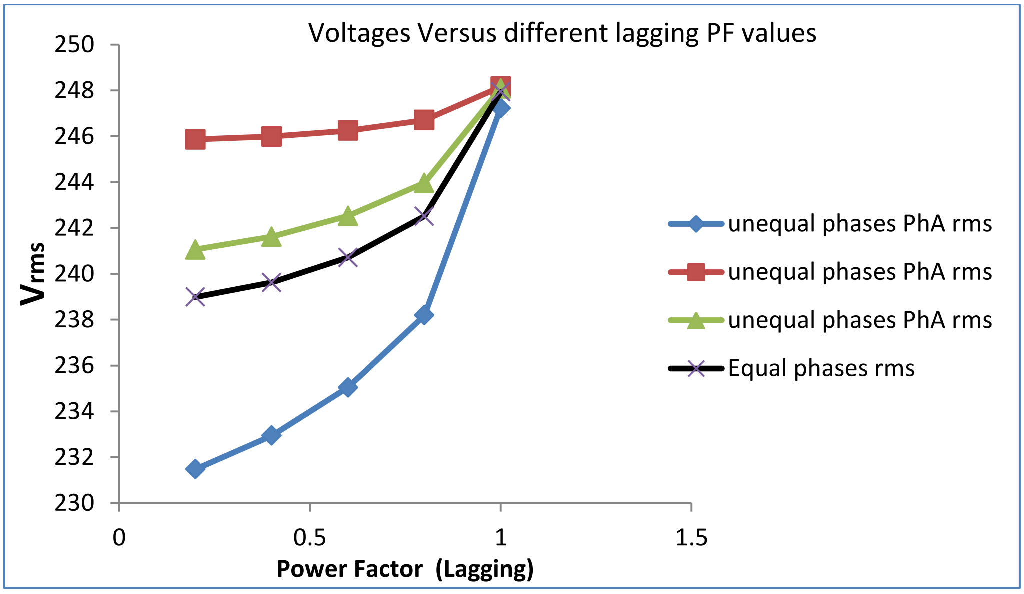


Figure 4.6: The effect of power factor on voltage level.

The results of voltage measurements (rms) are shown in figure 4.7 for capacitive loads when the network has a leading power factor values, whereby the voltage is increasing in case of injecting reactive power in the network instead of absorbing.

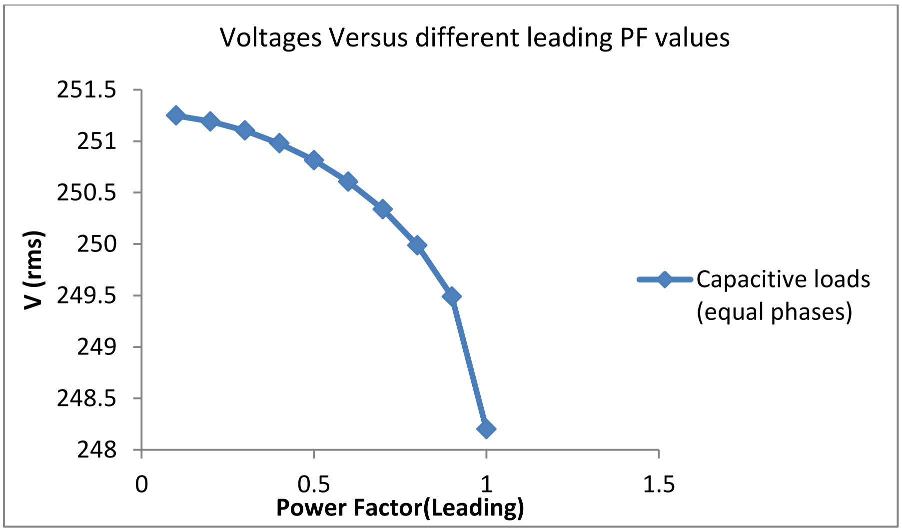


Figure 4.7: The effect of power factor on voltage level (capacitive load).

The effect of power factor in both of the conditions is shown in figures 4.6 and 4.7, where by decreasing the power factor, the voltage drop increases and the voltage level at the substation output decreases. This behaviour is justified according to equations 4.2 and 4.3, whereby (ΔP) is the active power losses and (ΔV) is the voltage drop [99].

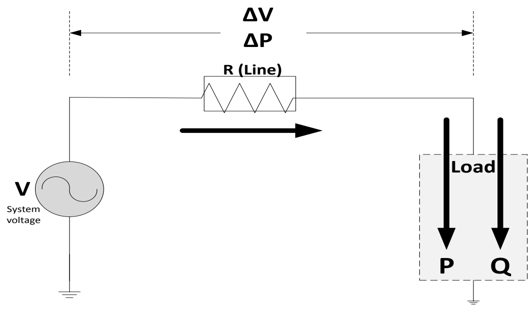


Figure 4.8: The effect of power factor on voltage level (capacitive load).

$$\Delta P = \frac{(P^2 + Q^2) \times R}{V} \tag{4.2}$$

$$\Delta V = \frac{3}{2} ((P^2 + Q^2)^{1/2} \times \frac{R}{V} \tag{4.3}$$

Where:

V is system voltage

R is the resistance of lines

As seen from figure 4.8, reducing the transported reactive power from the substation to the load will reduce the active losses (as seen in equation 4.2) where there is a positive relationship between the active losses ΔP and distributed reactive power Q. also there is a positive relationship between the voltage drops ΔV and distributed reactive power as seen in equation 4.3.

4.3.1.4 *Losses after and before regulation*

Voltage regulation has been applied on network by through simulated LV transformer in which is similar to the process of electronic tap changing. The transformer controlled the voltage at its gate by modifying the provided output voltage to give a constant voltage at its terminal in case of voltage drops. The technique of voltage control is applied using a programing code of MATLAB (attached in Appendix B) in order to enforce constant voltage level at its terminal in different loading scenarios. The purpose of applying voltage control using MATALB programing is to investigate the effect of instant voltage regulation on the losses of the network before investigating further a practical method that is capable to be used in real LV substations as seen in the following section. Table 4.7 shows the current condition of the tested LV substation and the target of the voltage control to be applied. The losses have been accounted according to the flowing current in the network as seen in figure 4.9.

Table 4.7: losses and voltage imbalance in the simulated system.

Current state of tested LV substation (secondary terminal)	Before regulation	After regulation (targeted)
Load Imbalance (%)	30% to %50	
Voltage Imbalance (%)	0.13% to 2.6%	
Line Losses of power along the phase	1.5% between loads	
Lowest measured Voltage	220.605 V (rms)	230V(rms)
Highest measured Voltage	249.1632 V (rms)	230V(rms)

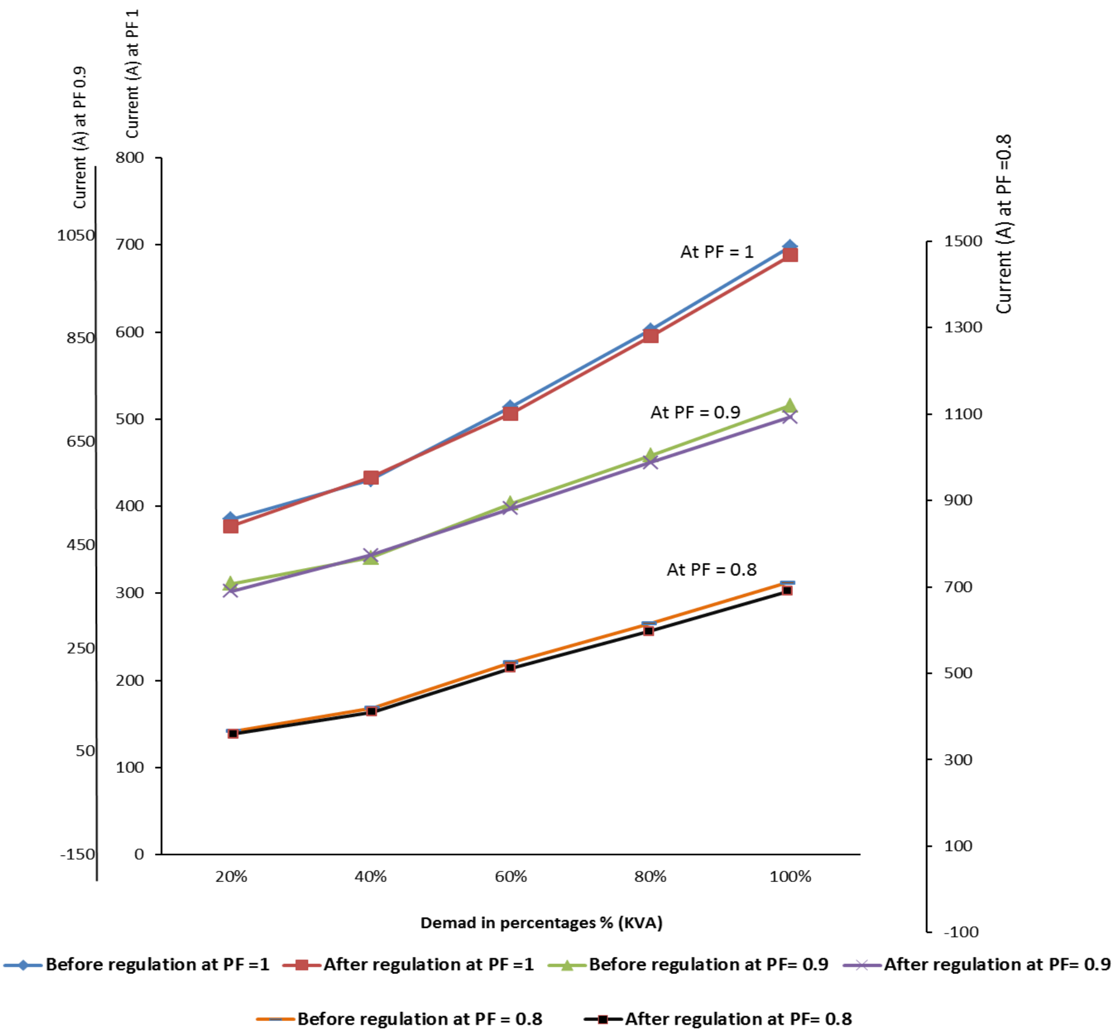


Figure 4.9: The delivered current at Power factor=1, 0.9 and 0.8 (before and after Voltage Regulation).

4.4 Voltage Regulation Techniques

Each phase of the three phase distribution transformer is allocated to a group of customers, unequal allocation leads to unbalanced 3 phase system. This issue is important and needs to be taken into account in voltage regulation studies. Integration of dedicated power converter designs should help to meet the requirements of the current and the future substations by operating interactively with other PE and conventional devices in the LV network to sustain continuous voltage regulation, voltage balance, and partial power factor correction with the aim of minimizing losses as much as possible [100].

Mechanical methods such as on load tap changers in distribution networks are not commonly used in voltage regulation in EU, especially the UK, for the following reasons [101]-[103] :

- Frequent maintenance requirements for mechanical parts.
- High amount of losses during the changing process.
- The distribution network demands frequent voltage control actions during the day, which decreases the lifespan of the mechanical taps significantly.
- In distribution network, the ARC of the tap changer is close to the load.

So voltage regulation term is commonly understood and applied (e.g. in the UK) in terms of several fixed voltage boosts that are applied at different areas of the network; this provides for constant voltage decrease, which could be true these days but which will not be true for the different future scenarios of the network [94], [104].

4.5 Design and Approach

The approach depends mainly on regulating the voltage for LV networks with a design based on the interaction between PE switches and the windings of the conventional transformer. The design is introduced as a hybrid distribution transformer, which is a voltage compensation approach that enhances the control at the low voltage side of the transformer (or the high voltage side in other configurations. The approach includes a distribution transformer with an attached fractionally rated PE converter, which contributes to supplying the transformer with additional controllability, and which could be used to control either voltage or reactive power compensation, or both of these functionalities in some control configurations.

If only a ±10% voltage limit for regulation is taken into consideration by the regulator [96], [97], the switches of the PE converter can be designed at fractional ratings (around 10-20%) of the total ratings of the LV transformer, which are the ratings that are needed to control the voltage regulation interval. The following functionalities for the Hybrid Transformer (HT) could be achieved and considered according to its configurations:

- Voltage regulation of up to ±20%.
- Reactive power control of up to ±20.
- A combination of both topologies may be achieved as long as the total rating of the PE part is not exceeded.
- The attached converter can be protected by being bypassed in case of a failure within the system.

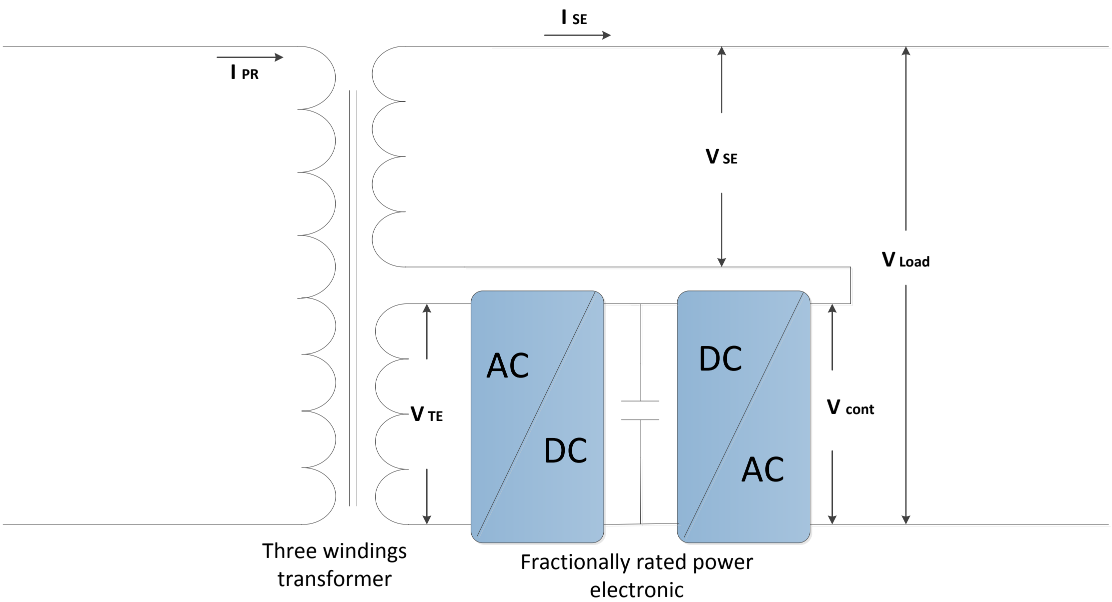


Figure 4.10: AC regulation by using basic hybrid transformer.

The fractional rating of the attached converter provides the overall system with the following advantages:

- Lower cost and higher reliability compared to the full rated PE
- Lower switching losses due to reducing the overall switches' ratings.
- The transformer is one of the most reliable devices in the network, thus its latent advantages are exploited.
- The system benefits partially from the PE functionalities that could be bypassed in case of PE failure

Fractional power electronics are designed as a back-to-back converter to control three unbalanced phases, each of which supplies three feeders to form nine lines that emerge from the transformer. Most feeders are made up of three phases and four wires, the latter of which is usually the neutral one. The three-phased feeder can usually range in length depending on load density, thus the introduced design takes into consideration an unbalanced system that needs voltage regulation for each phase separately [100], by attaching either three single-phase converters with the transformer, or using a three-phase converter in other designs. The main function of the converter is to sustain a constant output voltage, to minimise the voltage fluctuations in the event of high or low demand.

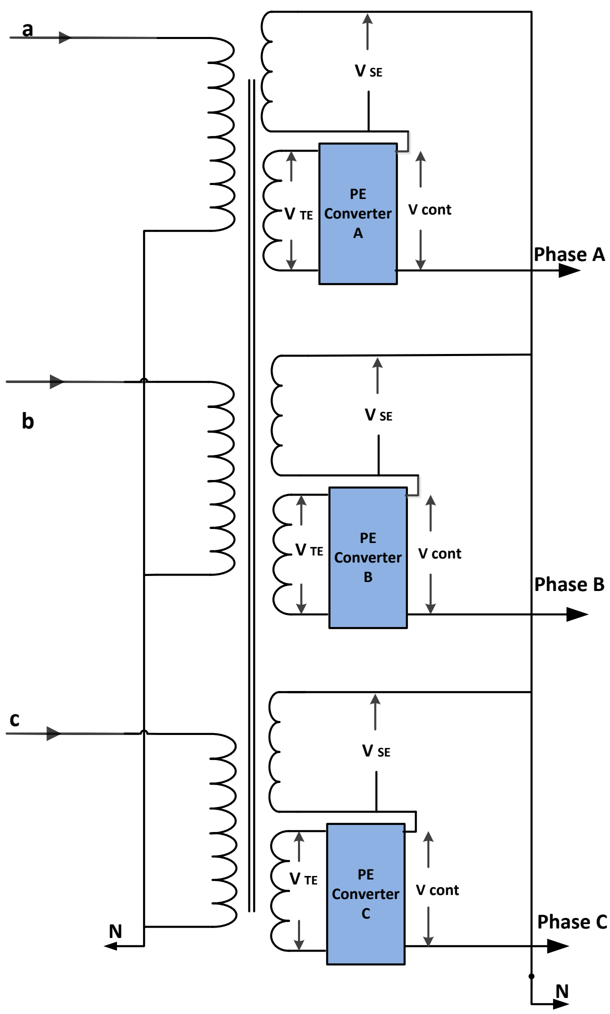
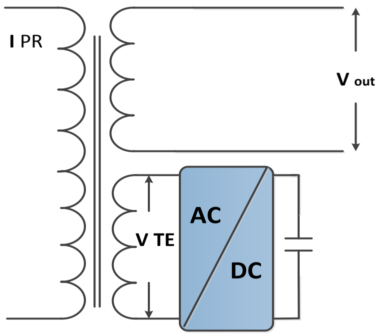
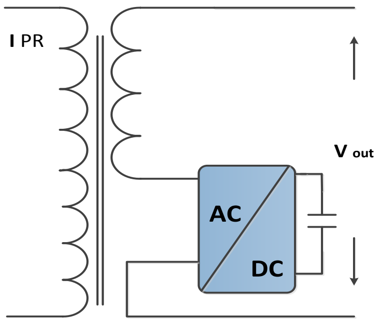
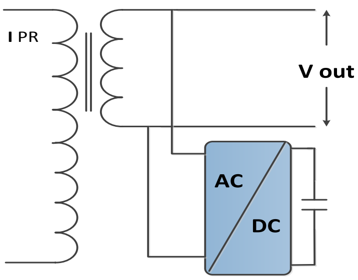


Figure 4.11: The proposed 3Ph hybrid transformer is introduced as a normal transformer that is attached partially with an AC/AC converter with a DC link.

Future scenarios require increasing attention to this function (e.g. increasing prevalence of electrical cars, whereby users plug and unplug their cars to charge frequently during the day), and it keeps the voltage and the current at the side of the transformer substantially in phase

4.5.1 Topologies and Options

Different positions and various configurations for PE converters allow the transformer to perform various functions as well as providing different techniques in regulating the voltage. These topologies and capabilities are shown in figures 4.12 to 4.23.

Conceptual schematics	Capabilities
 Figure 4.12: Topology A	Option one has the ability to operate a PF corrector for both displacement and distortion PF (harmonic filter). It also has an isolated DC source that could operate through the bidirectional DC-AC converter.
 *Figure 4.13: Topology B*	Option two is similar to option one but with an output that includes the voltage of the capacitor. It has the ability to do phase shifting and inject voltage as needed to maintain a constant level of operational voltage.
 *Figure 4.14: Topology C*	This option could be used as flicker control, whereby a bidirectional converter contributes to correcting the power factor and charge/discharge voltage in/from the secondary windings.

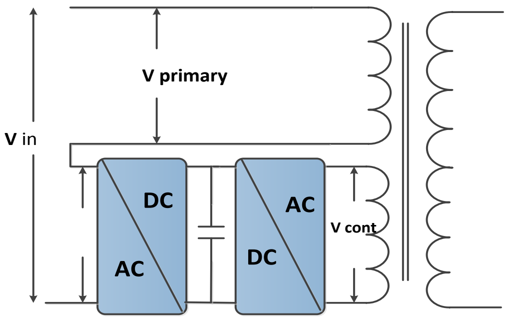
<table>
<tr>
<td>

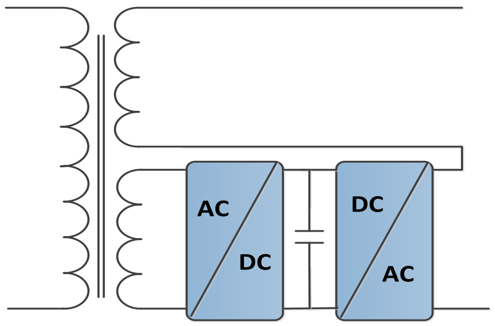
Figure 4.15: Topology D</td>
<td>This approach deals with problems from the HV side, regulating the voltage and undertaking phase shifting from the primary side. The converter deals with low current and high voltage ratings.</td>
</tr>
<tr>
<td>

Figure 4.16: Topology E</td>
<td>This approach does most of the mentioned functions and regulates the voltage with a converter that deals low voltage and high current ratings. It also has the ability to provide a DC link to the LV side.</td>
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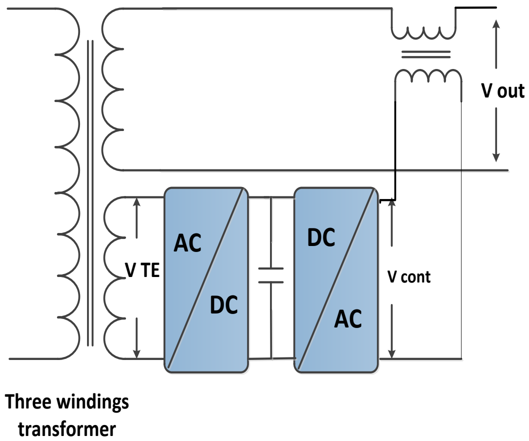
<td>

Figure 4.17: Topology F</td>
<td>Adding a series transformer would contribute to decreasing the rating of the current that the converter deals with. This means that the converter has the ability to deal with low ratings for the current and the voltage</td>
</tr>
</table>

The description provided for each figure suggests that every configuration has its own operational mode that provides the unit with different control abilities

4.5.2 Control Topology

A fractional rated back to back converter is used as seen in figures 4.10, 4.11 and 4.18. A resonant controller is taken into consideration to track a sinusoidal wave reference beside the need of controlling specific harmonic orders for a resistive load. Also, the *dq* transformation technique is used to control the voltage at the DC link terminals [105], whereby the overall controller as seen in figure 4.18 and 4.19 adds or decreases voltage (10% - 20%) to/from the total output voltage in order to control the whole output voltage of the transformer. The stages of the control for the DC link using vector control and the control of AC output voltage of the back to back converter is elaborated in the following subsections.

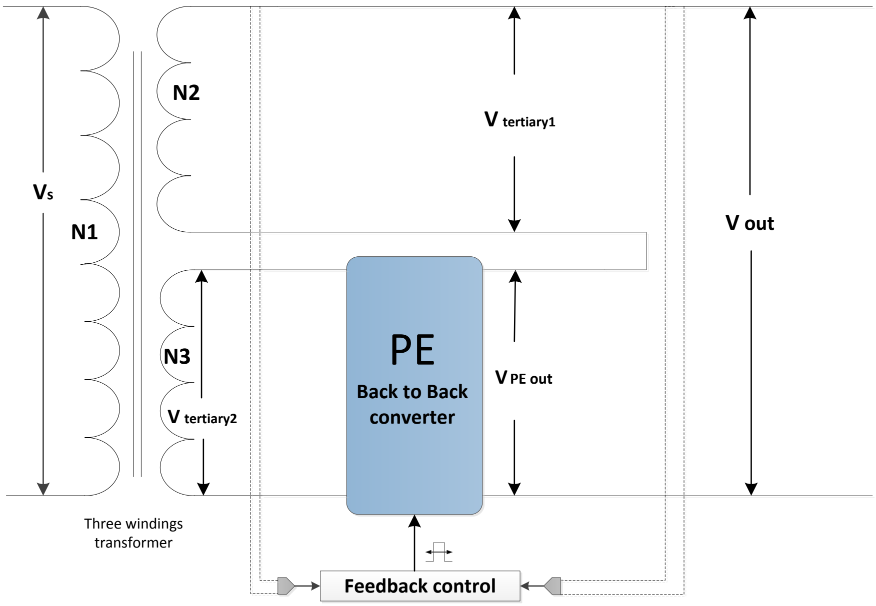


Figure 4.18: Overall control circuit of Hybrid transformer.

The transformer ratios are [95]:

$$\mathrm{V_{tertiary2}} = \frac{\mathrm{N3}}{\mathrm{N1}} \times \mathrm{Vs} \tag{4.4}$$

$$\mathrm{V_{tertiary1}} = \frac{\mathrm{N2}}{\mathrm{N1}} \times \mathrm{Vs} \tag{4.5}$$

$$\mathrm{V_{PE\ out}} = D \times V_{tertiary2} \tag{4.6}$$

Where $V_{PE\ out}$ is the output voltage of the converter, *D* is the duty cycle of the PWM signal, and N1,N2, and N3 are turns ratio of transformer as seen in figurer 4.18, and V_s is the primary voltage. Also N2 is smaller than N1, and N3 is smaller than N2.

Therefore, V_{out} can be expressed as:

$$V_{out} = V_{tertiary1} + V_{PE\ out} \tag{4.7}$$

$$V_{out} = \frac{N2+(D\times N3)}{N1} \times Vs \tag{4.8}$$

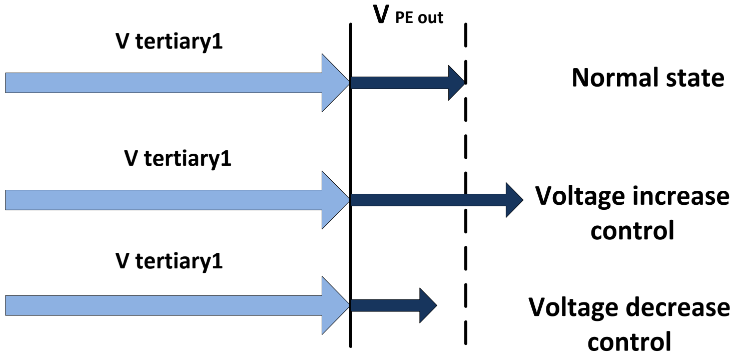


Figure 4.19: Voltage control is applied in case of over voltage or under-voltage incidents at the output of the transformer; voltage control is chosen as a balance between the output of the secondary windings and the ac-ac converter.

The transformer supports a part of supplied voltage and the PE converter controls the other part of the voltage (voltage variations). If a voltage decrease occurs in the distribution line, the converter duty ratio (*D*) correspondingly increases; conversely, when voltage increase occurs, the converter duty ratio decreases [106]. A vector diagram of voltage control is shown in figure 4.19

4.5.2.1 *DC-link vector control*

A vector control is one of the most popular methods used for voltage source converter (VSC) [13]. Voltage and currents are described as vectors in the stationary αβ and transformed after that to *dq* coordinates to be controlled by two loops: inner loop for the current control and outer loop for the DC voltage control. The vector control configurations and stages of using this technique in the inner and outer loops of the control are described in forthcoming sub-sections.

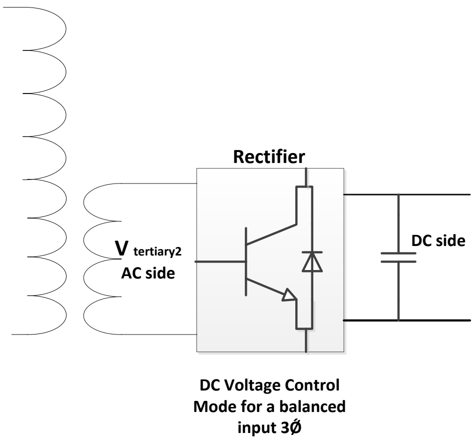


Figure 4.20: Control structure of the rectifier at the DC side.

4.5.2.1.1 *Capacitor configurations*

There are two factors that represent the characterisation of the capacitor, the amount of stored energy and the speed of charging/discharging, this is determined by the power ratings of the conversion process in the capacitor [107]. As shown in equation (4.10), capacitance (C) is a combinational relation between the stored energy (*q*) and voltage across the plates of the capacitor (V).

$$q = \mathrm{c} \times V \tag{4.10}$$

Capacitance itself (C) depends on the area of the plates (A) and distance between them (d), and the dielectric of the material (ε).

$$C = \frac{\varepsilon \times A}{d} \tag{4.11}$$

Equation (4.12) shows the stored energy in the capacitor (W), where the capacitance energy level is increased by increasing voltage ratings or capacitance itself [107]. The charging/ discharging process is shown in equation (4.13), where the voltage change is represented in *dV* and the current through the capacitor is illustrated as I_{cap}

$$\mathrm{W}=\frac{1}{2}CV^2 \tag{4.12}$$

$$dV = I_{cap} \cdot \frac{dt}{C} \tag{4.13}$$

4.5.2.1.2 *DC link configurations*

Inverters lifetime depends on capacitor lifetimes beside the cost issue, so decreasing the cost of used capacitors reduces the total cost of inverters and that by reducing the capacitors volume and ratings. On the other hand fluctuations in the capacitor voltage leads to shorten the life of inverters by using small capacitance volumes. The capacitance current is represented in equation (4.14).

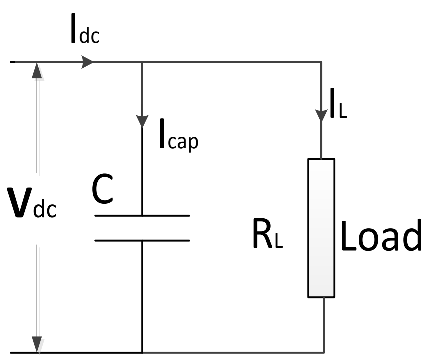


Figure 4.21: DC link configuration.

$$I_{cap} = C.\frac{V_{dc}}{dt} = I_{dc} - I_L \tag{4.14}$$

Where
$$I_L = \frac{V_{dc}}{R_L} \tag{4.15}$$

The minimum capacitance of the DC link is chosen according to the equation (4.16) as an initial value for the chosen capacitance, where less possible capacitance means less costs and losses [108]:

$$C_{min} = \frac{2.\Delta P.T}{V_{dc}^{*}.\Delta V_{dc,max}} \tag{4.16}$$

Where ΔP is the variations of the output power, $V_{\boldsymbol{dc}}^{*}$ is the reference voltage for the dc link, T is the time period of the AC voltage, $\Delta V_{\boldsymbol{dc}}$ is the voltage variations for dc link, and V_{dc} is the voltage of the dc link as seen in figure 4.21.

4.5.2.1.3 *Vector control configurations*

The vector control is used commonly in VSC [109] as illustrated in chapter 3. The *dq* transformation is applied using the *dq* transformation.

Before the *dq* transformation the three phase inputs (a, b and c) are transformed to αβ equivalent which is known as Clark transformation, which makes the control of active and reactive power straightforward.

4.5.2.1.3.1 Clark transformation

Clark transformation is done through the following equation (4.17).

$$\begin{bmatrix} \alpha(t) \\ \beta\ (t) \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{-\sqrt{6}} & \frac{1}{-\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} . \begin{bmatrix} a(t) \\ b(t) \\ c(t) \end{bmatrix} \tag{4.17}$$

The transformation is done within the stationery of the three phases and αβ frames as shown in figure 4.22.

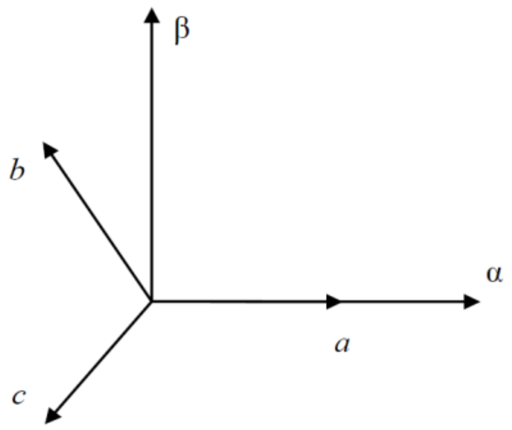


Figure 4.22: Stationary of ABC and Clark transformation.

4.5.2.1.3.2 dq transformation

By using Park transformation, the αβ frame could be transformed to *dq* as the in equation (4.18).

$$X_{dq} = X_{\alpha\beta}\, e^{-j\theta} \tag{4.18}$$

The vectors αβ rotates in the coordination with angular frequency ω, which is the same frequency of the voltage but in rads/s instead of Hz, thus by integrating ω, an angel is produced as θ(t) [110]. Therefore, equation (4.18) could take the following matrix form:

$$\begin{bmatrix} d(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} . \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{4.19}$$

Vectors *d* and *q* are current vectors that define active and reactive power conditions respectively, this transformation is done according to an accurate value for θ in order to find a correct *dq* components. The value of θ could be calculated according to equation (4.20) [110].

$$\theta = tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) \tag{4.20}$$

This angle is detected through using a track technique called Phase Locked Loop (PLL) [111]. Where it tracks and synchronise the behaviour of grid voltage by transferring a feedback references in a form that is suitable for controlling [112].

Therefore the input of the PLL is a three phase signals comes from the grid as a voltage and the output is an angle which represents the frequency of the voltage grid.

After transferring the three phases to DC components, a PI controller is used to reduce the steady state error for each of them (*d* and *q*) [109], the output of the controller is transformed again to three phases and fed to PWM to generate the controlled signals. In general the system of vector control consists of two control loops; inner loop for controlling the current or the power from/to dc grid, and outer loop for DC voltage level control, where both of the loops components depends on each other [109].

4.5.2.1.4 *VSC converter configurations in dq coordination*

According to figure 4.23, the grid and converter voltages could be described using Kirchhoff's law as the following [110]:

$$E_{abc} = L\frac{d}{dt}\, I_{abc} + V_{abc} + RI_{abc} \tag{4.21}$$

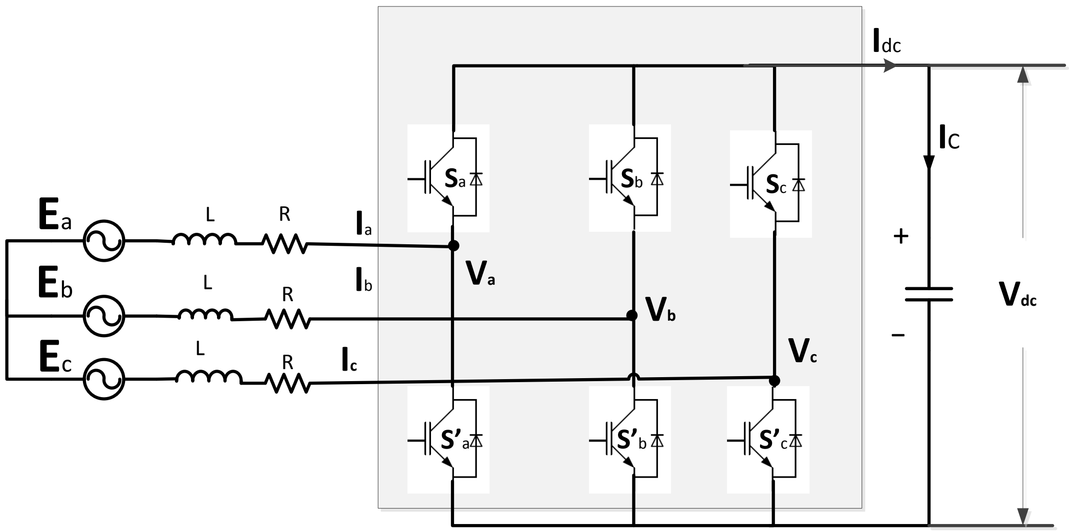


Figure 4.23: VSC schematic diagram.

Where V_{abc} and I_{abc} are the three phase input voltage, and current respectively, E_{abc} is the source voltages, and R and L are resistance and inductance respectively between the grid (secondary winding) and the converter. By transforming equation (4.21) to the *dq* form, equation (4.22) is introduced:

$$\begin{bmatrix} E_d \\ E_q \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega L\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \end{bmatrix} + R\begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{4.22}$$

The three phase currents and voltages of the source are transformed according to equation (4.22) to *dq* form with radial frequency ω (rad/s). Thus the separate *dq* voltages are shown in equations (4.23) and (4.24):

$$E_d = L\frac{d}{dt}I_d - \omega L I_q + V_d + RI_d \tag{4.23}$$

$$E_q = L\frac{d}{dt}I_q + \omega L I_d + V_q + RI_q \tag{4.24}$$

As seen from equations (4.23) and (4.24), the components of *d* and *q* are decoupled and share the same angular frequency. The power in *dq* frame (P_{dq}) is represented as the following:

$$P_{ac} = P_{dq} = \frac{3}{2}\,(V_d I_d + V_q I_q) \tag{4.25}$$

The dc power (P_{dc}) equals the ac power (P_{ac}) during a steady state operation for both sides so:

$$P_{dq} = P_{dc} = V_{dc} \times I_{dc} \tag{4.26}$$

From equation (4.25) and (4.26), the dc current is shown as in equation (4.27):

$$I_{dc} = \frac{P_{dc}}{P_{dq}} = \frac{3(V_d I_d + V_q I_q}{2V_{dc}} \tag{4.27}$$

4.5.2.1.5 *Current and voltage control loops*

The inner current controller processes the error signal that is resulted from the comparison between the reference and the real measured current. PI regulator process this resulted error besides a feed forward from the decoupling of equations (4.23) and (4.24) as seen in figure 4.24. The decupled feed is used to reduce the response time of the controller; the diagram of the inner controller is shown in figure 4.24 where it contains two PI regulators for each of *dq* components.

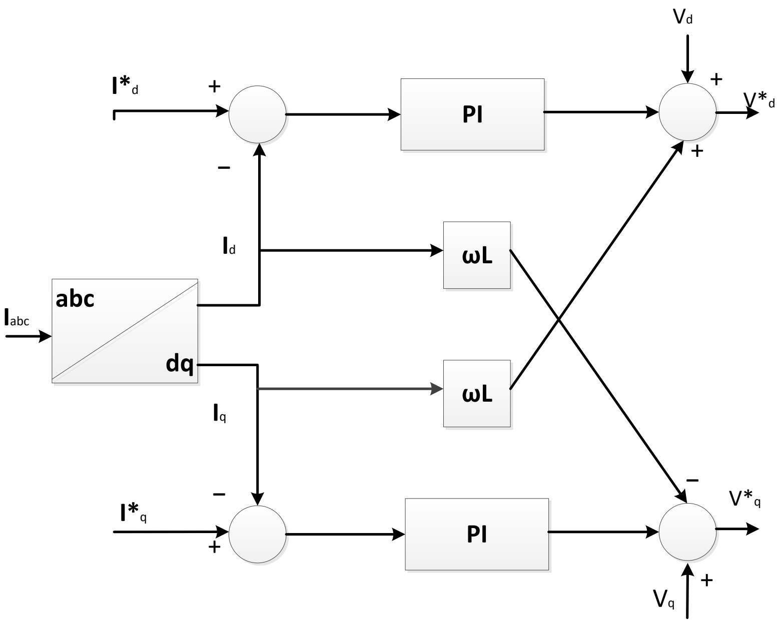


Figure 4.24: Inner control loop structure.

The outer controller loop is used to control active power, reactive power and DC voltage level. The reactive power is controlled through controlling I_q , and active power and DC level are controlled through I_d. The schematic diagram of the inner and outer loop of the control is shown in figure 4.25, whereby the inner loop takes its reference from the outcome of the outer loop. The control in figure 4.25 uses the ABC to *dq* transformation in order to control the active and reactive components separately.

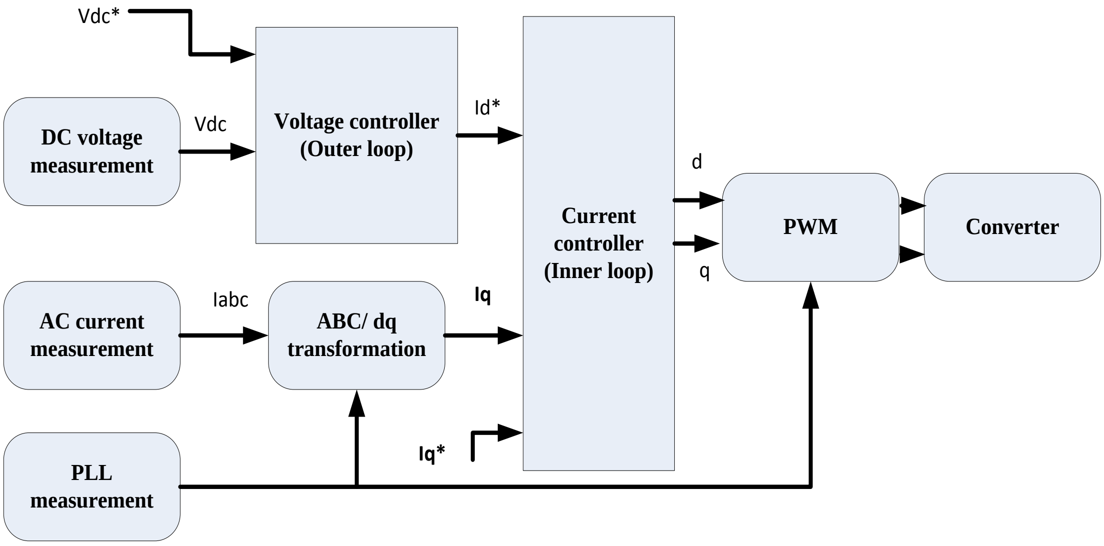


Figure 4.25: Vector control technique for the inner and outer loops.

4.5.2.1.6 *Control transfer function configuration*

In case of steady state power transaction at both sides of the converter, the following equations could be explaining this case [113]:

$$P_{ac} = P_{dc} = P_{cap} \tag{4.28}$$

By substituting from equation (4.25) and (4.26), the term ($P_{dc} = P_{cap}$) would be:

$$\frac{3}{2}V_d I_d + V_{dc}I_{dc} = V_{dc}I_{cap} \tag{4.29}$$

Where the ratio $\frac{3}{2}$ comes from the *dq* transformation as seen before in equation (4.25), the capacitor current is calculated according to equation (4.30), which is derived from equation (4.29) as the following:

$$I_{cap} = \left(\frac{3V_d I_d}{2V_{dc}} + I_{dc}\right) \tag{4.30}$$

The capacitor current could be written also according to equation (4.14) and figure 4.21 as the following:

$$I_{cap} = C\,\frac{dV_{dc}}{dt} \tag{4.31}$$

From equation (4.30) and (4.31), the DC voltage differential equation is provided as in equation (4.32):

$$\frac{dV_{dc}}{dt} = -\,\frac{3V_d I_d}{2V_{dc}}\left(I_d + \frac{2V_{dc}I_{dc}}{3V_d}\right) \tag{4.32}$$

Equation (4.32) shows that DC voltage is controlled by controlling the active power (*d* components), while the V_{dc} components is fed directly to the regulator of the controller as seen in figure 4.26.

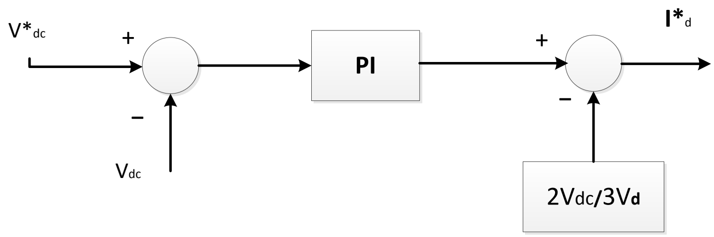


Figure 4.26: DC voltage regulator.

The open transfer functions for each loop (inner and outer) are supposed to be configured before the configuration of PI regulator. Therefore, the Laplace transformation for the electrical components of the system is specified first to determine the open loop Transfer Function (TF) for each loop. The main time delay comes from the inner loop delays with respect to the outer controller.

The inner loop TF and outer TF are stated in equations (4.33) and (4.34) respectively, where the feed forward elements are cancelled in order to obtain the Open Loop TFs.

$$G_{o.L} = Kp.\left(\frac{1 + T_i\,S}{T_i\,S}\right)\left(\frac{1}{1 + T_{eq}\,S}\right).\frac{1}{R}\left(\frac{1}{1 + \tau S}\right) \quad (4.33)$$

$$G_{o.L} = Kp.\left(\frac{1+T_i\,S}{T_i\,S}\right)\left(\frac{1}{1+T_{eq}\,S}\right)\left(\frac{3V_d}{2V_{dc}}\right).\left(\frac{1}{CS}\right) \quad (4.34)$$

Where $\tau = \frac{L}{r}$ is the time constant, T_i *and* Kp are PI controller parameters , T_{eq} is the time delay that is caused by VSC switches, and L and R represent the inductance and resistance between the converter and AC side (as seen in figure 4.24).

An equivalent Laplace transformation for the circuits' material is done in order to determine the parameter of the PI controller. By this control, the fluctuation in the DC link is minimised to enable fast and stable control for the AC side of the converter. The feedforward is used to minimize disadvantage of slow dynamic response of cascade control as seen in figure 4.27.

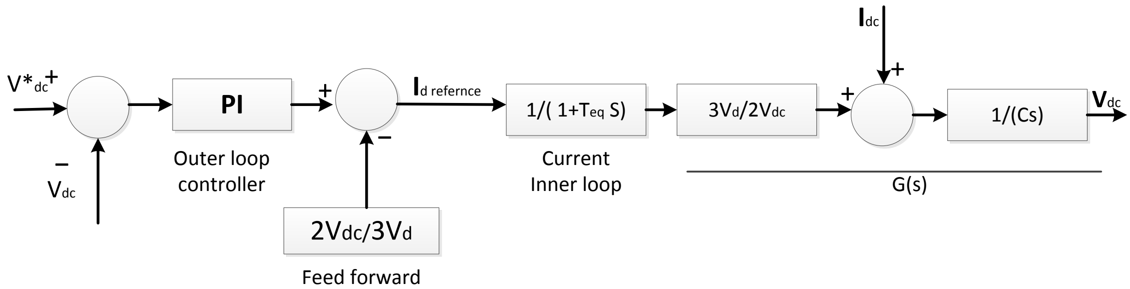


Figure 4.27: DC voltage regulator.

4.5.2.1.7 *Tuning controller parameters*

The PI control parameter is supposed to be tuned accurately in order to get the required level of performance in terms of [113]:

- Reducing the overshot limit if control response
- Decrease the time response by means of getting fast control response

In order to reach the previous two points, and reach the required point of stability and control speed, Modulus optimum technique is applied, which its application depends mainly on the TF of the system [114], where Modulus techniques is usually applied on the TF that have planet order less than three, and where the transfer function pole is not near the origin otherwise symmetrical optimum control strategy is used [114]. The Modulus technique for tuning according to the following equations for the inner PI regulator [112]:

$$K_p = \frac{\tau . r}{2T_{eq}} \tag{4.35}$$

$$T_i = \frac{L}{\omega_b . r} \tag{4.36}$$

Where K_p is the proportional gain and T_i is the integration time, which are considered the tuning components for the PI regulator. L and r represent the inductance and resistance between the converter and AC side. τ is time constant (5µs), and ω_b is the base frequency which is 314.16 rad/sec, the tuned parameters are utilised using MATLAB Single Input Single output Tool (SISO Tool) according to the following values; K_p =3.25 and T_i = 0.012.

Tuning is done for the DC voltage by using symmetrical tuning technique, which utilised the proportional gain K_{pv} and T_{iv} the integration time according to the following equations, where the subscript '*v*' means the voltage controller..

$$T_v = a^2 . T_{eq} \tag{4.37}$$

$$K_v = \frac{T_c}{aK . T_{eq}} \tag{4.38}$$

$$T_c = \frac{1}{\omega_b . C} \tag{4.39}$$

$$K = \frac{V_d}{V_{dc}} \tag{4.40}$$

Where T_{eq} is the delay for the inner loop, and a is the freedom degree for the controller and it is normally around 2 and 4 [115], so the value of 3 is used for a. According to the previous configurations and values, the tuning parameters for the DC voltage is utilised using MATLAB Single Input Single Output SISO Tool as the following; T_v= 0.0019 and K_v = 10.76. The closed loop diagram for the DC voltage controller is performed using PLECS as seen in figure 4.28, and the circuit configurations are provided in table 4.8 The following system partial ratings are considered for the TF and control parameters in for the partially attached secondary side of transformer and converter.

Table 4.8: Simulated circuit configurations.

Components	Ratings
Rated power	200 KVA
DC voltage V_{dc}	800V
AC voltage	48 V
Frequency	50 Hz
Filter impedance (R + j$\boldsymbol{\omega l}$)	(0.01 +j0.26) pu, L=0.00047H R= 0.06Ω
Switching frequency $\mathbf{f_s}$	5 KHz

As the switching frequency is f_s = 5 KHz, the converter time delay average) is $Ta = \frac{1}{2}f_s$ $=100 \times 10^{-6}$ seconds. The capacitance of the DC link is: $C = \frac{2\tau.S}{V_{dc}^2}$ = 312.5 µF

The inductor neutral voltage is controlled as a vector quantity in the *dq* domain, the advantage of using such kind of control is transferring the AC components to DC components that are easy to be controlled without tracking the error of AC components. After extracting the transfer function, a current controller is applied in the inner loop and the outer loop provides the current control with its reference, the control loops for the DC link is shown in figure 4.28.

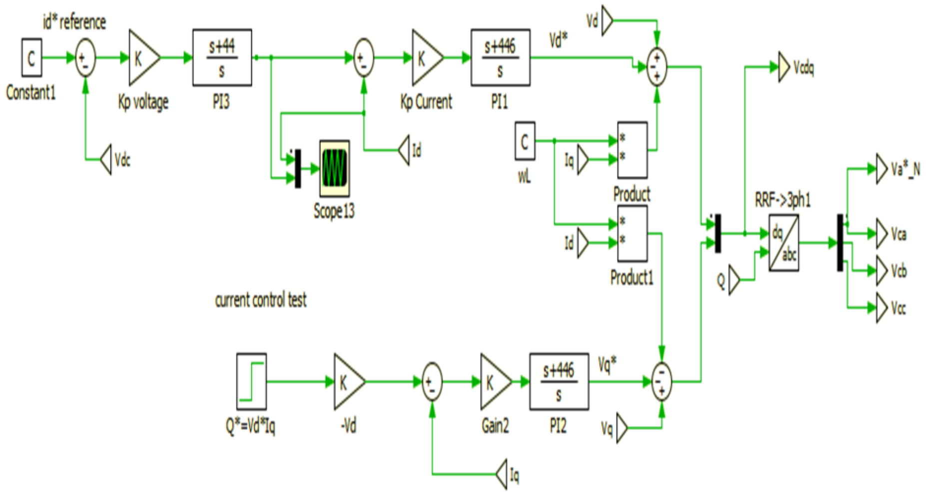


Figure 4.28: dq transformation technique.

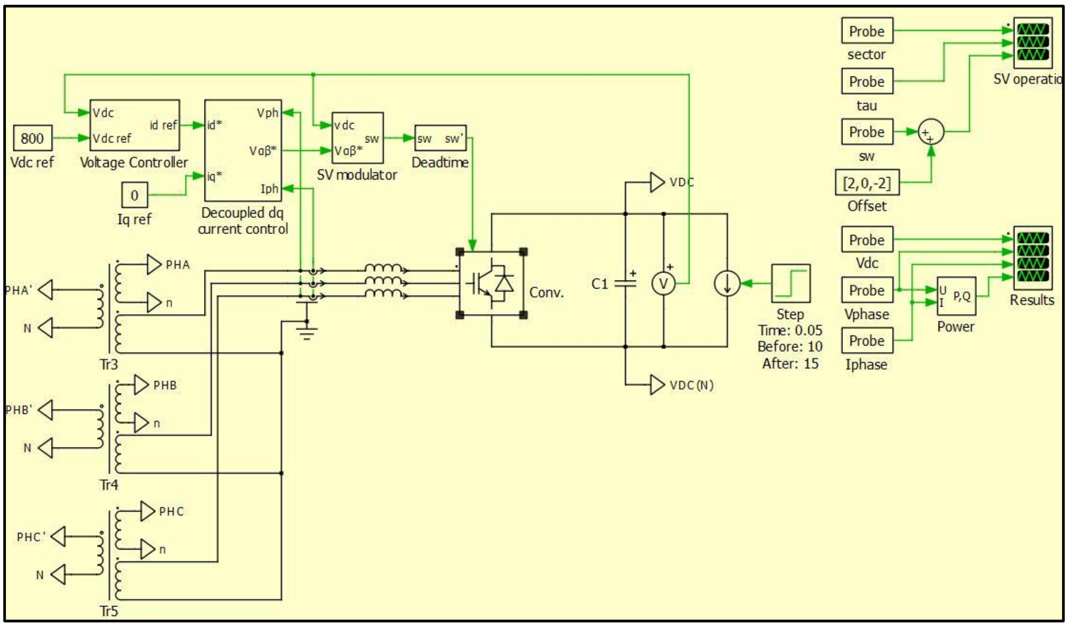


Figure 4.29: DC link circuit.

The DC link of the back-to-back converter is controlled by using a *dq* transformation, as seen in figure. 4.29 and 34. The control is used to maintain the DC voltage fixed at the terminal of the linked capacitor, in order to provide the AC part of the converter with a stable source of power [116]. The DC output responds to the reference of the controller and step up/down to the required value, as illustrated in figure. 4.30.

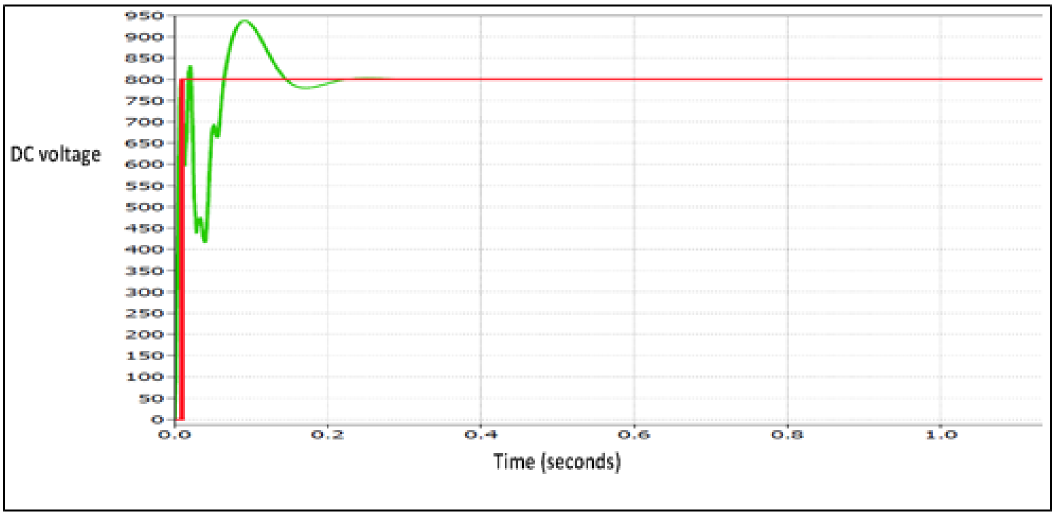


Figure 4.30: Control response for the DC link.

4.5.2.2 *Resonant control for the AC output voltage*

The vector control is used commonly in controlling a balanced three phase system, where it controls its transformed DC components in order to control the AC components [117]. The controlled DC values are rotating reference parts that are controlled through Park transformation and Clarks' or vector transformation. However the control of the AC side of the LV transformer (secondary side) is considered for the situation of unbalanced three phases, where each phase at the LV side is loaded differently, which is the case practically. This different loading scenario requires controlling each phase (single phases) separately. The control of single phase only contains one vector and not two as the case in the Vector control. Therefore the control strategy that is used in this stage could use different control strategy or structure for each phase as the one existed in Ref [117] . The used control strategy in this stage is called proportional resonant (PR) control that uses two integrators and poles that resonate at specific frequency that is chosen by the designer. The need for two integrators in this strategy is to cancel the steady state error completely without the need for voltage feed forward to cancel the inverse steady state error as the case in PI controller, where the steady state error is in an inverse direction with the proportional gain K_p [118].

The normal *dq* controller is appropriate for a balanced or slightly unbalanced system, whereby the transformation to *dq* frame can give an accepted performance, but in case of dealing with a severely unbalanced system the resonant controller (RC) or (PR) is applied, as it is used in several approaches such as distribution generation and wind and solar energy [118]. The final design that is used where the resonant controller is applied on its output voltage (V_{con}) is shown in figure 4.31

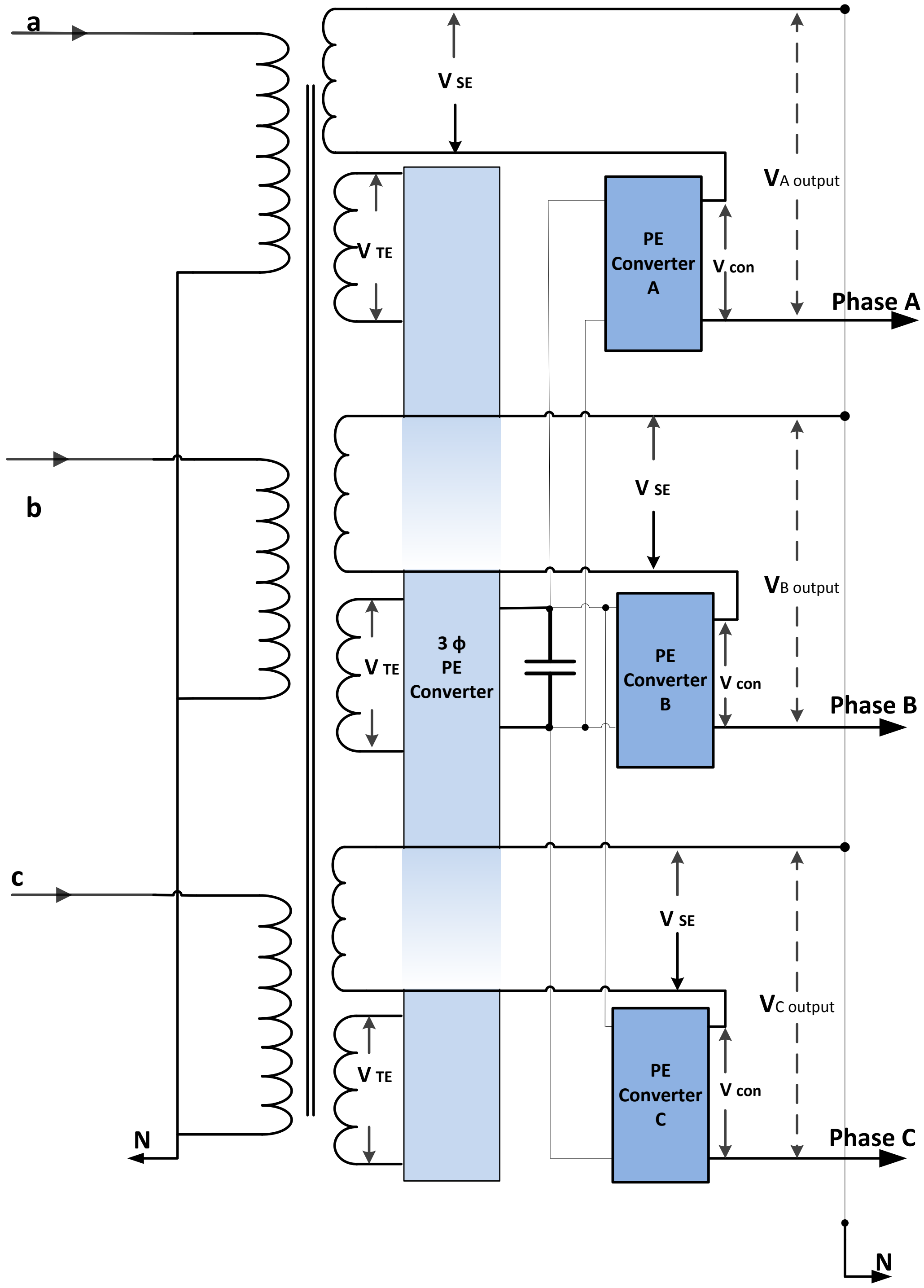


Figure 4.31: Last stage of the design of 3ϕ Hybrid Transformer.

4.5.2.2.1 *PLL configurations*

The phase locked loop (PLL) is used to synchronise the output voltage/current of the inverter with the voltage and current angle of the grid. Therefore it is considered as grid voltage monitor technique that gives a feedback of the frequency and the amplitude of the grid voltage signal, the design of the used PLL is shown figure 4.32.

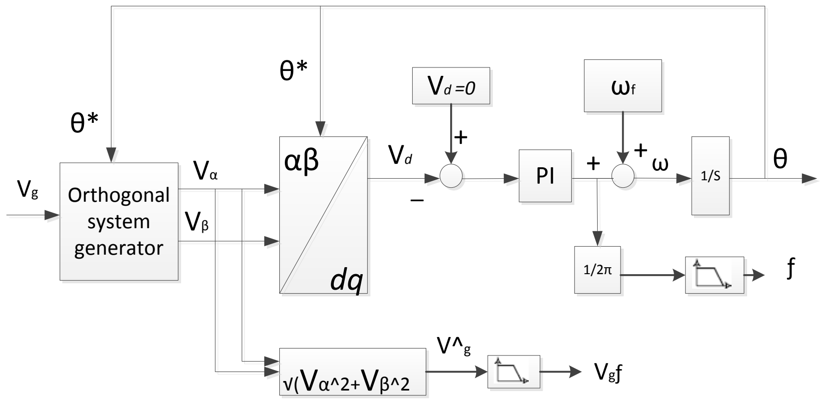


Figure 4.32: PLL schematic diagram (structure).

In three phase systems, the orthogonal voltage is generated by Park transformation using the three signals, but in a single phase signal, the orthogonal is made by more complex designs [119]. In literature, there are several strategies for generating orthogonal voltage for a single phase signal, as seen in Ref [119]-[121].

A simple technique is used for orthogonal generation in the single phase voltage, by producing a transport delay that causes a phase shift of π/2 compared to the fundamental; therefore two signals are generated by using this delay in order to produce an angle.

The transport delay technique is used in this design by using a buffer that generate delayed signal from the fundamental signal by one quarter of the fundamental cycle. The structure of the technique is shown in figure 4.33.

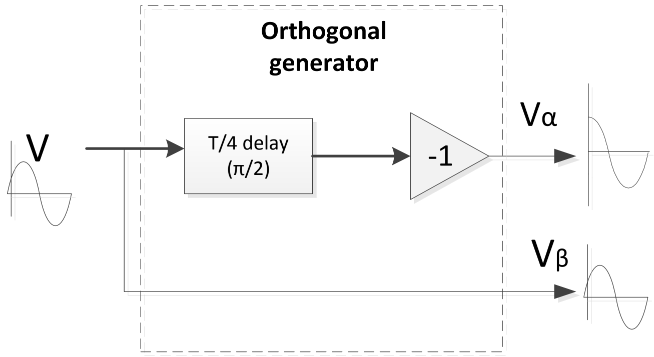


Figure 4.33: Orthogonal generation based on transport delay.

This technique is simple and doesn’t pose any challenges which make it preferable for the designs that don’t rely on very fast time control. However, there are disadvantages for this technique such as it doesn't depend on frequency tracking which makes it non reliable in case of frequency fluctuation in the grid, beside creating a signal that is not filtered and takes it as it comes from the source, the output of PLL is shown in figure 4.34.

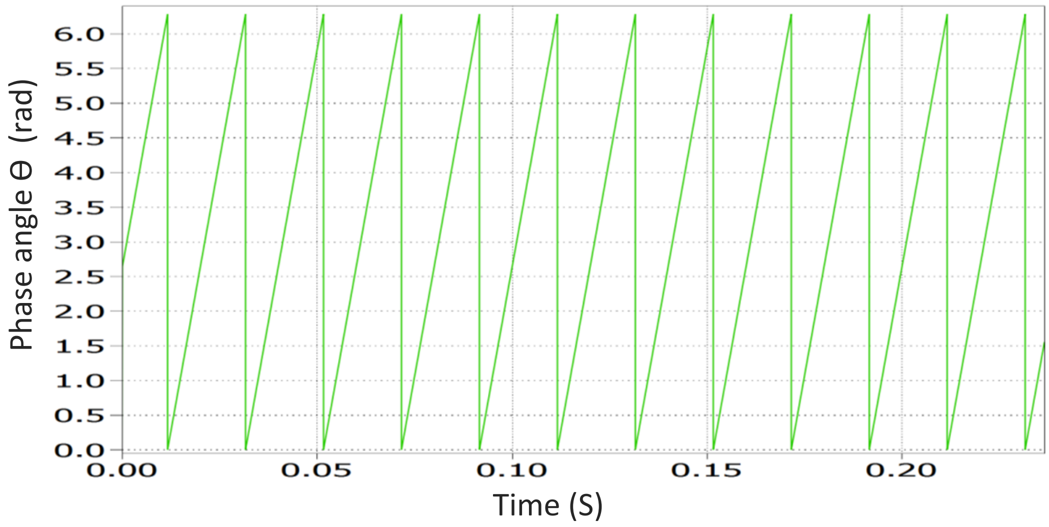


Figure 4.34: PLL theta output.

However several techniques are introduced in Ref [120] for signal delaying such as using Hilbert transformation. Other different approaches are used for orthogonal generation such as using inverse Park transformation such as in [120], [122], [123].Other techniques use pass filters as in Ref [119], and Kalama estimator filter as in Ref [124].

4.5.2.2.2 *PI and PR controller*

The conventional PI controller is used commonly in grid connected voltage source inverters, where it uses a feed forward voltage to cancel the steady state error for the PI regulator. The PI controller is defined as in equation (4.41) [118]:

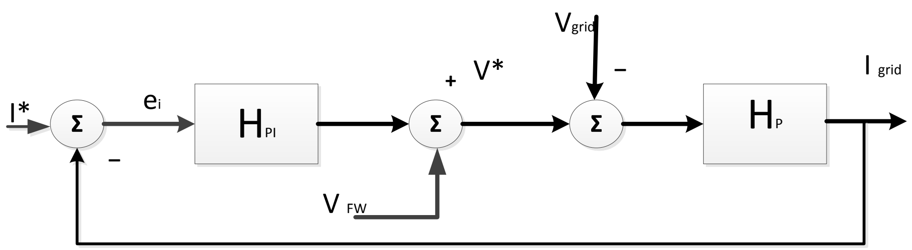


Figure 4.35: PI controller.

$$H_{PI} = K_p + \frac{K_{vi}}{s} \tag{4.41}$$

The voltage forward is processed before using it in the control strategy through a filtering stage which can cause delay and stability problems. So an alternative strategy is used to control the three single phases instead of the normal PI controller, the PR controller is introduced as in equation (4.42) [117], [125].

$$H_{PR} = K_p + K_i \frac{s}{s^2 + \omega_0^2} \tag{4.42}$$

PR could be used at specific frequencies (ω_o), or for dealing with specific harmonics at chosen harmonic frequencies (ω_{ho}) as attached controllers in parallel with the main PR controller, as introduced in equation (4.43) and figure 4.36:

$$H_H = \sum_{h=3,5,7} K_{th} \frac{s}{s^2 + \omega_{h_0}^2} \tag{4.43}$$

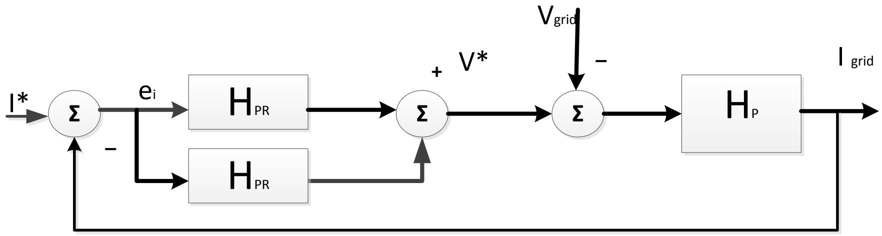


Figure 4.36: PR controller.

The PR is chosen to control the voltage of the three phases separately by tracking a sinusoidal reference that takes its angle from phase locked loop (PLL) measurements from the network [126]. The resonant controller is used to eliminate specific harmonic orders besides controlling the output voltage as in Ref [127].

4.5.2.2.3 *PR controller*

The proposed resonant control design is shown in figure 4.37 and 4.39; each phase is controlled separately due to the fact that each one is loaded differently. An LCL filter is used at the output of the inverter with the following parameters; inductor at the inverter side L_{inv} = 1520 µH, capacitor C= 2.4 µH, and inductor at grid side L_{grid} = 760 µH. the filter is connected to the grid through a series transformer with inductor of 2.2mH. The control parameters are K_p = 35 and K_i = 1200.

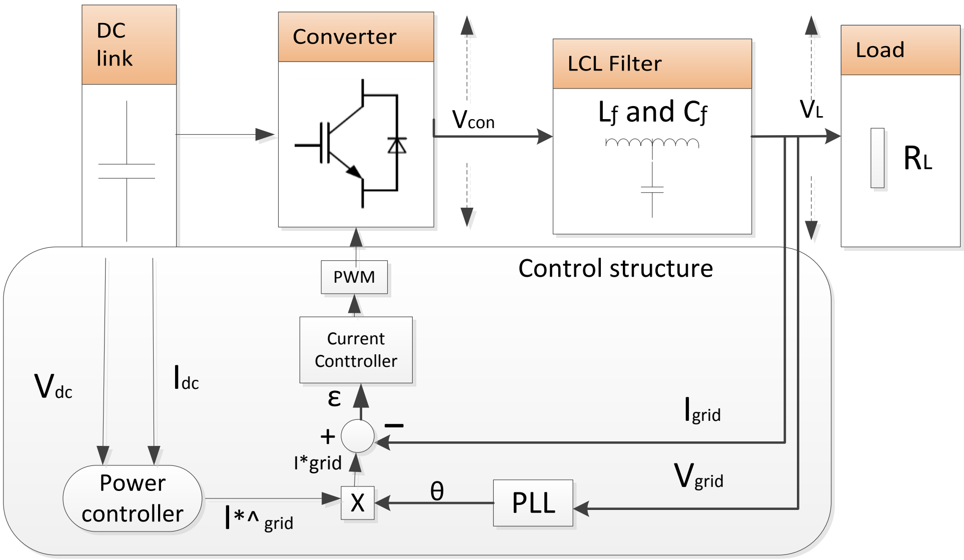


Figure 4.37: Schematic diagram for the used PR control for the system.

Considering the circuit in figure 4.37, the transfer function of the plant in s-plan is shown in equation (4.44).

$$\frac{V_L(s)}{V_{con}(s)} = \frac{R_L}{S^2 R_L C_f L_f + S L_f + R_L} \tag{4.44}$$

Where V_L and R_L are the voltage and resistance respectively at the Load side, V_{con} is the voltage at inverter terminal, and C_f L_f are the total capacitance and inductance of the filter.

The typical TF for the (RC) is in s-plan as shown in equation (4.45);

$$G_c(s) = K_C \frac{s^2 + 2\zeta\omega_n s + \omega_n^2}{s^2 + \omega_o^2} \tag{4.45}$$

The frequency (ω_0) is the required frequency (50Hz), ζ is the damping factor, ω_n is the resonant frequency, and Kc is the controller gain. The zeros in the numerator of equation (4.45) are located close to resonant poles in order to improve the dynamic response.

The s-plan transfer function is a transferee to z-plane, as in equation (4.46) [127].

$$G_{c\,(z)} = K_{cz} \frac{z^2 + a_1 \ + a_2}{z^2 + b_1 z + b_2} \tag{4.46}$$

The transfer function is transferred to z-plane in order to facilitate the locating of resonant poles within the unity circle in SISOTool as seen in figure 3.38 with respect to real axes of ω_o and the sampling time T_s. The poles of the controller are located along the edge of the unity circle in z-plan for the purpose of considering the worst case for the controller by assuming no load is connected at the inverter output ($R_L \rightarrow \infty$).

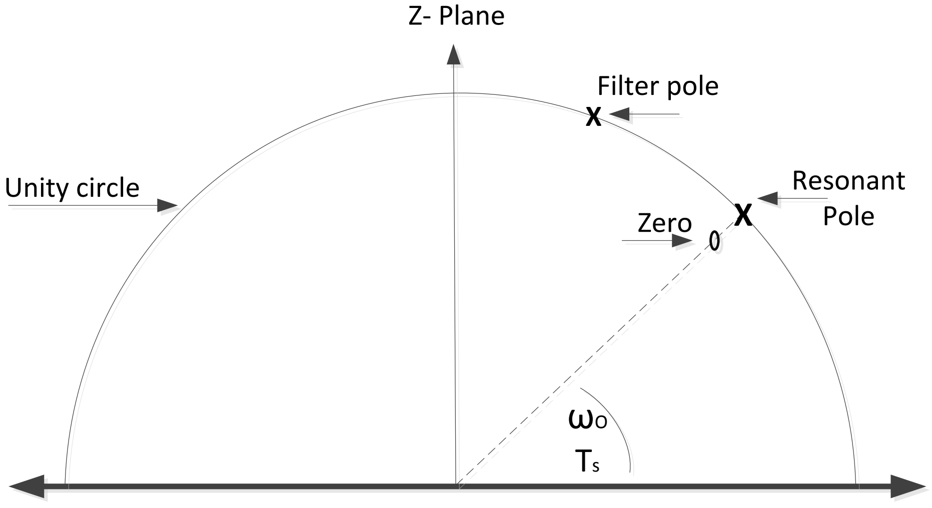


Figure 4.38: Schematic diagram for the used PR control for the system.

A schematic diagram for the resonant control system that is used in this stage is shown in figure 4.39, where a simplified diagram is shown for the resonant controller block, the sample time delay and the zero order hold device

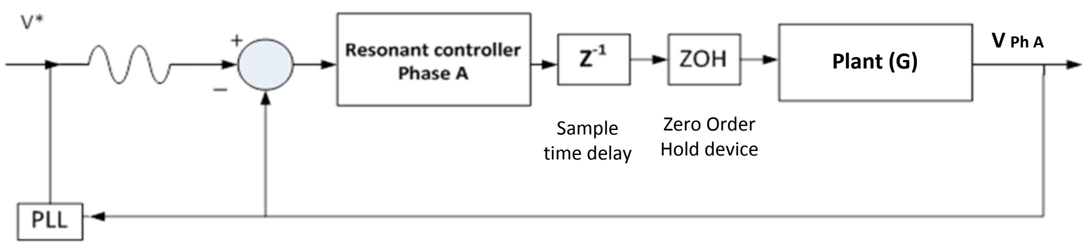


Figure 4.39: Proposed resonant control diagram for each phase

The resonant controller is performed using PLECS software, where each phase for the output voltage of the AC side of the inveterate is controlled separately as seen in figure 4.40.

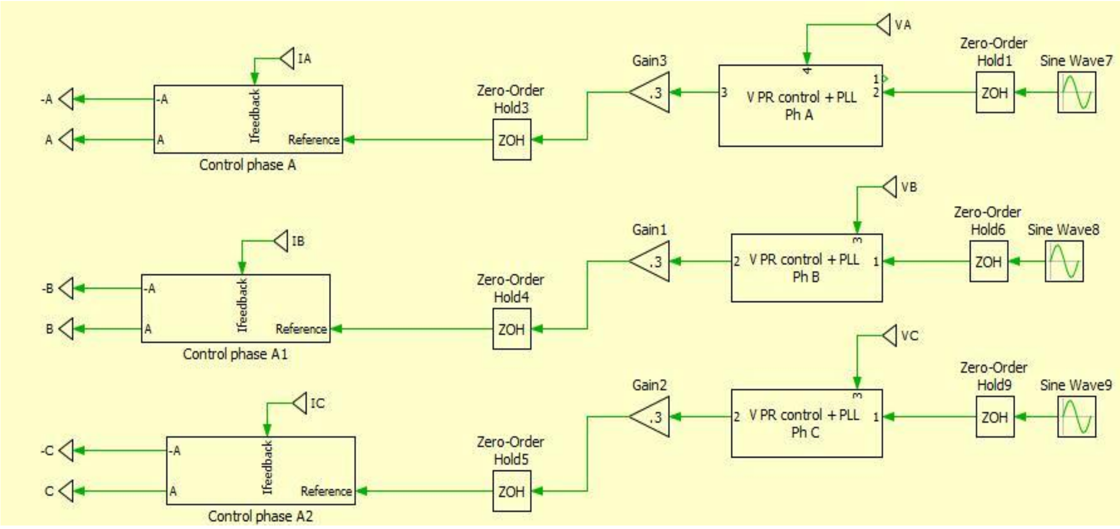


Figure 4.40: PR controller for separate three phases.

The RC can be used also to eliminate a specific harmonics at specific frequencies by applying their frequencies in parallel implementations for the TF functions, as in equation (4.47) and figure 4.41. The control operates at the frequencies of the required harmonics that need to be eliminated [127], where $\omega_o = 2\pi f_o$.

$$G_c(s) = K_C \frac{s^2 + 2\zeta\omega_n s + \omega_n^2}{s^2 + \omega_o^2} + K_{Ca} \frac{s^2 + 2\zeta\omega_{na} s + \omega_{na}^2}{s^2 + \omega_{\circ a}^2} + K_{cb} \frac{s^2 + 2\zeta\omega_{nb} s + \omega_{nb}^2}{s^2 + \omega_{ob}^2} + \ldots . K_{Cm} \frac{s^2 + 2\zeta\omega_{nm} s + \omega_{nm}^2}{s^2 + \omega_{om}^2} \quad (4.47)$$

Where K_C is the control gain for the fundamental frequency, K_C, K_a, K_b and K_m are the control gains for other chosen frequncies (150Hz, 250Hz, and 350Hz) for purpose of hrmonic distrotion.

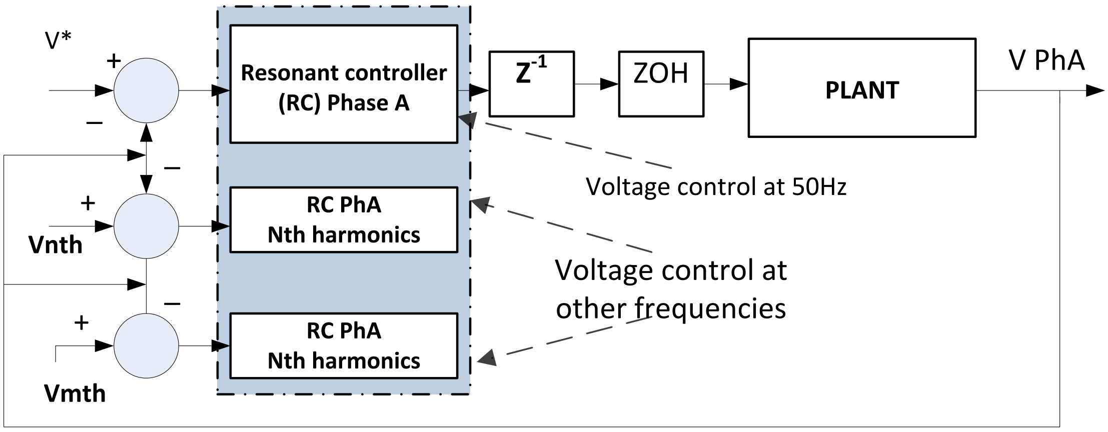


Figure 4.41: RC for Voltage control at 50Hz and several harmonics elimination.

The PR controller and High order controller design are tuned to show a high stability margin according to the root locus and bode plot diagram in figure 4.42 for a damping factor of 0.7, and the step response for the control system is shown in figure 4.43

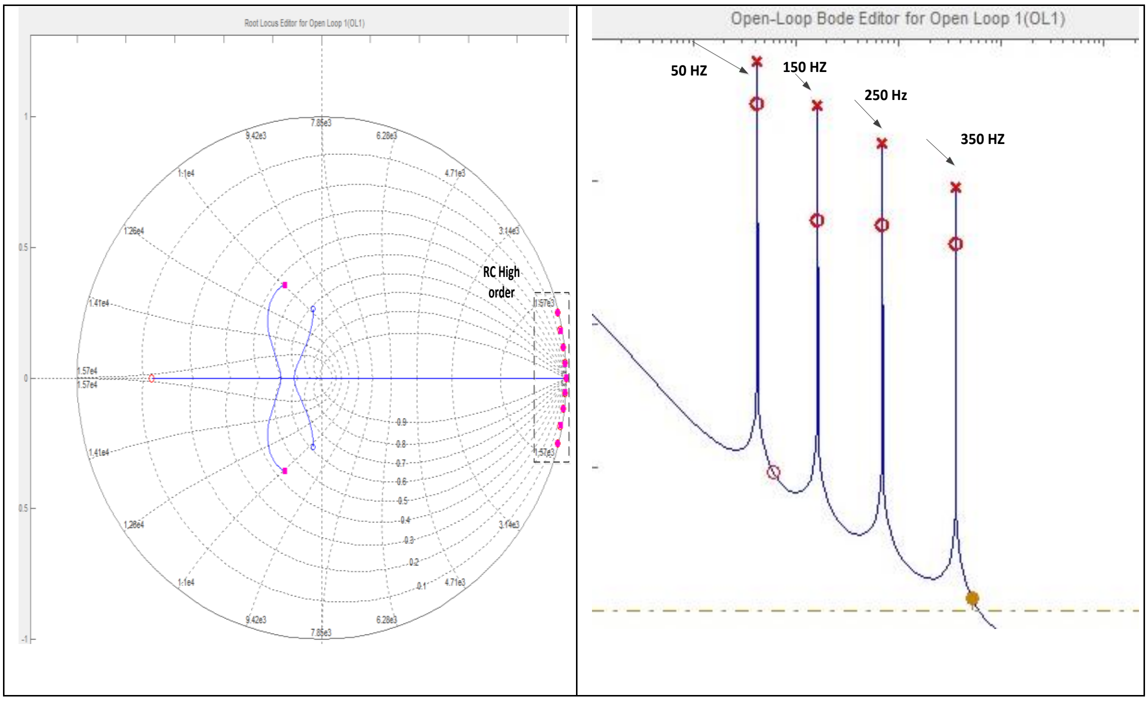


Figure 4.42: Bode and root Locus diagram for RC.

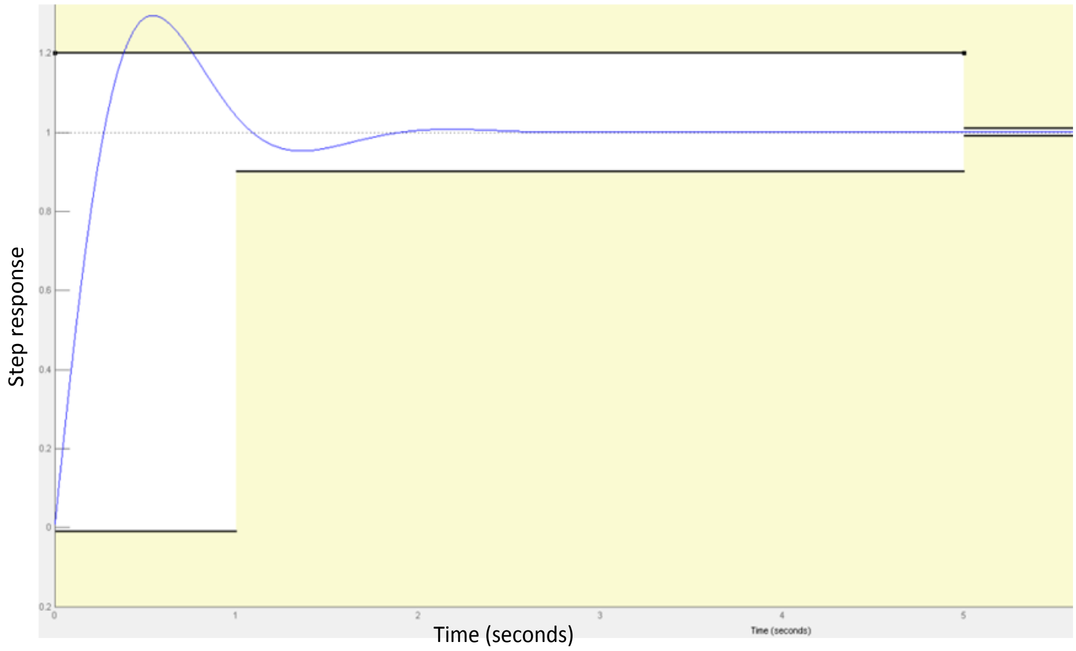


Figure 4.43: Step response for the system control.

4.5.2.2.4 *Findings and Results*

The AC side of the converter (V_{output}) is controlled using the circuit in figure 4.31, where the output of the converter is operating under several loading conditions, including voltage variations such as sags and short transient time. The output voltage of the converter V_{con} is controlled to add or decrease voltage to the overall output voltage of the phase ($V_{A\ output}$, $V_{B\ output}$, and $V_{C\ output}$). LC filter is used to obtain a sinusoidal wave. The operation of the overall control of circuit 4.31 is explained in a schematic diagram illustrated in figure 4.44.

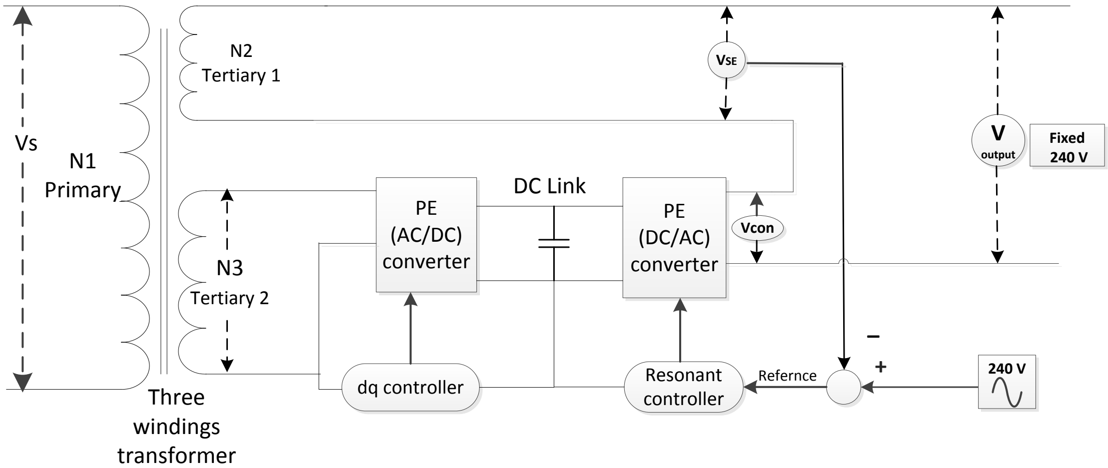


Figure 4.44: Schematic diagram for the overall control of the output voltage.

The control logic that is used to control the overall output voltage for the hybrid transformer is illustrated in figure 4.45.

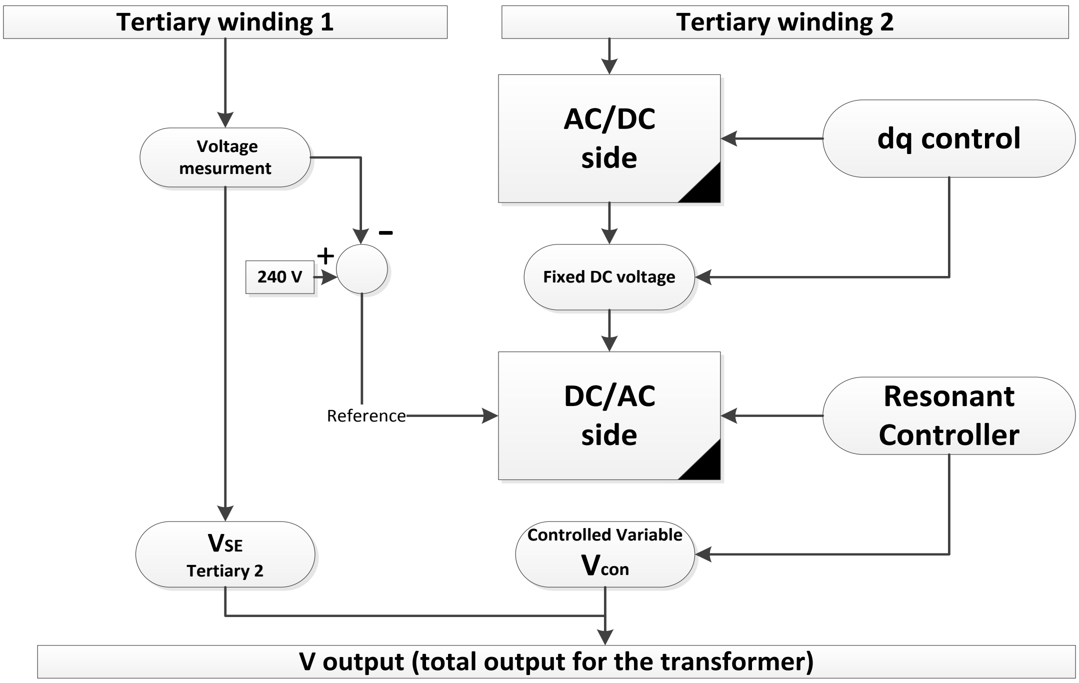


Figure 4.45: Schematic diagram for the overall control of the output voltage.

Voltage fluctuations such as (sag and swell) are simulated using disturbances scenarios such as heavy loads, and light loads that are applied before the main load in order to cause a decrease/increase in voltage. The output voltage is fixed at the secondary side of the hybrid transformer at 246 V (rms). A voltage swell is applied on the circuit and the overall control forced the voltage to settle down to it reference value after 1.5 second as seen in figure 4.46

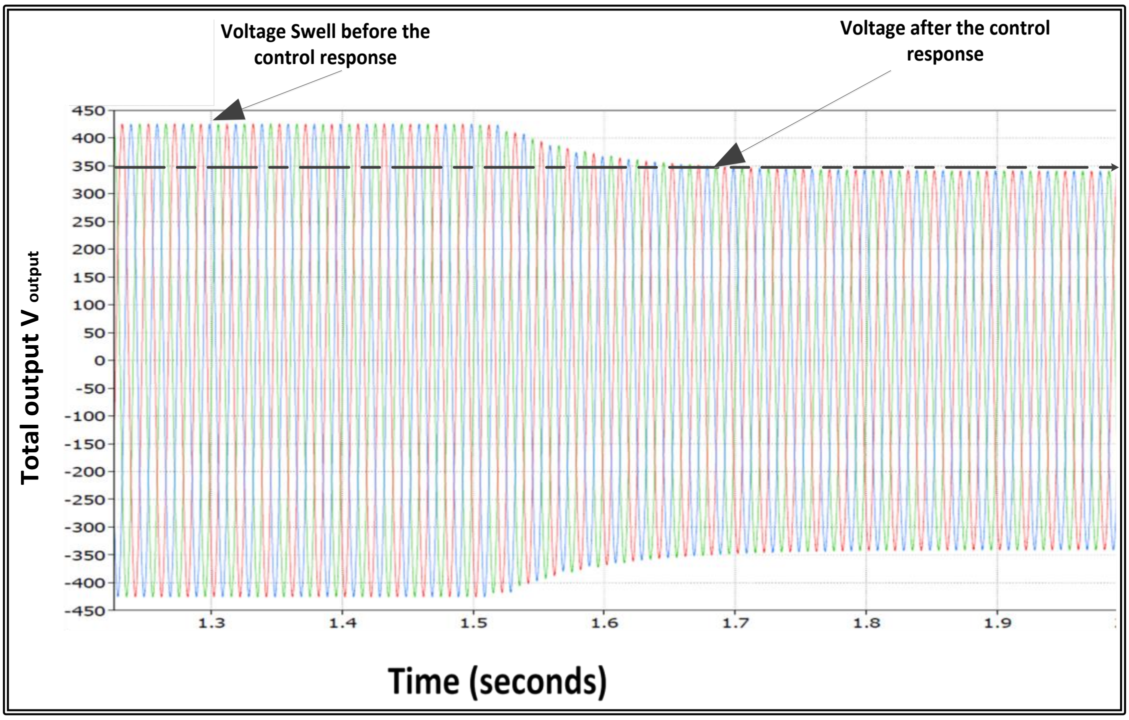


Figure 4.46: Voltage swell and the overall control response.

This approach also provides the possibility of regulating the voltage over frequent transient voltage fluctuations (second by second), as seen figure 4.47, where both of voltage sag and voltage swell are applied on the output voltage during 4 seconds, the control response is shown in figure 4.43. The reference of the total output voltage control is fixed and controlled in this case at the nominal voltage level, so the voltage regulation interval is decreased to be almost ±0% instead of ±10%.

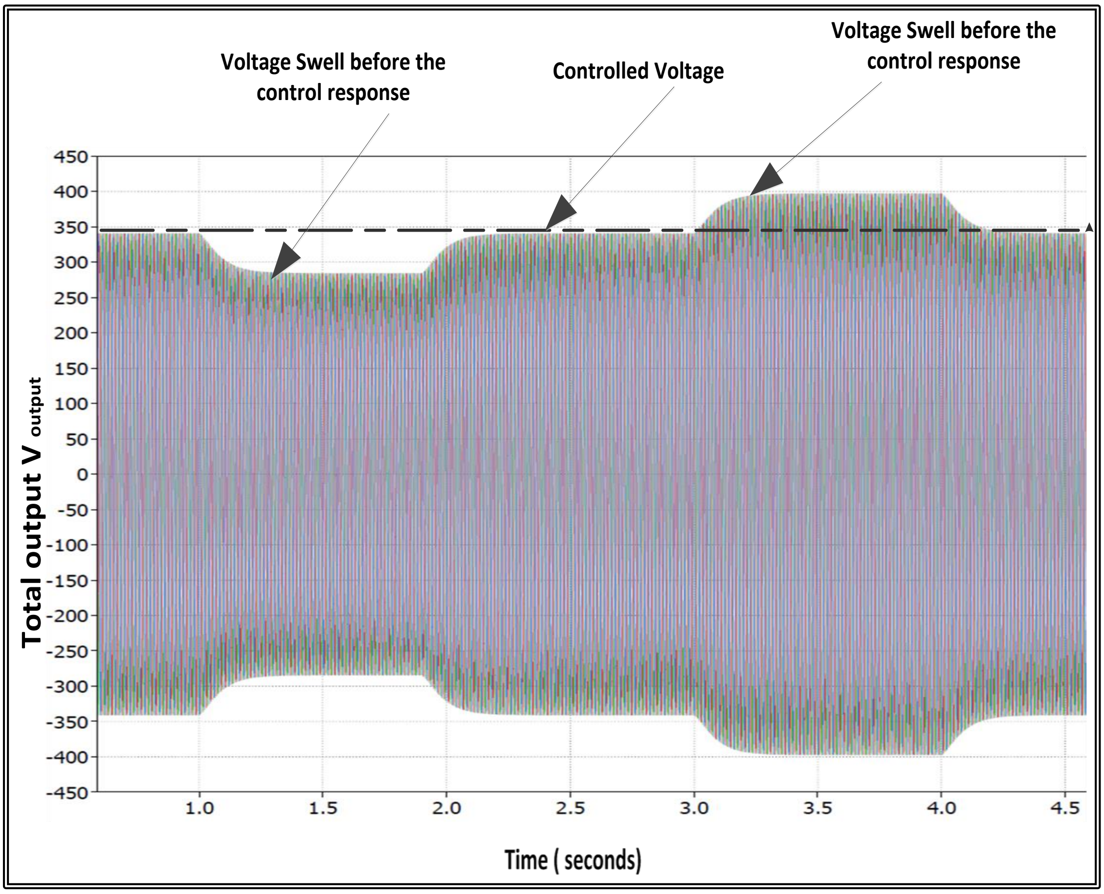


Figure 4.47: Voltage fluctuation regulation.

The voltage output is controlled during single and frequent time variations, which enhances the operation of sensitive voltage loads that require a firm and accurate voltage level, such as applications in medical equipment, where over-voltage can damage some electronic devices and reduce their operational life. On the other hand, decreasing the voltage can result in disabling the operation of these sensitive devices. The control of switches tries to provide a stable a DC link as a first level of control in order to isolate the variations of the input from the output, which ensures stable operation for the control at the AC side (final output), The DC link has the ability to be improved and used to provide a DC output source for a DC line or network in an enhanced form for the control, so it could operate synchronously between providing stability for the AC side and feeding a DC line (such as a DC network or charging a battery to be used in case of system failure) as a UPS approach as in Ref [128].

4.6 Conclusions

Future substation design depends on finding a way to employ the efficiency of the solid state switches of power electronics in the LV network that dispels the drawbacks of the traditional legacy system. Electronic approaches will inform the acceptable choice for future hardware implementation of substation from a power electronics viewpoint, necessitating a trade-off between flexibility, control function, efficiency and cost. In distribution transformers, the ratio between the secondary and primary voltage is fixed and cannot be changed, where the use of the on-load tap changers (used in transformers) is limited, especially in the UK [95]. Poor voltage regulation is a direct reason for losses and shortening the life of several devices, whereas proper voltage regulation improves the quality of the delivered power. In low voltage conditions, the equipment works with a lower power factor and draws more current with constant power consumption, which means more losses in the feeders due to the relation $=I^2R$ [95]. The designers of conventional substation transformers maintain the nominal voltage at the secondary side of the transformer to compensate the voltage drop accrued by the transformer and the impedance of the feeders. The tolerated voltage is usually 10% [95], [97].

Several scenarios for LV network are simulated and tested under verity of loading conditions. The voltage behaviour is tested and obtained using MATLAB in the light of:

- Distance between loads and substation
- Equal feeders and phases
- Unequal feeders and phases
- Power factor corrections
- Its effect on losses

The researcher addresses analysis and optimisation of the design of the power converter that achieves Interaction with other (PE) devices in the LV network to reach the following 4 points:

- Continuous Voltage regulation
- Voltage balance
- Reducing losses and used PE ratings as possible

The hybrid distribution transformer is introduced as an approach that has the potential to upgrade the operation of the new LV substation to a new level that has the ability to meet the demand of the future distribution grid from an efficiency, controllability and volume perspective. Different conceptual schematics for the design of hybrid distribution transformer were introduced that have different abilities in serving several requirements in the LV network according to expected incidents of voltage variation scenarios and VAR control. Back-to-back converter is designed to represent the attached PE, which is controlled at two stages; the first stage uses *dq* transformation for the purpose of fixing the voltage of the DC link, and the second stage aims to individually control each of the three phases at the AC output of the transformer using a resonant controller that has a sinusoidal voltage wave as a reference. The results of this design have illustrated the converter's ability to control the voltage over single and frequent time voltage variations, which informs the choice of future substation hardware implementations by initializing a reasonable percentage of PE switches that operate with conventional reliable equipment, such as transformers.

5 Reactive power compensation using Hybrid Transformer

5.1 Introduction

The demand of reactive power in the last mile of the networks is increasing by the time due to the change of loading types by time, beside increasing the total demand itself where new technologies are being introduced depend mainly on different types of electrical support such as electrical cars and more electronic devices in consumption process. This expected situation would lead to take into consideration new approaches in the last mile substations in order to mitigate the drawbacks of the conventional legacy and that by providing more functions in the last mile substations that could provide more flexibility and functionality regarding voltage level, Reactive Power (RP), amount of demand and losses [95]. This chapter focuses on the consideration that are taken in designing a distribution transformer that provide additional abilities in regulating the voltage and controlling the RP that is injected in the Distribution Network (DN) by using a fractional rated converter that is attached partially with the windings of the transformer. This approach aims mainly to enhance the unit with more flexibility in controlling the flow of the RP at the last mile of the network in order to decrease the losses that are caused by transmitting RP through long transmission networks. The design of the power electronics (PE) modules is detailed and its functionality in compensating Var power is discussed. This approach contributes in meeting the future expectations of the low voltage (LV) networks changes and loading, this contribution is comprised of providing the substation unit with fractional rated power electronic converter that is attached partially with the winding of the LV transformer to provide the load with a specific level of its demand from RP, whereby the solid state switches are controlled according to the immediate need for Var control and support in low voltage (LV) networks [95].

The design of new substations cannot ignore the rapid change in the type of loads changing and amount of consumptions, where simple comparison between the number and types of loads that are existed in the 1990’s house are much different than the devices that are used in current houses [95], furthermore the expected coming devices technologies forms a considerable concern regarding several issues in the LV network flexibility such as voltage and RP regulation, where both of the regulations participate in necessity and differs in the technique as the voltage is needed to be fixed at a specific level regardless the amount of load demand [95]. On the other hand RP regulation concept depends on providing the load unit of whatever needed from Var power in order not be transferred through the long way of the transmission lines and causes more losses retroactively [95]. The provided RP contributes in maximizing the amount of real power that can be transferred across a congested transmission line and decrease the heat that is generated from transferring it through the HV and MV lines. It is important to place the reactive power compensation source as close as possible to the location of the load (within the last mile) where RP does not have the ability to travel far.

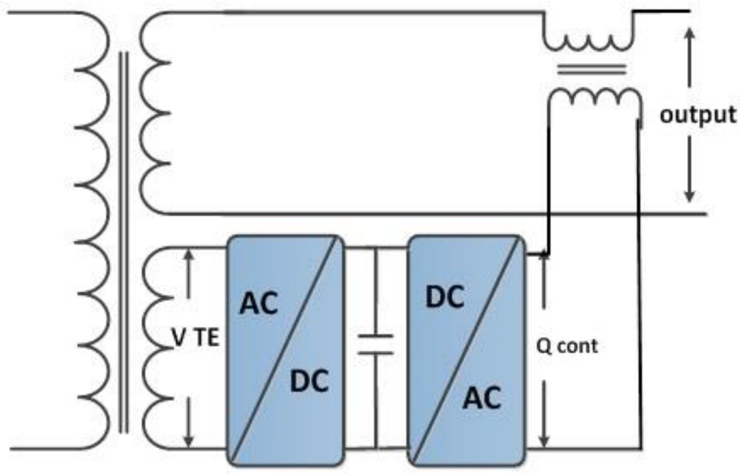


Figure 5.1: Introduced approach design for the VAR control hybrid transformer.

This approach introduces a solution that contributes mainly as in chapter four in keeping the voltage at a specific value or at least within the agreed voltage regulation limits (normally ±10%), and providing the unit with a specific amount of RP from the total load demand of RP, where this amount of supported Var are restricted by the ratings of the fractional attached PE. The proposed PE consists of converter designed to enhance the load unit with partial Var from its total demand in order to decrease losses as possible and to improve the power factor on the other side of the network (medium voltage network) by decreasing the transferred amount of RP in the transmission lines. The new design is based on the synchronous interaction between solid state switches and the low voltage windings of the conventional transformer or with the HV windings in some other configurations, where this combinations of PE and transformer is called the 'Hybrid Distribution Transformer' (HT), which is a voltage and RP compensation approach that provides a control function at the low voltage side of the transformer or the high voltage side. The design provides a voltage control as in the previous chapter or RP compensation, and both of these functionalities in some control configurations.

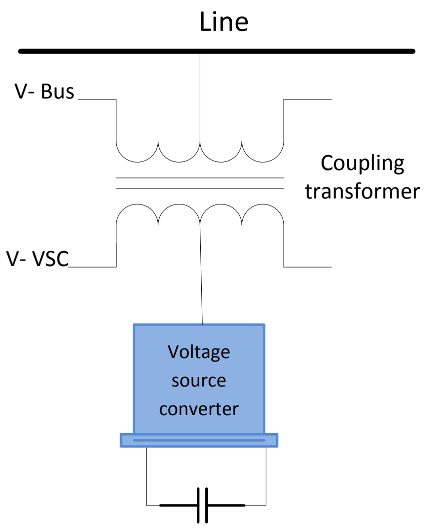


Figure 5.2: STATCOM connected in shunt with a transmission line [129].

Energy storage has got more attention also recently which can be one of the important parts in the operation of the STATCOM and its control, but it still represents a high cost which is determined by the amount of the energy storage, and the cycle life of the device. Energy storage charging and discharging also still show some challenges such as losses and shortening the reducing the life of the storage device [129].

5.2 Reactive power in distribution networks

Over the last few years, the sudden increase of the use of non-linear loads such as personal computers and TV sets created a Power Factor (PF) problem. Although such loads consume relatively small amount of power, however the large number of these loads resulted on huge distortion in the power quality. Also demand itself at the last mile has been increased significantly which makes it a large network and this is not the case as before when the last mile network used to serve a specific amount demand and end users, therefore the reactive power compensation issue has been growing at the distribution networks. In the meantime, fossil fuel prices are growing day by day, which enforces the consumers to minimize energy consumption. To optimize the use of the available apparent power (VA), the flow of reactive power should be eliminated or minimized. Another important term to quantify this problem is the power factor (PF). Its definition is correlated with the phase difference between the voltage and the current in AC circuits. In such circuits, they are supplied by sinusoidal voltage. The PF is represented for linear loads by (cos Φ), where Φ is the angle between the supplied voltage and the line current [130]. Generally, PF is considered as the measurement of how the power is optimized in inductive/capacitive loads. In other words, if the apparent power (VA) available to a customer equals to the real power (W) consumed then the PF will equal to unity (current and voltage are in phase). The main reason for poor PF is that electric circuits accumulate certain energy. This scenario is clearly well known in both linear and non-linear loads. In linear loads the PF is mainly a function of the reactive and resistive components of the load. Such PF can be adjusted/ corrected by introducing appropriate amount of leading or lagging reactive currents. Of course as the load changes the required amount of the reactive currents should also change automatically to maintain a unity or near unity PF. In this case an automatic generation of the reactive current is required in the distribution networks [131].

In non-linear loads, the PF is not just a function of the reactive and resistive components but also a function of the non-linearity of the load (diodes; switches; etc.). In such loads PF cannot be just corrected by passive reactive compensators but it also needs active compensators. Normally the power factor correction (PFC) circuit is placed in parallel with the load in order to compensate the RP so that the line current is in phase with the supplied voltage, but this is not the scenario for the future expectations when there is need for RP at most of the common coupling points in the LV network. Next section will propose a new approach and design to adapt with current and future needs of RP for the DN, where it combines between both of the advantages of:

- Reliable conventional device advantages which is the distribution transformer.
- And the power electronic flexibility, functionality and controllability.

Both of the parts are taken into consideration, due to the fact that there is still a big chance to a conventional device such as the transformer to be used as one of the most reliable devices in the distribution and transmission systems beside the need of tasting new technology of PE technology that has more controllability to be used over the reliability of the transformer.

5.3 Approach and design

As in chapter 4, if only a ±10% voltage limit for regulation is taken into consideration by the regulator, the attached solid state switches of the converter can be designed at fractional ratings (around 20- 30%) of the total windings of the LV transformer, which are the ratings that are needed to control the voltage regulation interval and to cut from the total power (S) part from the RP by making an angle between the degree of the voltage and the current [96]. The following functionalities for the HT could be achieved and considered according to its configurations:

- Voltage regulation of up to ±20% as in chapter 4.
- Reactive power control of up to ±20.
- A combination of both topologies may be achieved as long as the total rating of the PE part is not exceeded.
- The attached converter can be cancelled and protected by being bypassed in case of a failure within the system.

The aim behind the fractionally in the ratings of the transformer is to provide the designed overall system with following features [96]:

- High in reliability and low cost reliability relative to the full rated converters
- Reducing switching losses due to operate within lower switches' ratings.
- The latent advantages of one of the most reliable devices in the network -which is the transformer-, are exploited.
- The system tastes partially the flexibility of the PE and its functionalities that could be bypassed in case of PE failure

Power electronic part is represented as a back to back converter that have the ability to supply a dc output in case of further modifications, the converter is set up to control three unbalanced phases separately where each phase supply three feeders in the last mile of the network to for 9 lines in general, as most feeders are made up of three phases and four wires, the latter of which is usually the neutral. The three phases differs in length and number of connected loads which means different voltages drops and different demands, this situation requires a voltage regulation and Var compensation separately of each phase [100], by using three single converters, or by using a three phase converter. There are two functions for converter that could be exploited; keeping the voltage constant at the regulated line and injecting/absorbing RP with a specific amount that is restricted by the fractional ratings of the solid state switches of the transformer, where this amount could be increased in the future by depending on more reliable PE switches and proportionately with the increase of future demand.

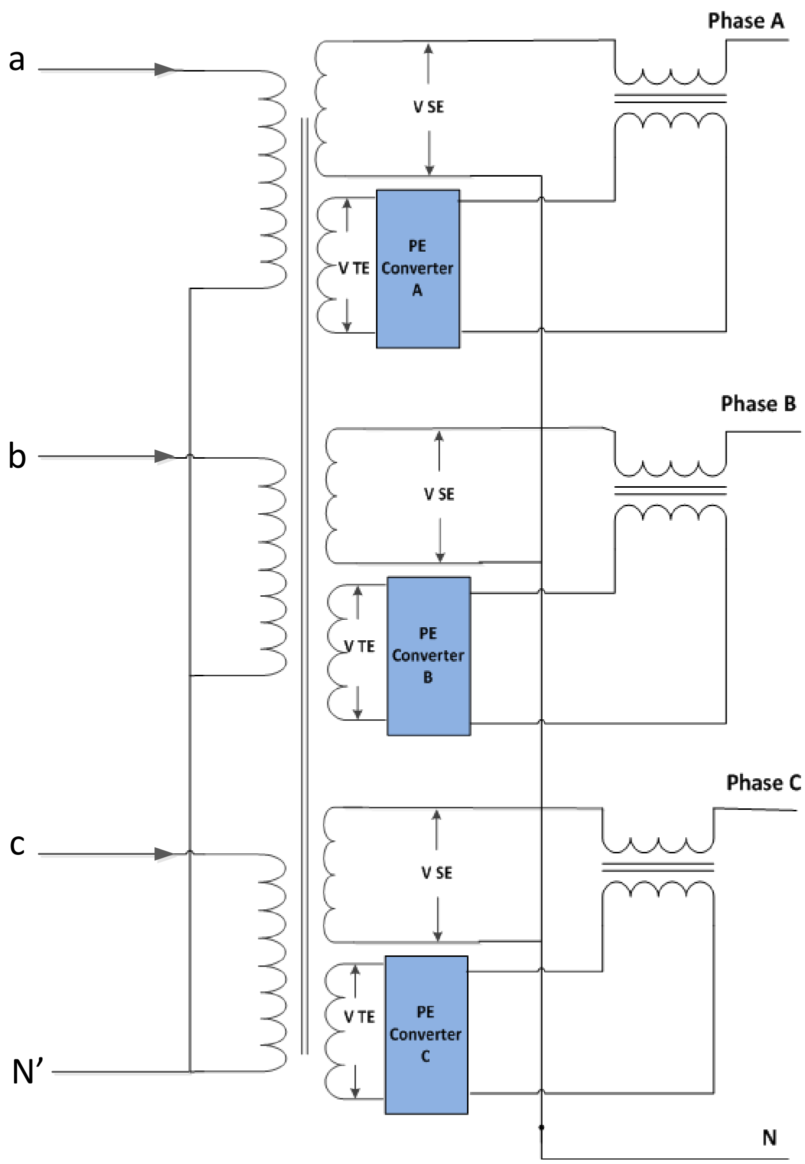
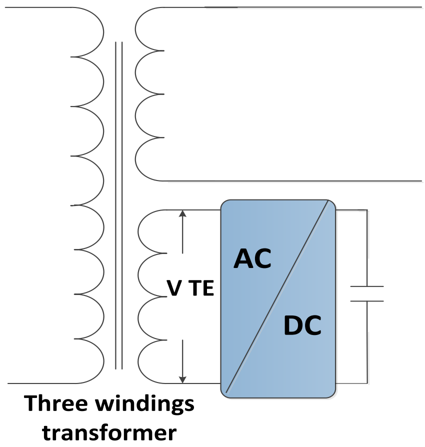
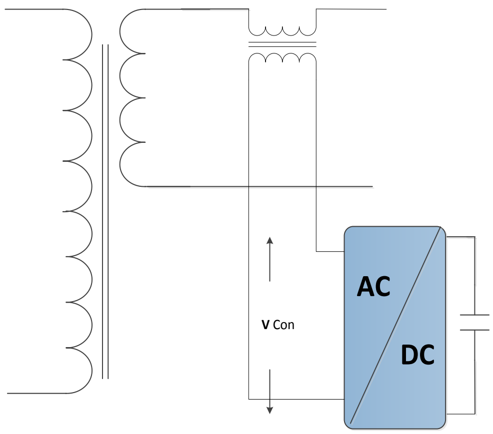


Figure 5.3: The proposed HT is introduced as a normal transformer that is attached partially with an AC/AC converter with a DC link and series transformer.

As in the transmission grid, using RP compensation is generally for voltage stability, using it also in the DN is a necessity to keep the voltage constant in case of the existence of huge RP demand and extra loads that depends on RP at the end line, in this case an instantaneous Var compensation is required for the aim of voltage stability, this scenario could be seen in the last mile of the network, as the increasing prevalence of electrical cars, whereby users plug and unplug their cars to charge frequently during the day, this requires an intervention from the closest point in the network which is the distribution transformer in order to keep voltage and current in phase.

5.4 Topologies and options

There are different configurations that the HT could take depending on different considerations in order to perform various functions at the last mile, where every consideration such as voltage regulation, voltage stability, RP flow and Var compensation has its own topology that contains mainly the configuration of attachments for the PE and the connection of the new amendments with network lines.

Conceptual schematics	Functionality and ability
	Figure 5.4a: Conceptual 1 This option has the ability to correct the PF for both of the distortion and displacement power factor. The DC source could be charged and discharged through the bidirectional converter.
	Figure 5.4b: Conceptual 2 This option has similar function as SSSC, where it has a separate DC source. The converter takes the power from the DC source and inject it as voltage in the line (in capacitive and inductive mode)

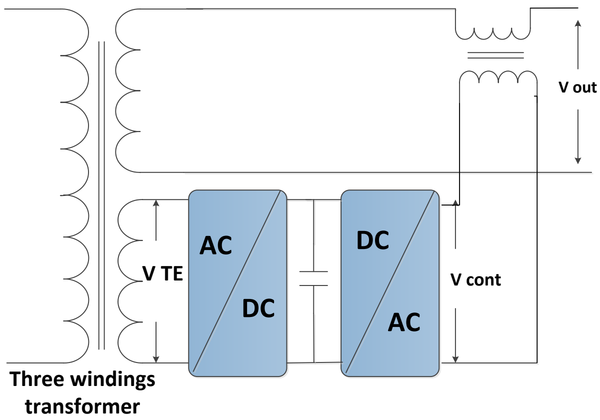


Figure 5.4c: Conceptual 3

This option is considered the main option that is used in the design to inject the RP as voltage by using a back to back converter

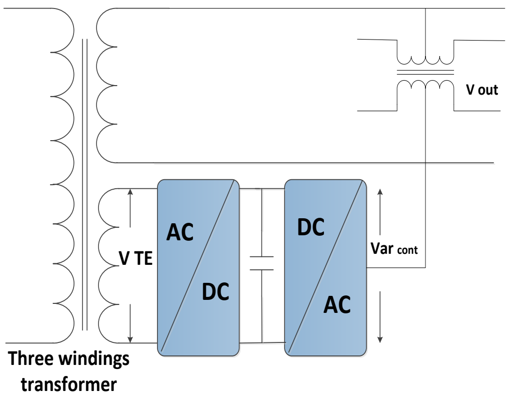


Figure 5.4d: Conceptual 4

This configurations operation is similar to the operation of the STATCOM where it injects the RP through a parallel restricted rated transformer.

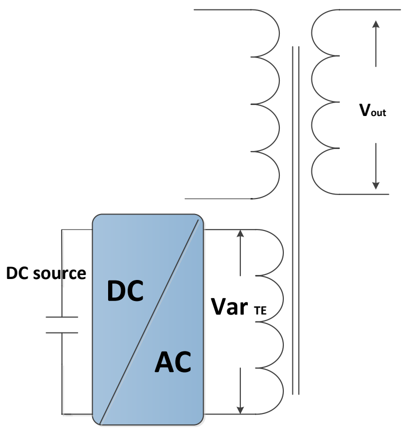


Figure 5.4e: Conceptual 5

The configuration also includes the secondary side of the distribution transformer, where it compensate the RP at the secondary side with lower ratings for the solid state switches that operate high voltage and lower current ratings

Figure 5.4: Different conceptual topologies to perform several operations (mainly voltage regulation and Var compensation)

5.5 Control topologies

For the configurations that uses a back to back converter as in the conceptual schematics c and d in figure 5.4, Power control topology is considered, and the *dq* transformation technique is used to control the voltage at the DC link terminals, whereby the overall controller adds or decrease voltage (20%) to/from the total output voltage in order to control the whole output voltage of the transformer [105].

A vector control is used to control the supply of RP by using other configurational options which are similar to the configurations in chapter 4, as vector control is one of the most popular methods used for voltage source converter (VSC) [105].

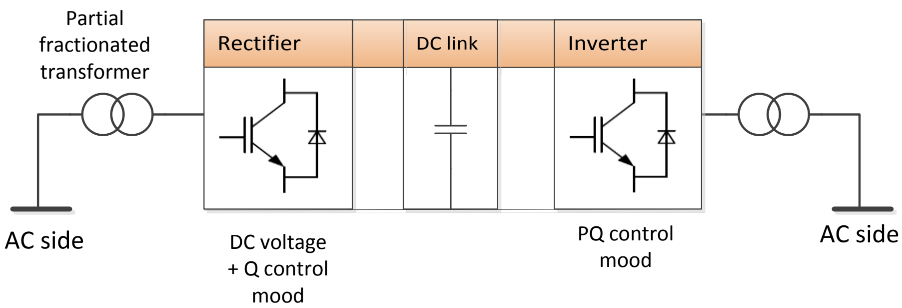


Figure 5.5: Overall PE design structure of the VSC in the DC side.

The rectifier side controls voltage at the DC voltage and reactive power injection, while the active power is controlled through the inverter side. The reactive power can be controlled in both of the converters separately without affecting the DC voltage. Therefore using Back to back converter gives the possibility of controlling the reactive power, active power, ac voltage and DC voltage [132]. Figure 5.5 shows the used mode in this approach.

5.5.1 Power angle control principle

It is possible to control the power through controlling the power angle between two electrical points as seen in equations (5.1) and (5.2), where controlling reactive power is dependent on the voltage difference between the two nodes, and active power control is dependent on the phase angle. Equations 5.1 and 5.2 represent the fundamental of power angle control [133].

$$P = \frac{V_1 V_2 \, sin\theta}{X} \tag{5.1}$$

$$Q = \frac{V_1^2 - V_1 V_2 \, cos\theta}{X} \tag{5.2}$$

Where V_1 and V_2 represents the voltages values for both of the electrical nodes, while θ and X represent the phase angle and line reactance respectively. Therefore the reactive power could be controlled through changing the voltage magnitude between the two nodes and active power could be controlled through changing the phase angle between the two nodes. However, the power angle control principle is rarely used in for power control in the practical life due to several disadvantages such as the limitations in controlling the current and bandwidth in converters [113], where those drawbacks represent serious problems regarding protection issues [133].

5.5.2 Reactive and active power controller

The vector control that is applied in chapter 4 could be applied in this chapter depending on the values of each type of power on the components of *dq* transformation, the power *dq* transformation could be written as the following:

$$P = V_d I_d \tag{5.3}$$

$$Q = V_q I_q \tag{5.4}$$

Where $V_d I_d$ and $V_q I_q$ are currents and voltages in *dq* coordinates. Active and reactive power controller is shown in figure 5.6.

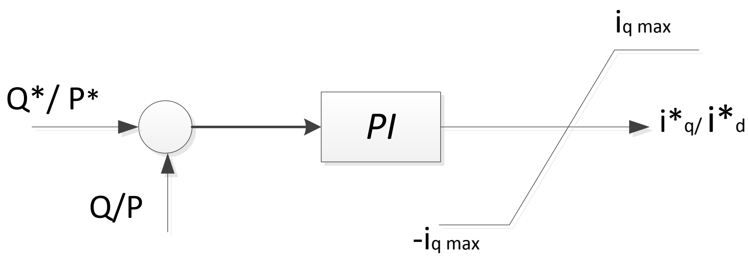


Figure 5.6: dq frame reactive and active power controller.

5.5.3 DC Link control using Power control principle

The back to back converter is used due to its advantage in performing fast control for power flow; the variations in the DC voltage at the DC link could be avoided if the power at the DC link from the rectifier side and power at the DC link from the inverter side are balanced [134]. Therefore the current level at the DC link is not distorted.

The size of DC link is an important issue regarding the balance of power transfer between both of the converters and the grid. Installing small size DC links or capacitor increases the possibility of current distortion and voltage variations at the inverter output, furthermore, small capacity contributes in DC ripples in case of affecting the AC voltage source with any harmonics or unbalanced situation [135]. Therefore, the capacity problem at the DC link could be solved or improved by using Film capacitor at the DC link as energy storage [136]. Capacitor size and efficiency is very important issues as it affects seriously the life time of the converter and its total cost.

By minimising the capacitor size, the total cost and volume for the design is reduced, but without affecting the performance of the converters as mentioned before such as producing more ripples and voltage fluctuations. However the control method that is used in chapter 4 doesn’t take into account the power balance issue between both of the converters due to the aim of regulating the synchronised voltage. Chapter 4 provides a control method without considering power flow dynamics of converters. Since the operation of rectifier depends on the operation of the inverter status, considering the power control between both of them contributes towards faster control. it is possible to control the active or reactive current by the rectifier which enables the inverter to be fed with the exact amount of its need from current. Hence, the voltage fluctuations could be avoided due to controlling the amount of current that flows through DC link.

The DC link voltage is controlled in this approach according to power balancing between inverter and rectifier as it is explained in the following sections. The Voltage controller for the DC link is applied according to the following equations which are used in the following sections. The stored energy (W), and power in the capacitor P_{Cap}, are represented as:

$$W = 0.5\, CV_{dc}^2 \tag{5.5}$$

$$P_{Cap} = V_{dc}I_c \tag{5.6}$$

$$\frac{d}{dt} W = P_{cap} \tag{5.7}$$

5.5.3.1 ***Inverter and rectifier power dynamics***

The inverter schematic diagram connected with grid is shown in the figure 5.7, in order to understand the inverter behaviour the output voltage is represented in equation (5.8).

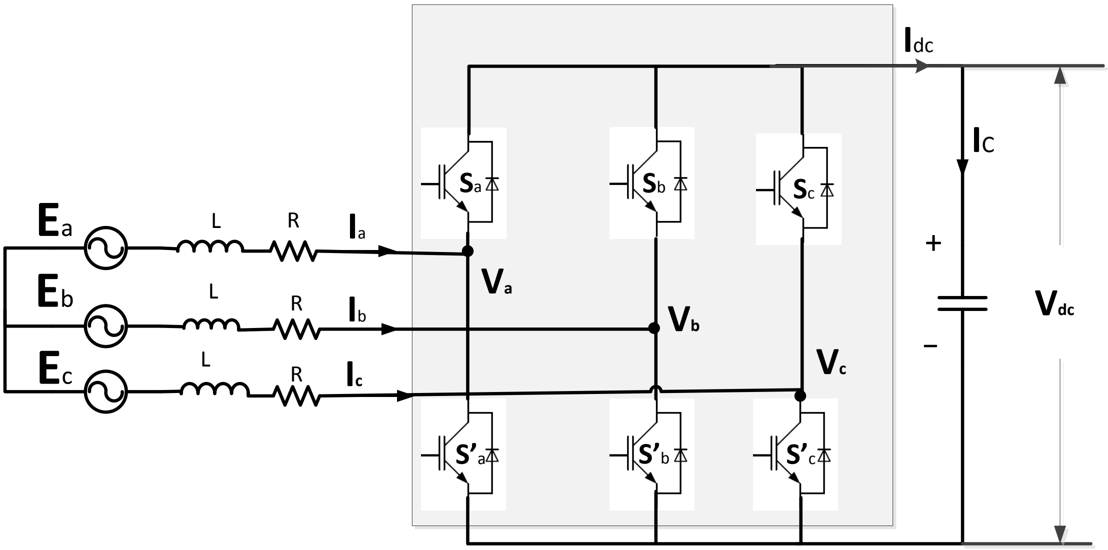


Figure 5.7: Inverter schematic diagram connected with grid.

5.5.3.1.1 *Inverter part*

According to figure 5.7, equation (5.8) could be written as the following [113]:

$$E_{abc} = V_{abc} - RI_{abc} - L\frac{d}{dt}I_{abc} \tag{5.8}$$

Where E is the grid voltages and V_{abc} / I_{abc} are the grid currents and converter input voltages respectively, (L+R) is the inductance and resistance between converter and grid. The equation is written in equation 5.9 as the equivalent after *dq* transformation [113].

$$V_d = L\frac{d}{dt}i_d - \omega L i_q + E_d + Ri_d \tag{5.9}$$

$$V_q = L\frac{d}{dt}i_q - \omega L i_d + E_q + Ri_q \tag{5.10}$$

The line currents derivation is as the following:

$$\frac{d}{dt} i_q = -\frac{R}{L} i_q + \omega i_d + \frac{V_q}{L} - \frac{E_q}{L} \tag{5.11}$$

$$\frac{d}{dt} i_d = -\frac{R}{L} i_d + \omega i_q + \frac{V_d}{L} - \frac{E_d}{L} \tag{5.12}$$

The inverter voltage derivation is as the following [113]:

$$V_d = E_d - \omega i_q + K_p \left(I_d^* - I_d \right) + T_i \int_0^t e_d \, dt \tag{5.13}$$

$$V_q = E_q - \omega i_q + K_p \left(I_q^* - I_q \right) + T_i \int_0^t e_q \, dt \tag{5.14}$$

Where T_i and K_p are the PI control coefficients. And the error is represented in e_q and e_d as $(I_d^* - I_d)$ and $\left(I_q^* - I_q \right)$ in the *dq* transformation frame as I_d^* and I_q^* are the reference feed in the current control loop.

The inverter power that is taken from the DC link is described in equation (5.15) which is similar to equation (4.25)

$$P_{inv} = \frac{3}{2} \left(V_d I_d + V_q I_q \right) \tag{5.15}$$

By substituting the values of equations (5.11) to (5.14) in the derivation of equation (5.15), and after simplification, the inverter power dynamics according to time is illustrated as in equation (5.16):

$$\frac{d}{dt} P_{inv} = -\frac{R}{L} P_{inv} + \zeta \tag{5.16}$$

Where ζ is the inverter power dynamic variable and it is used by the inverter in order to update the rectifier with current status of the inverter, which enhance the current control at the dc link between the rectifier and inverter.

5.5.3.1.2 *Rectifier part*

The rectifier operates in this case according to the controlled status of the inverter. The rectifier has the following power transfer dynamics according to the inverter power dynamics, whereby the voltage and currents are described according to the following equations:

$$I_c = C\frac{d}{dt}V_{dc} \tag{5.17}$$

$$L\frac{d}{dt}i_d = -V_d + \omega L i_q + E_d \tag{5.18}$$

$$L\frac{d}{dt}i_q = -V_q - \omega L i_d + E_q \tag{5.19}$$

Where I_c is the capacitor voltage, V_d/V_q and i_d / i_q are the *dq* axis of the rectifier terminal voltages and currents respectively. ω is source voltage angular frequency. Bring into line the *q* frame control in case of supposing $E_d = 0$. Then the power from the rectifier to the DC link is obtained as:

$$P_{rect} = \frac{3}{2}\left(I_d E_d + I_q E_q\right) = \frac{3}{2}\left(I_q E_q\right) \tag{5.20}$$

$$\frac{d}{dt}P_{rect} = \frac{3}{2}\frac{E_q}{L}(E_q - V_q) \tag{5.21}$$

In case of supposing Eq = 0:

$$\frac{d}{dt}P_{rect} = \frac{3}{2}\frac{E_d}{L}(E_d - V_d) \tag{5.22}$$

5.5.3.2 *Transfer function power control*

As the inverter side is connected to the side of LV grid, it represents the synchronisation part of the system, and the rectifier is acting as the source gate for the inverter. Therefore rectifier follows the power dynamics of the inverter. The transfer function of the inverter is utilised from Equation 5.16 as the following:

$$G_{inv} = \frac{1}{S + {}^{R}/_{L}} \tag{5.23}$$

The transfer function of the rectifier according to equations (5.21) and (5.22) is as the following:

$$G_{rect} = \left(\frac{3E_d}{2L}\right)\frac{1}{S} \tag{5.24}$$

Therefore:

$$V_d = E_d - \left(\frac{2L}{3E_d}\,.\,G_{inv}\,.\,\zeta\right) - K\,(P_{inv} - P_{rect}) \tag{5.25}$$

$$V_q = E_q - \left(\frac{2L}{3E_q}\,.\,G_{inv}\,.\,\zeta\right) - K\,(P_{inv} - P_{rect}) \tag{5.26}$$

Where K: is the control coefficient that is represented in the following diagrams. Therefore from equation (5.7), (5.24) and (5.25) the control diagram for the DC link is applied as in figure 5.8:

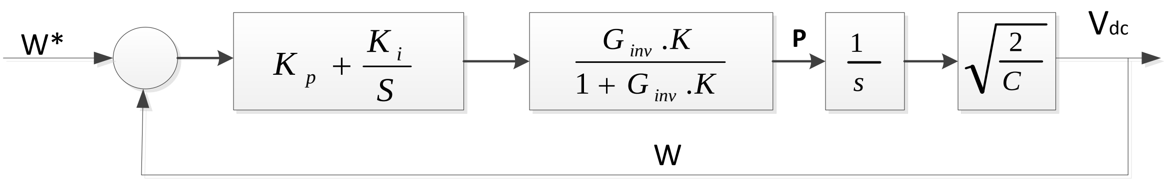


Figure 5.8: Control loop for DC link.

The feedback for the closed loop is the error between the power and it reference as equation (5.27):

$$\frac{W}{W^*} = \frac{G_{rect}.K\left(K_p + \frac{K_i}{S}\right)}{(1 + G_{rect}.K) + \ G_{rect}.K\left(K_p + \frac{K_i}{S}\right)} \tag{5.27}$$

The whole control system for the converter is shown in the following figure depending on the power dynamics between the inverter that is connected with the LV side and rectifier that is connected with the transformer.

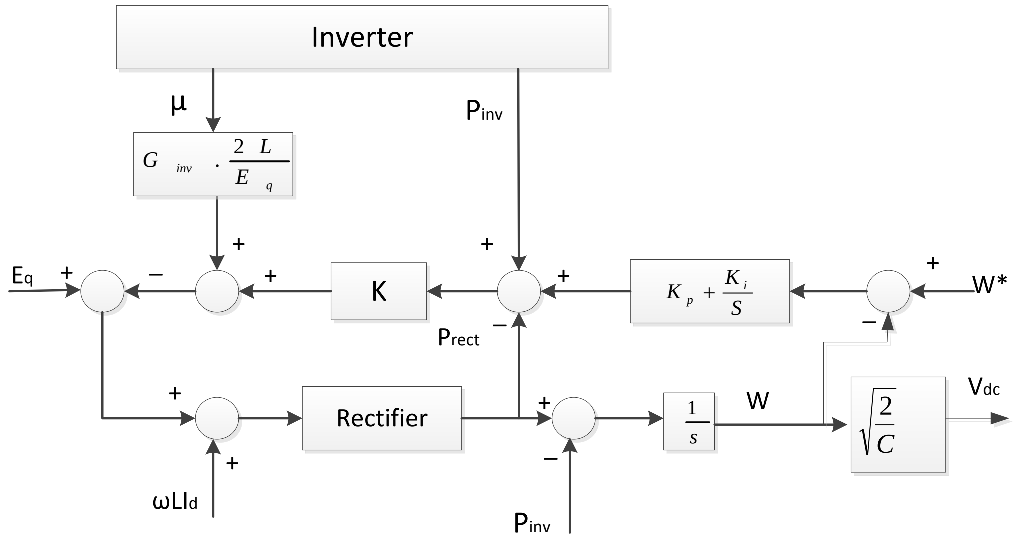


Figure 5.9: Schematic diagram of the power control system.

5.5.4 Results

On the contrary of chapter 4, the approach in this chapter assume Id = 0, and depends mainly on the power transfer strategy between both of the converters, the control divides the power into two terms d and q, where q represents the reactive power and d represents the active power. Voltage and currents are described as vectors in the stationary αβ and transformed after that to *dq* coordinates to be controlled by two loops: inner loop for the current control and outer loop for the DC voltage control. The controlled coordinates are then transformed to feed the PWM generator in order to control the DC output of the converter [137].

An equivalent Laplace transformation for the circuits' material is done in order to determine the parameter of the PI controller. By this control the fluctuation in the DC link is minimised to enable fast and stable control for the AC side of the converter. The control for the RP compensation is tested according figure 5.10, where the HT is controlled to support the load with its partial need from RP, instead for taking it from the transmission grid so the *q* component that is transferred from the transmission line to be zero, and it is produced by the HT instead.

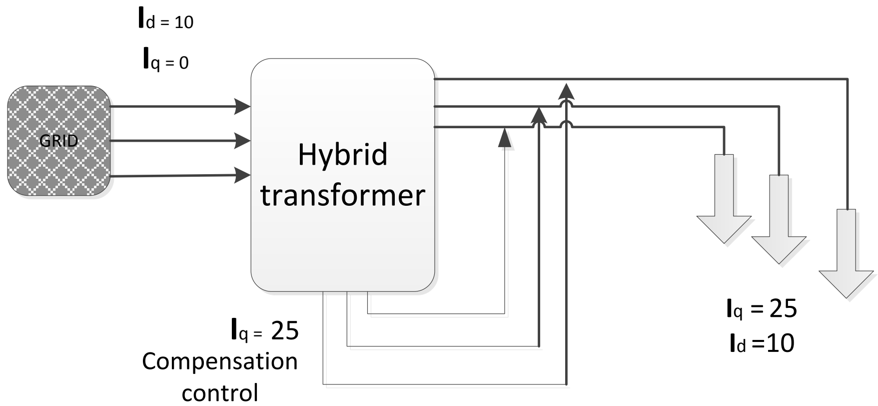


Figure 5.10: Control diagram for the hybrid distribution transformer.

The *dq* transformation is used, as shown in figure 5.11, where PLECS software is used to get the simulated results, whereby *q* components represent the reactive power or current part.

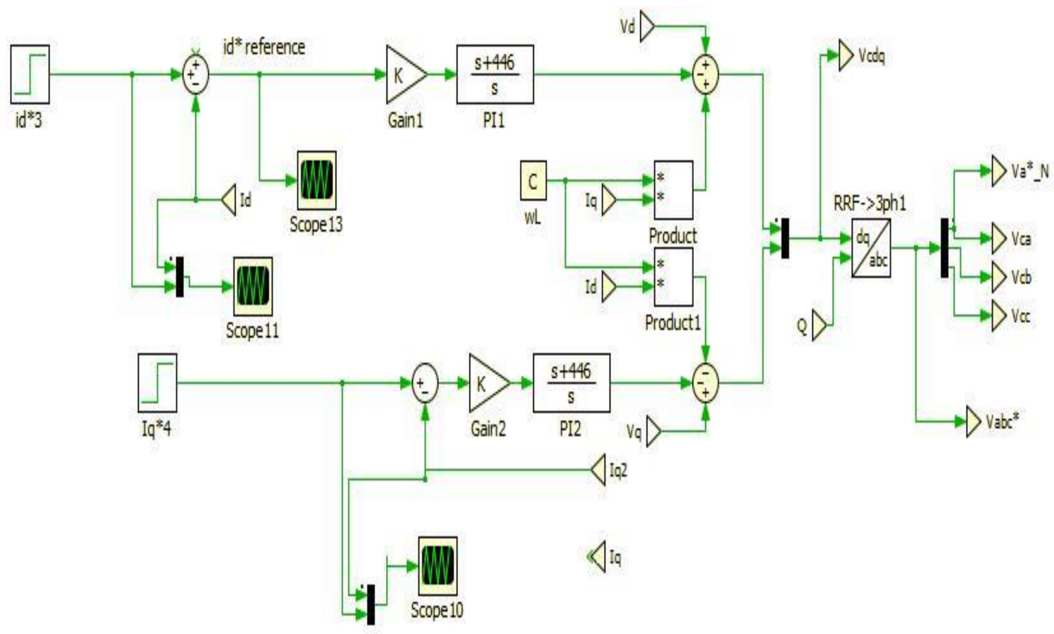


Figure 5.11: dq transformation technique for the fractional converter.

The AC side of the converter is controlled where the output of the converter is operating under several loading conditions, As in Chapter 4 LC filter is used to get a sinusoidal wave; the injected RP, the transferred Var through transmission grid and the loaded RP after the secondary side of the transformer are shown in figures 12 to 20 for different loading scenarios. The vector transformed value of the current is illustrated as I_q indicates to the amount of reactive current.

- Loading scenario (L_{1})

The reactive power that is transferred through the transmission line (before the 11/0.43 KV transformer) is zero, and the load is taking its need from reactive power from HT as seen in figures 5.12 to 5.14

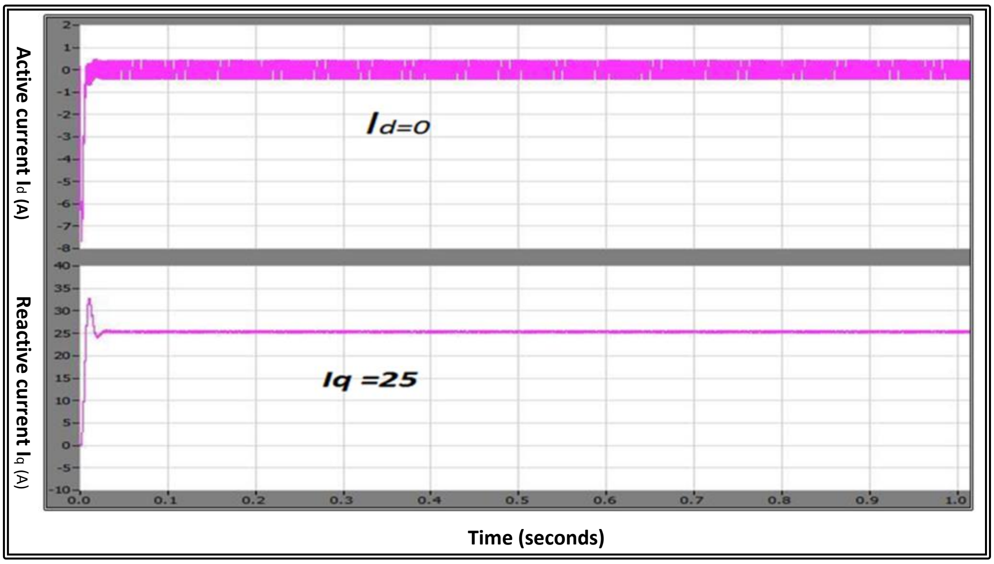


Figure 5.12: dq components of the injected RP for L_1.

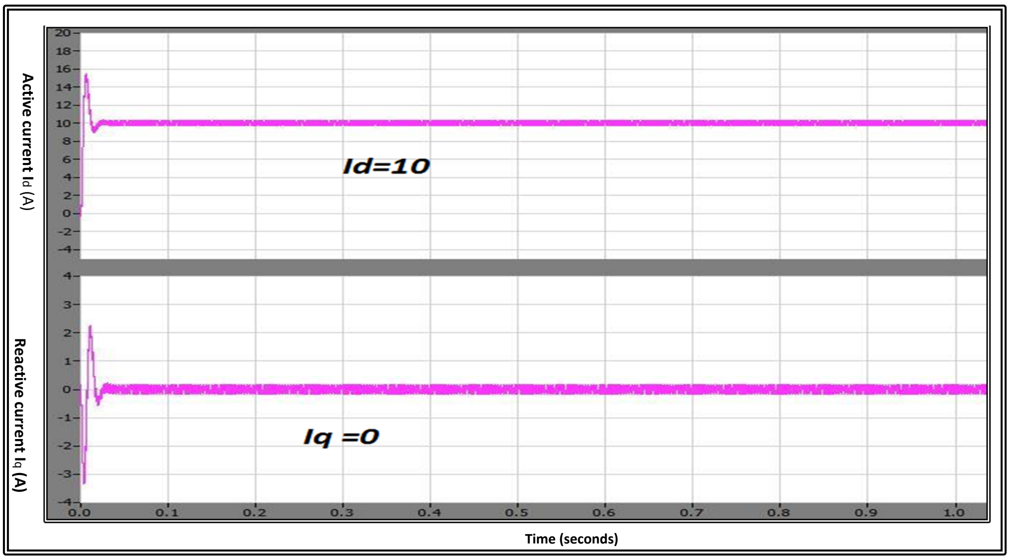


Figure 5.13: dq components of the transferred current in the transmission lines for L_1.

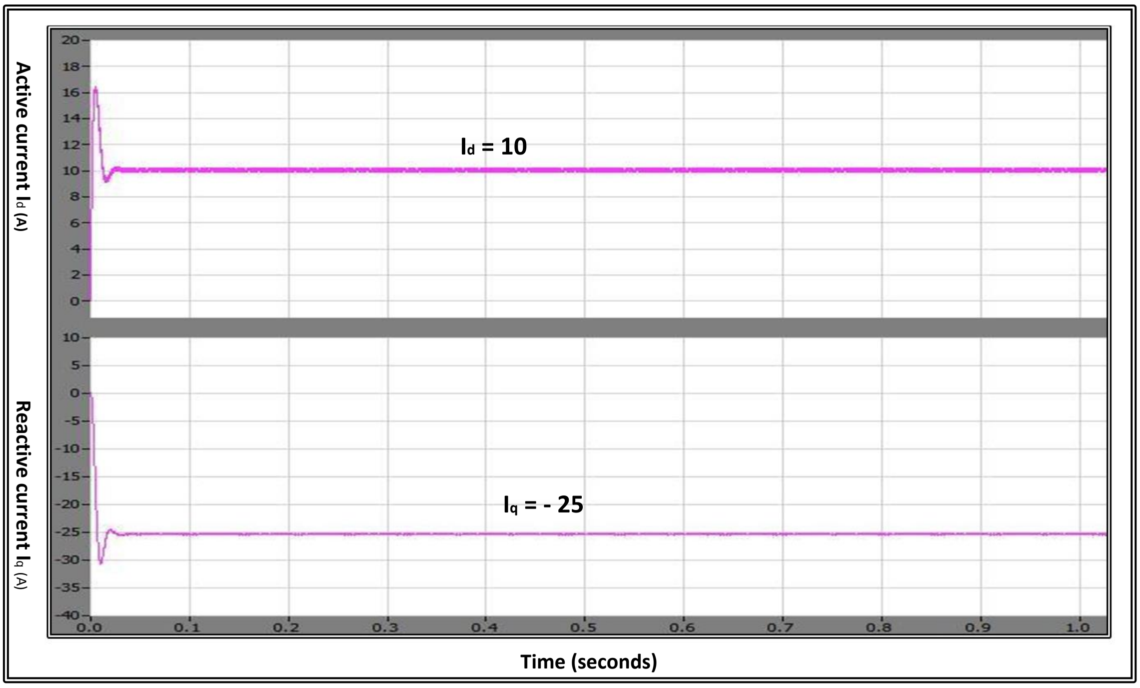


Figure 5.14: dq components of the distributed current for L_1.

- Loading scenario (L_2)

The demand of reactive power is increased in this loading scenario, where the load takes most of its need from the HT and the rest is transferred through the grid. The transferred reactive power (before the HT) is decreased in this case as seen in figures 5.15 to 5.17.

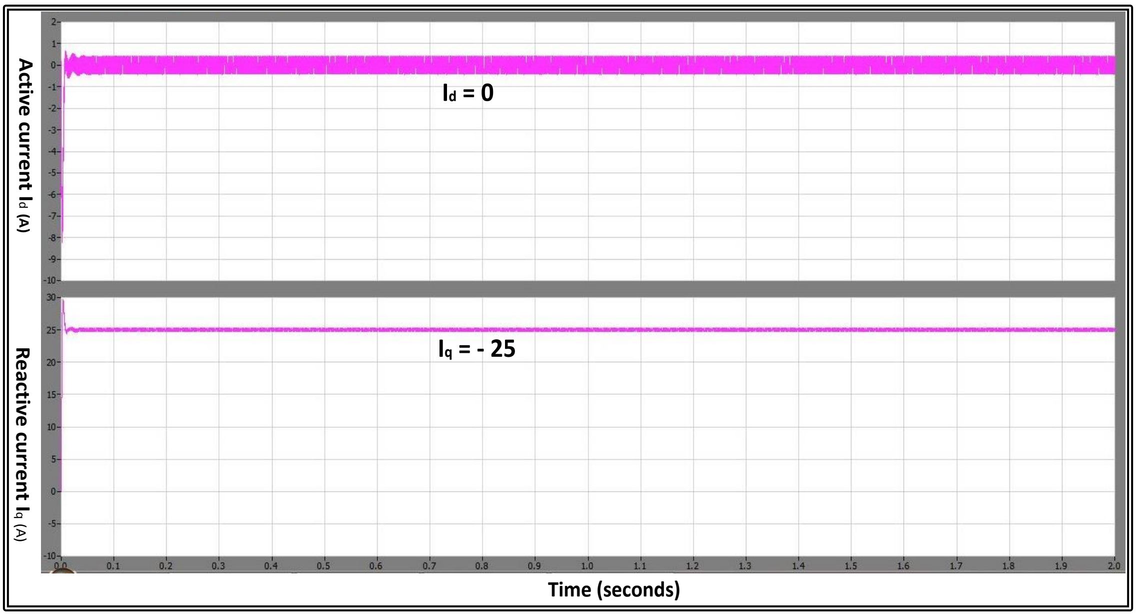


Figure 5.15: dq components of the injected RP for L_2.

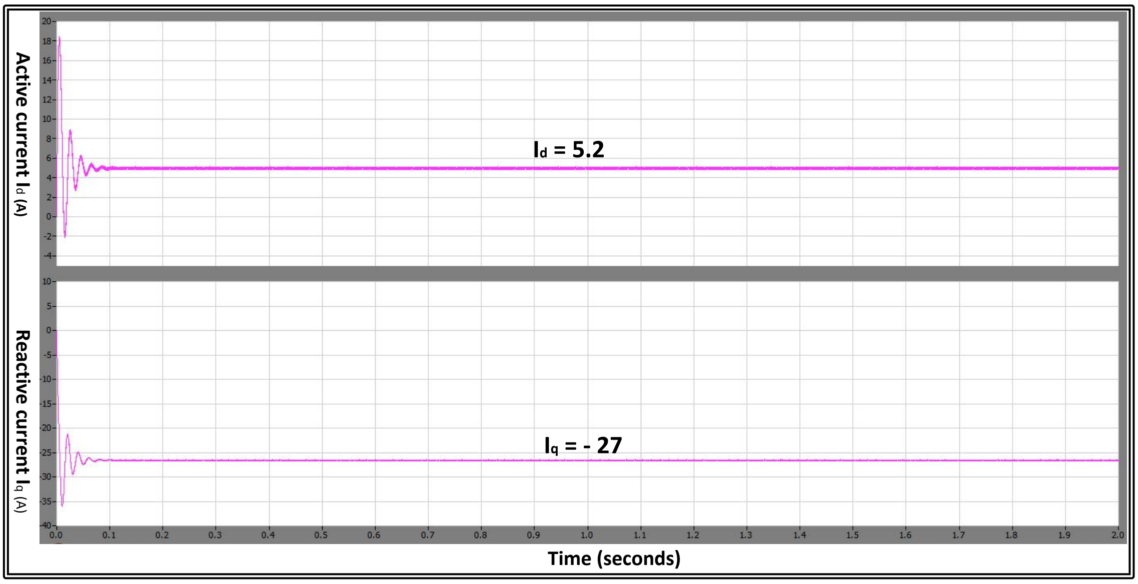


Figure 5.16: dq components of the distributed current for L_2.

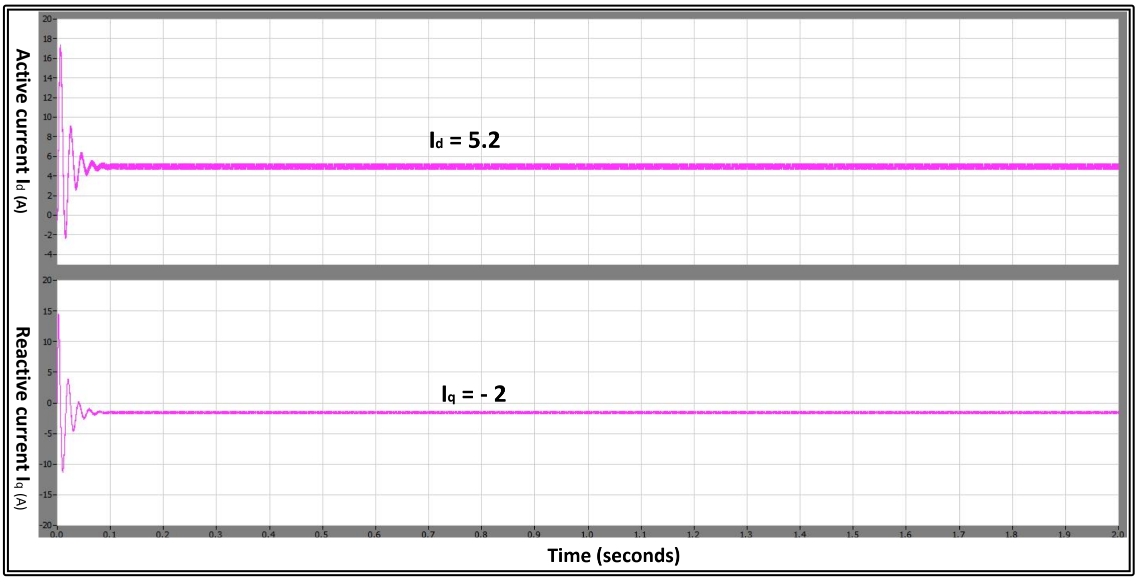


Figure 5.17: dq components of the transferred current in the transmission lines for L_2.

- Loading scenario 3 (L_3)

The reactive power demand is increasing for the case of load 3, where the transferred amount of reactive power before the HT is increasing also, but the HT keeps supplying its share from reactive power to the load which contributes significantly in decreasing the transferred losses through the transmission cables, the results of this scenario is shown in figure 5.18 and 5.19.

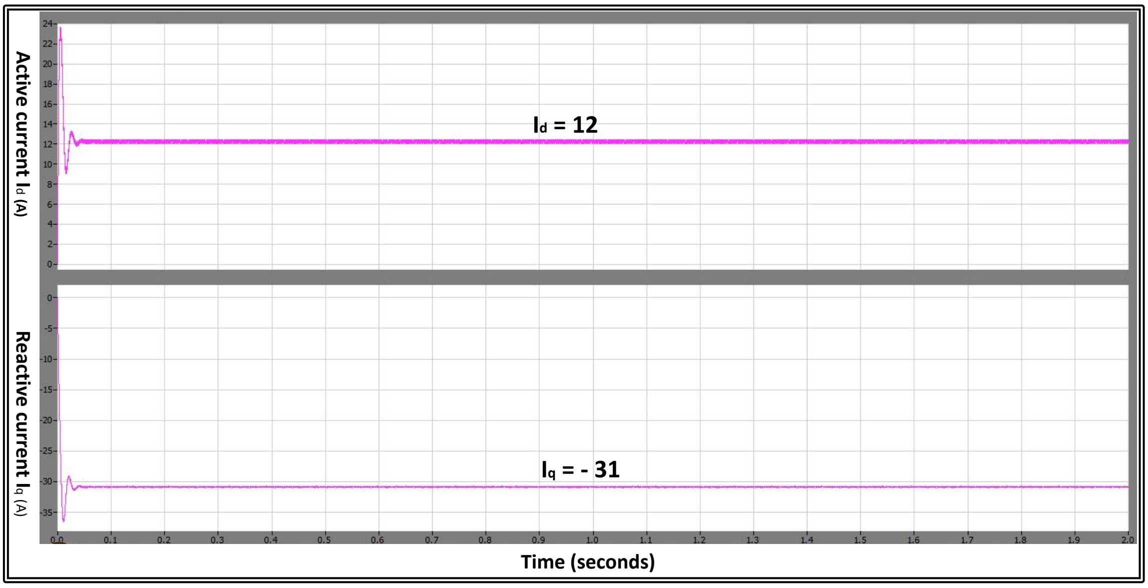


Figure 5. 18: dq components of the distributed current for L_3.

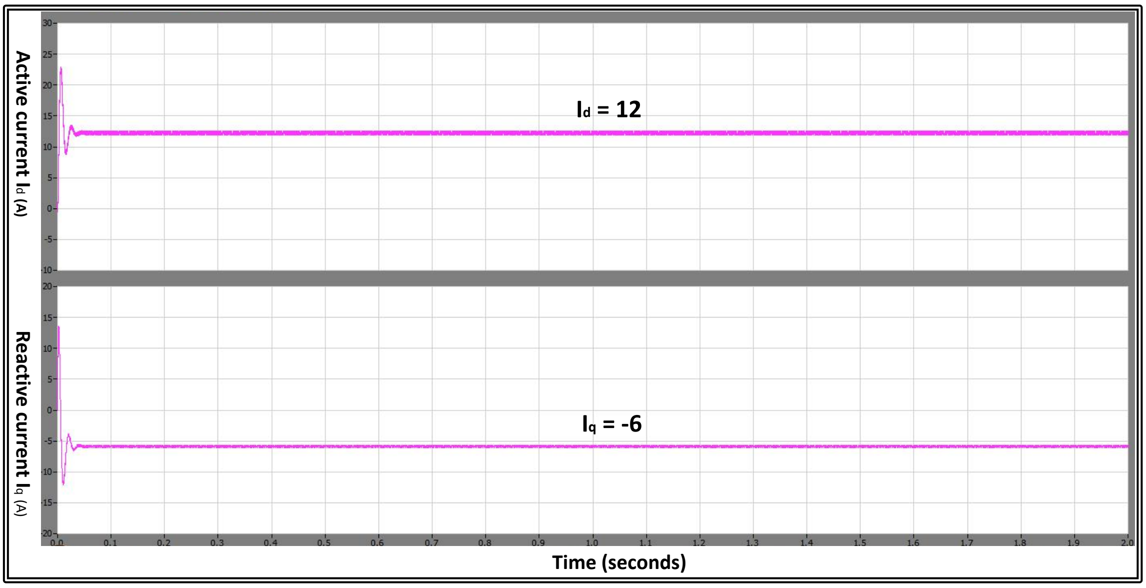


Figure 5.19: dq components of the transferred current in the transmission lines for L_3

- Loading scenario 4 (L_4)

The ratings of PE in HT could be increased in case of increasing the demand of reactive power for the connected loads, therefore the ratings of the PE switches and HT ability to supply reactive power depend mainly on the nature of the loads. However, increasing the ratings of PE switches means increase the cost and losses. The results of loading scenario 4 (L4) is illustrated in figure 3.20 and 3.21.

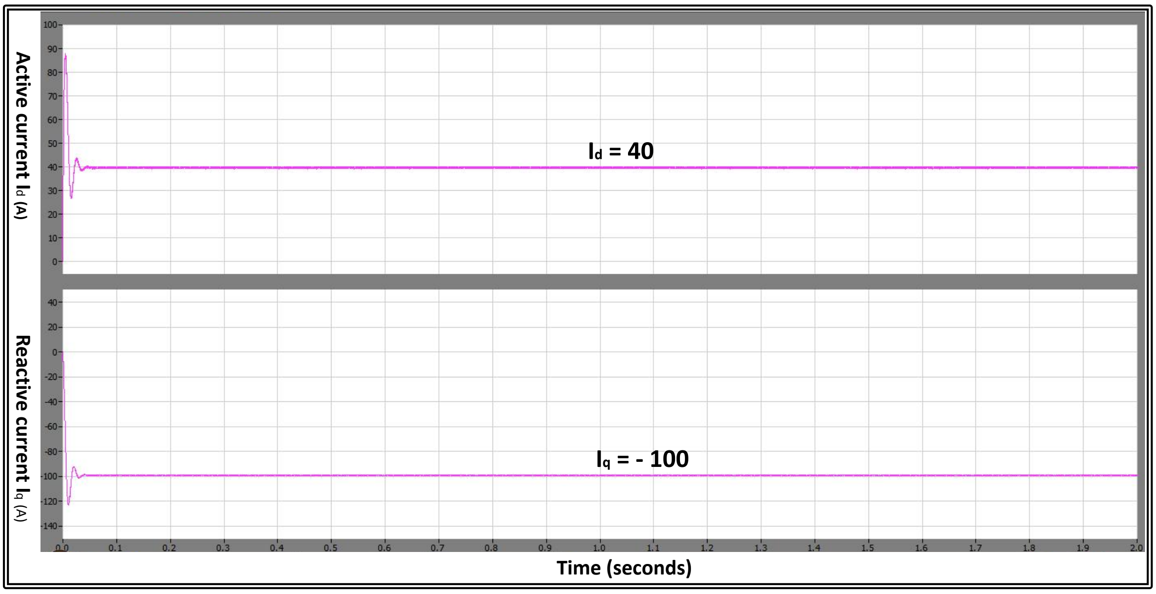


Figure 5.20: dq components of the distributed current for L_3

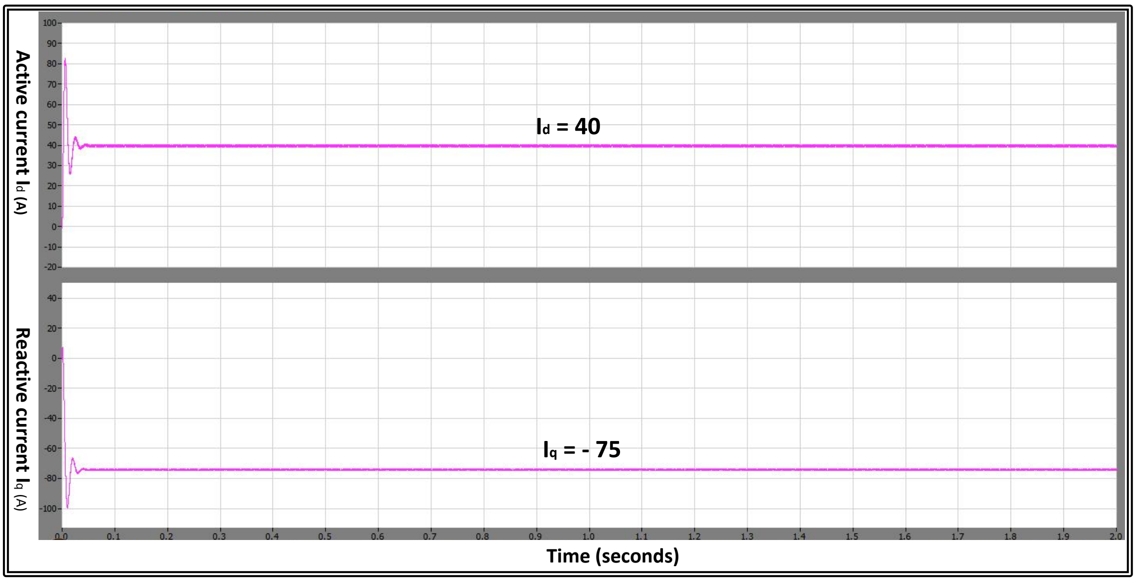


Figure 5.21: dq components of the transferred current in the transmission lines for L_3

The DC link/ source has the ability to be improved and used to provide a DC output source for a DC line or network in an enhanced form for the control, so it could operate synchronously between providing stability for the AC side and feeding a DC line (such as a DC network or charging a battery to be used in case of system failure) as a UPS approach as in Ref [128].

5.6 Conclusions

Depending on the recent research expectations of increased load growth in the current time and future, the layout of the last mile substations and especially transformers entails specific modifications and requirements in order to gain more flexibility, controllability and functionality and that by depending on the latest improvements in the solid state switches that could be used as PE converter synchronously with the operation of the current reliable parts in the grid such as the transformer. The current transformer could address a problem nowadays in case of loading rich feeders in the last mile of the network beside the issue of changing the types of loads such as the appearance of the electrical cars [95]. Var regulation or compensation could be feasible in the LV network by using PE functionality attached with the last angle in the network which is the distribution transformer in this case. The HT is introduced as an approach that has the potential to upgrade the operation of the new LV substation to a new level that has the ability to meet the demand of the future distribution grid from an efficiency, controllability and volume perspective and that is by providing the ability to control the RP in the DN, which is considered a feature for todays' distribution substation and requirement for the future demand. Different conceptual schematics for the design of HT were introduced that have different functionalities in serving several demands in the last mile network according to Var control scenario [3]. A back to back converter is attached with transformer to represent the operation of reactive power option.

Power transfer control topology is considered in this chapter by using *dq* transformation technique which is used to control the reactive power injection or Var control as it is used in chapter four to control the voltage level at the DC link. PLECS simulation tool is used to test its ability to compensate the load with its need from RP instead of being fed from the transmission grid at the primary side of the DT. The results of this have illustrated the fractional converter's ability to control the Var and its feasibility in the LV network, which lead to form the future choice substation features by initializing a reasonable percentage of solid state switches that work with conventional reliable devices in the network without digging every pavement in the last mile of the network for the purpose of improvement and matching the future changes and requirements.

Some end-user applications require more reactive power than others, such as inductive motors and factories that uses machines that consume high amount of reactive power. This kind of applications demand could cause high losses at the transmission network. On the other hand distribution networks are partially capable of providing reactive power to common loads such as homes according to the introduced design in this chapter. However, the following chapter discusses this scenario and introduces an approach that helps in meeting the demand of such case.

6 Reactive power injection using Switched Capacitors

6.1 Introduction

This chapter introduces the technique of switched capacitor as an approach to feed the load over the last mile with its need from reactive power instead of using a single capacitor that is used to compensate a fixed value of reactive power. This technology was first introduced by Marouchos in 1982 as a reactive power compensator [50] and as filters for power applications in 1987 by Darwish [51]. Also, it has been used as a harmonic distortion eliminator, such as by Ref [138]. After the significant improvements in the operations of switches and semiconductors, this technology is drawn upon in this chapter by using it in the last mile of the network and by applying it within a controlled closed loop application in order to feed the load with its exact reactive power requirements. The introduced control technique is designed by aiming for simplicity in the control operation and depending on the behaviour of the load for the last mile of the network. The feedback strategy is used according to the demand behaviour of the load by using the simulation programs PSpice and MATLAB for further verification and more accurate results.

This approach is employed owing to the fact that some loads require a high amount of reactive power and thus, when providing them it is more efficient to be as close as possible to the load in the last mile of the network [139]. Therefore, this approach is located after the HT transformer and at point that is very close to loads that require high reactive power demand in order to save the losses of transmitting the Var through the transmission and distribution networks.

The semiconductors and switches industry has witnessed significant progress, which has resulted in them being used in higher percentages in many electrical systems and applications. A switched capacitor technique depends on employing the efficiency of the switches process and the capacitor’s ability to supply the load with its reactive power needs [51]. This chapter employs the technology introduced in Ref [51] within a controlled closed loop that feeds the load with its reactive power requirements in both the capacitive and inductive modes.

6.2 Overview of a switched capacitor

The circuit of the switched capacitor consists of a number of switches and at least one capacitor that are connected in series, as seen in figure 6.1.

Normally the components of the circuit are as follows:

- An inductor L, which limits the current that enters the circuit (current limiter);
- Resistance R, which represents the resistance of the circuit components;
- At least one capacitor and two switches.

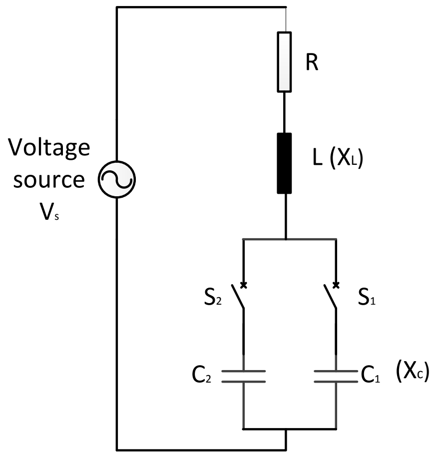


Figure 6.1: Switched Capacitor Circuit.

As seen in figure 6.1. The capacitance variable values change due to the change of the switching time of the duty cycle T_D. The controlled circuit acts as a source of inductive reactive power in the case of X_L>>X_c and capacitive reactive power in the case of X_c >> X_L [50], [51].

6.3 Types of switched capacitor circuits

Darwish [51] introduced five types of circuits every one of which had its own configuration modes and characteristics. The aim of the five types is to generate the reactive power depending on the semiconductor switches. In this chapter two types of them are used as a controlled reactive power compensator [50], [51]:

- The double switch double capacitor circuit DSDC.
- The double switch single capacitor circuit DSSC.

6.3.1 The Double Switch Double Capacitor circuit (DSDC)

The Double Switch Double Capacitor Circuit (DSDC) operates in the capacitive mode [50], [51], where resonance between L and C is absent. The anti-phase in the switching process creates the value of the duty cycle (D) for each switch, as seen in figure 6.2 [50], [51].

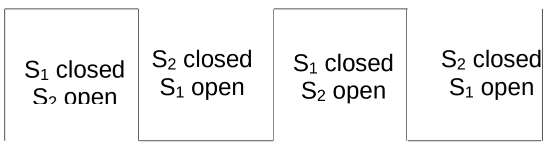


Figure 6.2: Operation of S1 and S2.

The duty cycle 'D', is defined as the ratio of the 'on' period to the pulse period [140].

$$D = \frac{T_{on}}{pulse\ period} \tag{6.1}$$

The duty cycle of switching, in addition to the values of the capacitors and inductors in the circuit, determines the value of the produced reactive power (VARs) as well as the produced harmonics. The DSDC can be represented in the steady state by the following differential equations (6.2 to 6.5) and as shown in figure 6.3 [49], [51], [140]:

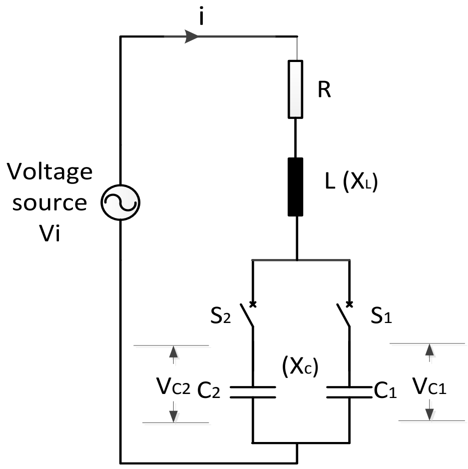


Figure 6.3: DSDC circuit.

During S_1 is closed and S_2 is open [49], [51]:

$$\frac{di}{dt} = \frac{1}{L}\left(v_i(t) - v_{c1}(t) - Ri(t)\right) \tag{6.2}$$

$$\frac{dv_{c1}}{dt} = \frac{1}{C1}\, i(t) \tag{6.3}$$

During S_1 is open and S_2 is closed [49], [51] :

$$\frac{di}{dt} = \frac{1}{L}\left(v_i(t) - v_{c2}(t) - Ri(t)\right) \tag{6.4}$$

$$\frac{dv_{c2}}{dt} = \frac{1}{C_2}\, i(t) \tag{6.5}$$

So, when S_1 is closed the voltage across the terminal of C_2 is constant and the current that goes through it is zero. While S_2 is closed the voltage across the terminal of C_1 is constant and the current that goes through it is zero [51].

6.3.1.1 *The calculation of the effective value for capacitance (C_{eff})*

The switched capacitor acts as a controlled variable capacitor, whereby its value changes by changing the duty cycle of the switches, which is due to the load change in that every load requires a specific value of reactive compensation. The effective value for the all circuit can be calculated according to the following equations (6.6 to 6.11) and procedures that take all the circuit components in figure 6.3 into consideration.

1) Calculate the C_{eff} for the two capacitors without L [49], [51], [140].

$$C_{eff} = \frac{C_1}{D^2 + \gamma(1-D)^2} \tag{6.6}$$

Where:

$$\gamma = \frac{C_1}{C_2} \tag{6.7}$$

2) Calculate the X_{ceff} and X_L

$$X_{Ceff} = \frac{1}{2\,\pi f\, C_{eff}} \tag{6.8}$$

$$X_L = 2\,\pi f L \tag{6.9}$$

3) Calculate X_{eff}

$$X_{eff} = \sqrt{R^2 + (\mathrm{X_{ceff}} - \mathrm{X_L})^2} \tag{6.10}$$

The total C_{eff} for the all switched capacitor circuit is :

$$C_{eff\ total} = \frac{1}{2\,\pi f\, Xeff} \tag{6.11}$$

The previous procedures were followed by using Excel to find manually the equivalent C_{eff} that could be used in the simulation in order to meet different loads. Several duty cycle values are applied (from 0.1 to 0.9) for different values of C_1, where C_2 is fixed at 100 μF, as seen in table 6.1. More calculations are shown in Appendix C. Table 6.1 is chosen to be used in the closed loop in the following sections, where C_1 =20μF, C2 = 100μF, L=10mH and R=1Ω. The $C_{eff\ total}$ for this table shows linear behaviour against several values of D.

Table 6.1: Calculations of the C_{eff} total for DSCS.

Duty cycle (D)	C_1 (μF)	$K = \frac{C_1}{C_2}$	D^2	1-D	(1-D)^2	$D^2 \times (1-D)^2 \times K$	C_{eff} (μF)	X_c (Ω)	X_L (Ω)	X_{eff} (Ω)	C_{eff} (μF)
0.1	20	0.2	0.01	0.9	0.81	0.17	116.3	27.4	3.1	24.3	131.2
0.25	20	0.2	0.06	0.8	0.56	0.18	114.3	27.9	3.1	24.7	128.7
0.3	20	0.2	0.09	0.7	0.49	0.19	106.4	29.9	3.1	26.8	118.8
0.4	20	0.2	0.16	0.6	0.36	0.23	86.2	36.9	3.1	33.8	94.2
0.5	20	0.2	0.25	0.5	0.25	0.30	66.7	47.7	3.1	44.6	71.3
0.6	20	0.2	0.36	0.4	0.16	0.39	51.0	62.4	3.1	59.3	53.7
0.7	20	0.2	0.49	0.3	0.09	0.51	39.4	80.9	3.1	77.7	41.0
0.8	20	0.2	0.64	0.2	0.04	0.65	30.9	103.1	3.1	100	31.8
0.9	20	0.2	0.81	0.1	0.01	0.81	24.6	129.2	3.1	126	25.2

From these calculations, the curve below has been drawn to show the linear effect of the duty cycle on the produced C_{eff}, as shown figure 6.4. In Appendix C, the curves are plotted for other values of $C_{1.}$

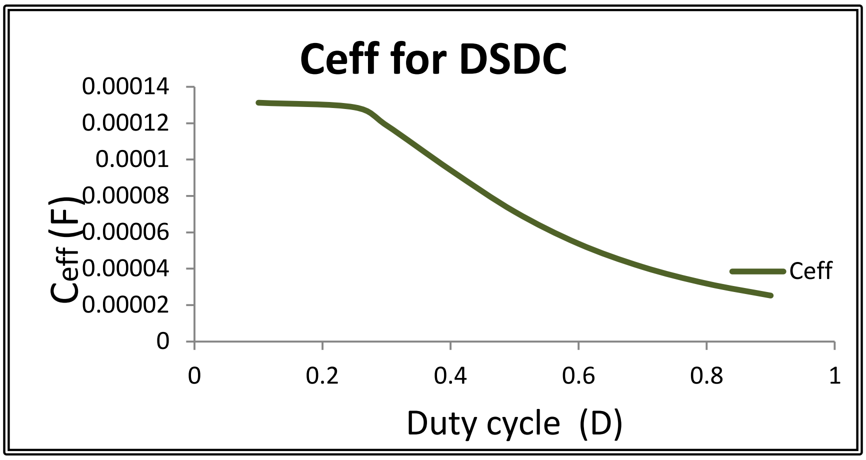


Figure 6.4: Effective values of the capacitance at several values of D for DSDC.

The value of X_L in this circuit is smaller than the value of $X_{c,}$ which means the circuit operates in the capacitive mode. So, the behaviour of the circuit could be changing from a leading reactive compensator to a lagging reactive compensator (inductor) by increasing the value of X_L in this circuit.

6.3.1.2 *DSDC open loop simulation (PSpice and MATLAB)*

Simulations using both of the PSpice and MATLAB are carried out for more verification and accurate results. The simulations are performed using PSpice and MATLAB are performed for the following objectives:

- Power factor corrections by decreasing the phase difference between the voltage and the current;
- Finding the suitable duty cycle that is required for generating the appropriate reactive compensation value C_{eff}.

6.3.1.2.1 *DSDC PSpice circuit simulation*

The DSDC circuit is simulated as seen in figure 6.5, whereby a load of 25Ω and 30mH needs a 42.13μF to improve the power factor to unity, as discussed in chapter three. This value of capacitance (42.13μF) can be given by choosing the duty cycle of the switches manually and as seen in table 6.1, the closed value from 42.13 μF is 41.05μF at duty cycle 0.7, hence this is chosen to be the duty cycle for the switched capacitor. The same procedures can be followed to choose manually the suitable duty cycle for any load as follows:

1. Calculate the suitable reactive compensation C that is needed for PF correction;
2. Choose the suitable duty cycle that gives this value of capacitance from the tables in Appendix C.

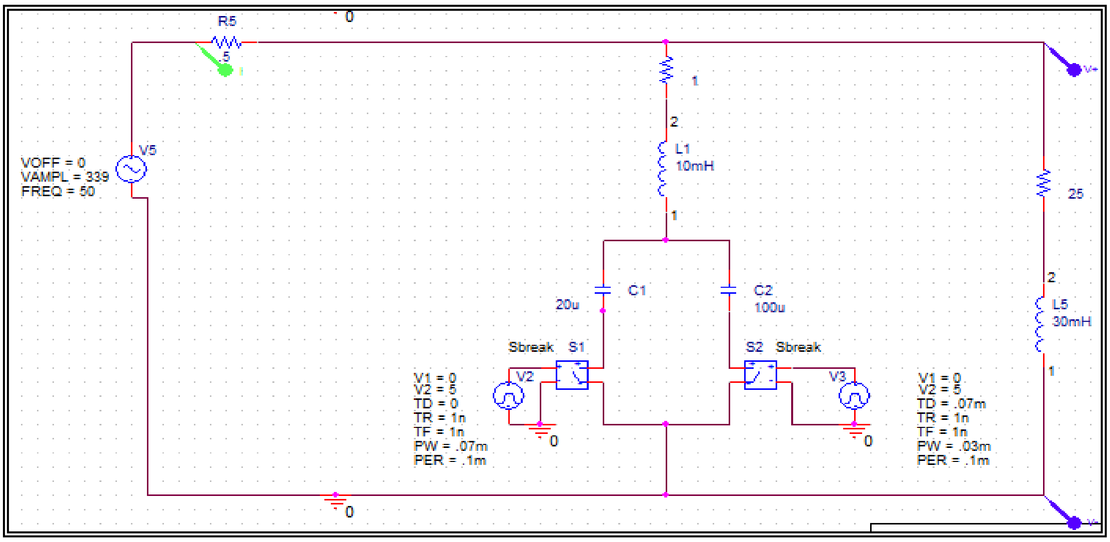


Figure 6.5: DSDC circuit PSpice design.

In figure 6.5, the frequency of the switches is taken as 10KHz, and the duty cycle for S_1 is 0.7 and 0.3 for S_2, So, the pulse width for S_1 is 0.07ms, which is 70% of the time period ($\frac{1}{f}$ = 0.1ms) and the pulse width for S_2 is 0.03ms, which is 30% of the time period 0.1ms. Time delay is given as S_2 = .07ms, which is the pulse width for S_1. When the 'on mode' for S_1 is on the 'delay' is on for S_2 in order to form the output pulse of the duty cycle.

The results from using the DSDC circuit in figure 6.5 to improve the power factor are shown in figures 6.6 and 6.7, where the phase difference between the voltage and the current is decreased to almost zero by injecting the required demand of reactive power in the load.

- The phase difference before adding the DSDC

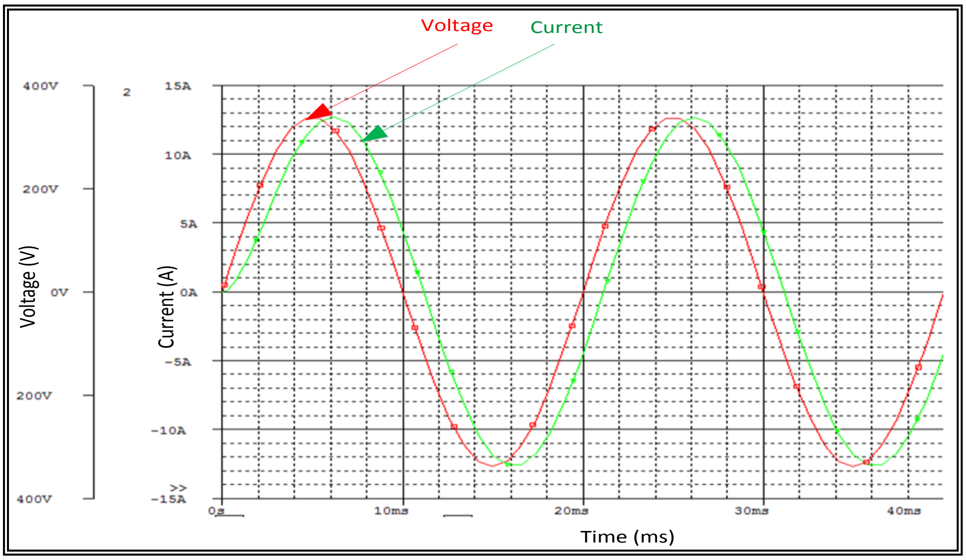


Figure 6.6: The current lags the voltage before adding DSDC circuit.

- The phase difference after adding the DSDC

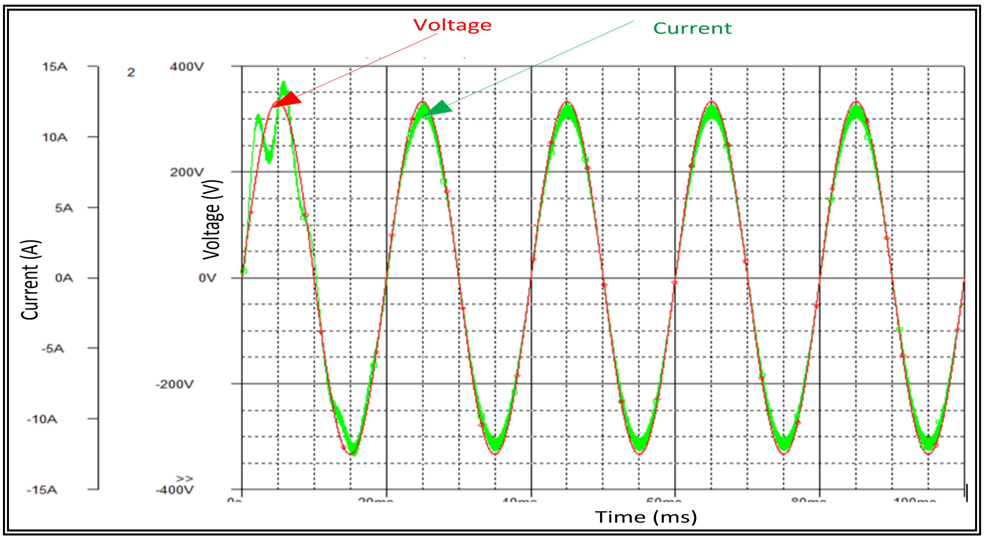


Figure 6.7: Voltage and current are in the same phase after adding the DSDC.

After adding the DSDC circuit, the noise that takes a rippled appearance appeared in the current wave, as seen in figure 6.7. This is because of the switching process that generates noise during the creation of the pulse duty cycle. This problem appears during the charging and discharging of the capacitors in the DSDC circuit. It appears in the distortion factor and can be treated by using filters as in non-linear loads.

6.3.1.2.2 *DSDC MATLAB simulation*

The DSDC is performed using MATLAB simulation in this subsection for more verified results. The DSDC circuit showed advantages over the DSSC circuit in terms of its flexibility in providing a suitable C_{eff} over several values of D, as seen in figure 6.4. The DSDC circuit in figure 6.8 is simulated using MATLAB. The results of the DSDC effect in correcting the power factor by showing a zero phase difference are shown in figure 6.9

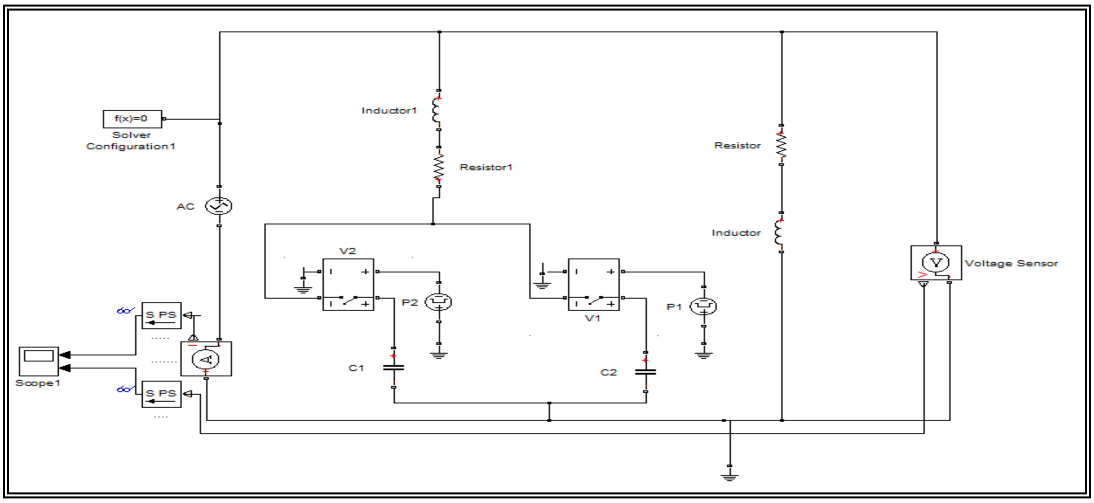


Figure 6.8: Switched capacitor circuit simulation using MATLAB.

The phase difference is highlighted by the red line in figure 6.9.

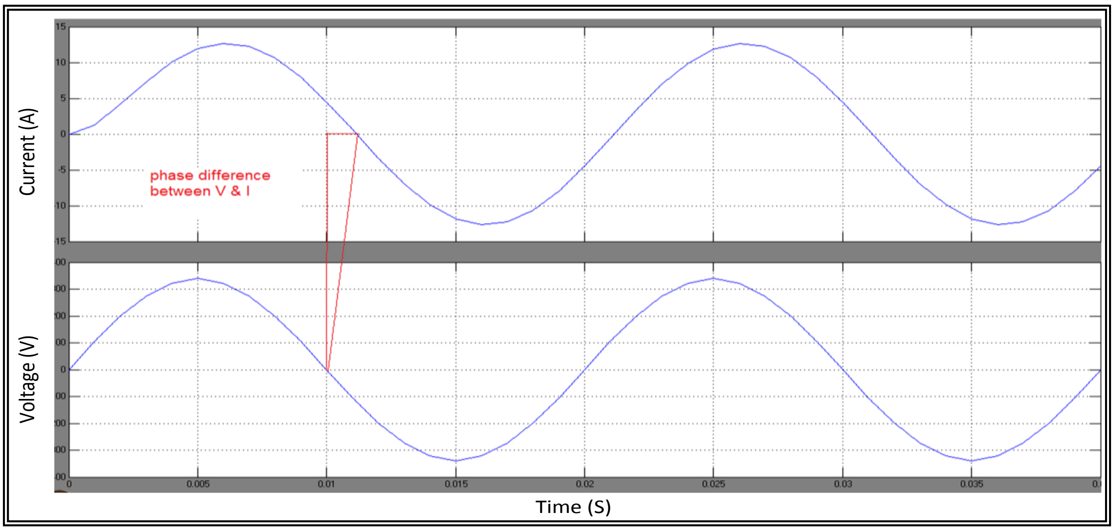


Figure 6.9: The phase difference before adding the DSDC.

After adding the DSDC circuit using MATLAB the phase difference is almost decreased to zero, as seen in figure 6.10.

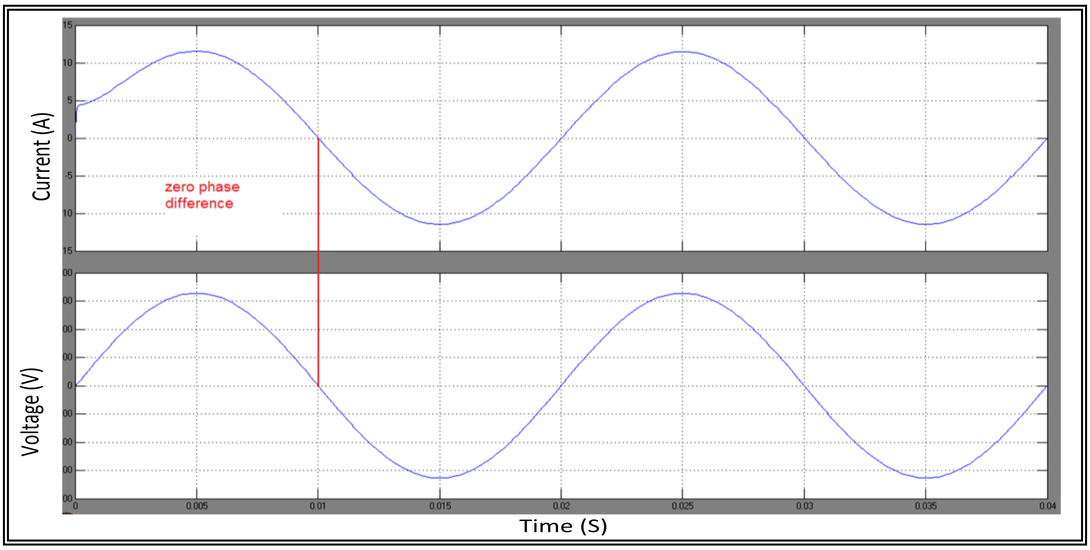


Figure 6.10: The phase difference after adding the DSDC.

6.3.2 Double Switch Single Capacitor (DSSC)

The DSSC circuit simply consists of double switches one of which is connected to a capacitor. This combination is connected with an inductor and resistor that represent the resistance of the DSSC components, as in the DSDC this circuit acts as a variable capacitor through applying the switching process on one capacitor instead of two. Such a circuit has two modes, the inductive mode and the capacitance mode and depending on the values of X_L and X_c, the circuit behaves capacitively or inductively, whereby:

- If $X_L >> X_c$ it takes the inductive mode, as seen in figure 6.11 and it supplies leading reactive power;

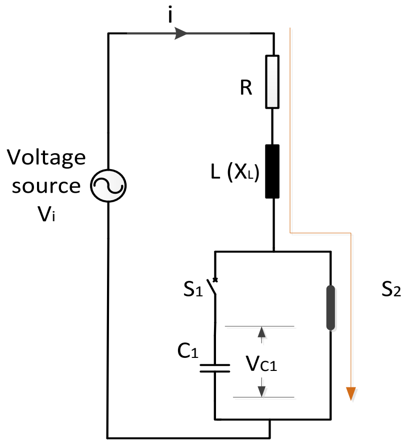


Figure 6.11: Inductive mode of the switched capacitor

- If X_L<<X_c it takes the capacitive mode, as seen in figure 6.12 and it supplies lagging reactive power.

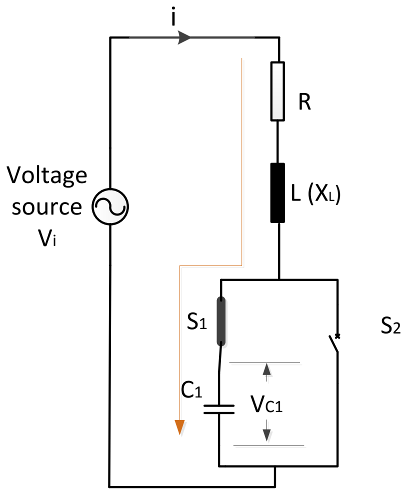


Figure 6.12: Capacitive mode for the switched capacitor.

The operation of DSSC is based on changing the path of the current between both of branches in an alternative way that avoids interference or off-periods in the switches operation [51]. This means that the capacitor works according to the value determined by the voltage pulse of the switch, being a voltage based device and supplies capacitance according to the voltage at its terminals. The DSSC can be represented in the steady state by the following differential equations (6.12 to 6.14) and as shown in figures 6.11 and 6.12 [49], [51], [140]:

When S is open:

$$\frac{di}{dt} = \frac{1}{L}\left(v_i(t) - v_{c1}(t) - Ri(t)\right) \tag{6.12}$$

$$\frac{dv_c}{dt} = \frac{1}{C_1}\, i(t) \tag{6.13}$$

When S is closed:

$$\frac{di}{dt} = \frac{1}{L}\left(v_i(t) - v_{c2}(t) - Ri(t)\right) \tag{6.14}$$

6.3.2.1 *How is the effective value for C calculated?*

The effective capacitance value of the DSSC that could be controlled is calculated through the following equation that is reduced from equation (6.6) [51].

$$C_{eff} = \frac{C_1}{D^2} \quad (6.15)$$

The same steps that are used in the calculations of C_{eff} in the DSDC circuit are used in the DSSC. Table 6.2 below is the calculation of the C_{eff} total when C_1=20μF, L=10mH and R=1Ω for the duty cycle values from 0.1 to 0.9. More calculations for different values of C_1 can be found attached in the Appendix D.

Table 6.2: Calculations of the C_{eff} total for DSSS.

Duty cycle (D)	C1 (mF)	D^2	C_{eff} (mF)	X_C (Ω)	X_L (Ω)	X_{eff} (Ω)	C_{eff} (mF)
0.1	0.03	0.01	3.00	1.06	3.14	2.31	1.38
0.2	0.03	0.04	0.75	4.24	3.14	1.49	2.14
0.3	0.03	0.09	0.33	9.55	3.14	6.49	0.49
0.4	0.03	0.16	0.19	16.98	3.14	13.87	0.23
0.5	0.03	0.25	0.12	26.53	3.14	23.41	0.14
0.6	0.03	0.36	0.08	38.20	3.14	35.07	0.09
0.7	0.03	0.49	0.06	51.99	3.14	48.86	0.07
0.8	0.03	0.64	0.05	67.91	3.14	64.77	0.05

The effects of the duty cycle on the capacitance are shown in figure 6.13.

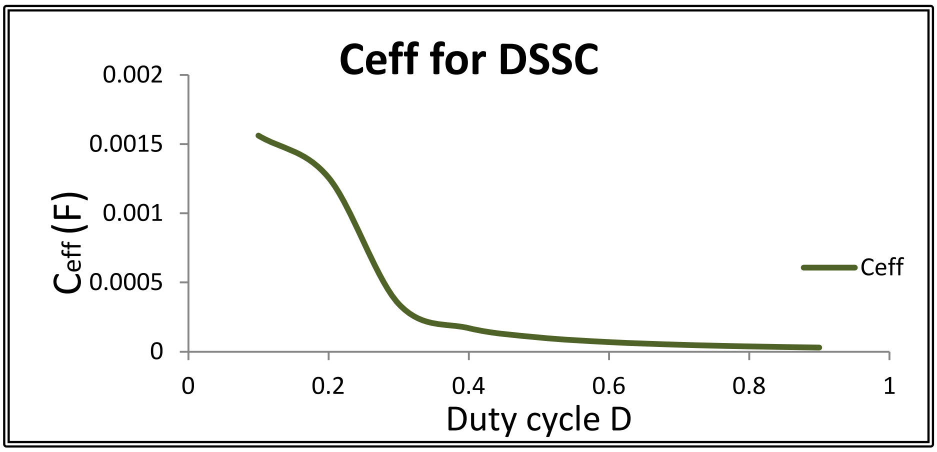


Figure 6.13: Effective values of capacitance at several values of D for DSSC.

As shown in figure 6.13, the linearity of the C_{eff} curve of the DSSC circuit is less than that of the C_{eff} curve of the DCDS circuit in figure 6.4. The gradation values for C_{eff} in table 6.2 are more linear than those in table 6.1. This result is due to the fact that in DSDC, both of the capacitors work in a compatible mode to reach the desired C_{eff}, which makes the DSDC circuit preferable in closed loop design to the DSSC circuit.

6.3.2.2 *DSSC open loop PSpice simulation*

The DSDC circuit in figure 6.14 is simulated using one capacitor instead of two and by using table 6.2 to calculate the total $C_{eff,}$ as well as choosing the suitable duty cycle D.

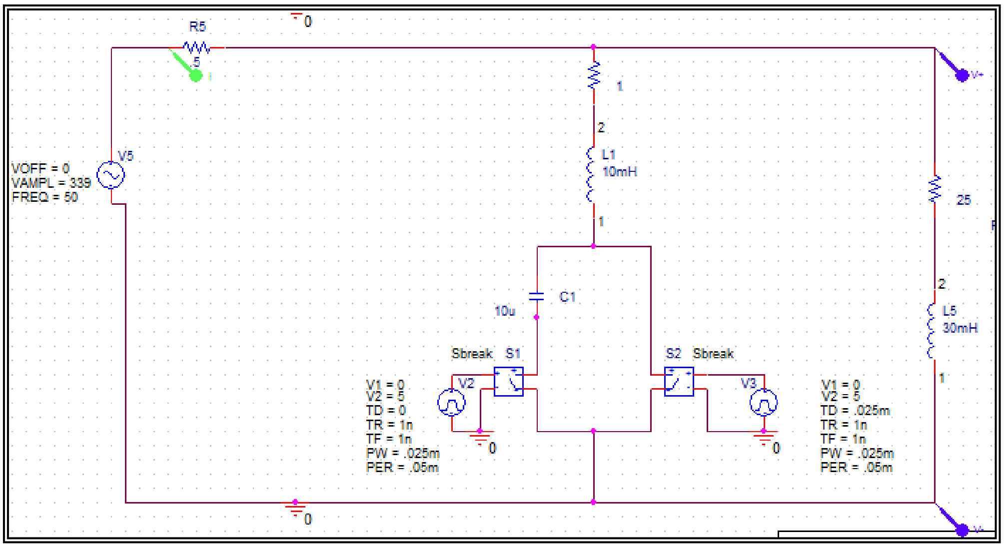


Figure 6.14: DSSC circuit in PSpice design.

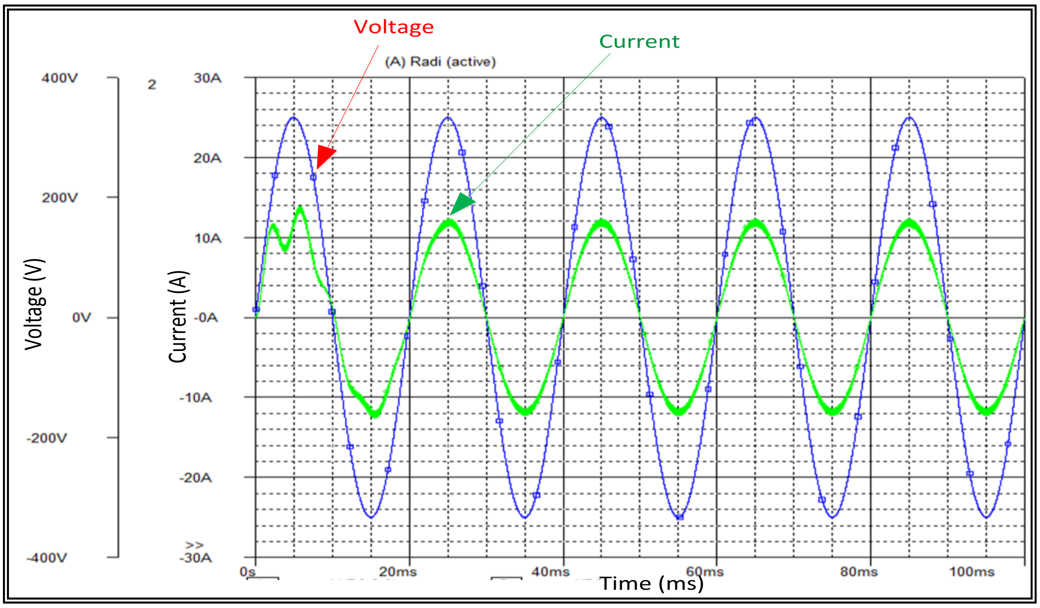


Figure 6.15: Voltage and current are in phase after adding the DSSC.

6.4 DSDC or DSSC

As seen the in phase difference that is created from the inductive load is treated as in figures 6.7, 6.10 and 6.15 for both of the circuits, DSDC and DSSC, where both the voltage and current waves are corrected so as to be in the same phase. By increasing the switching frequency, the noise or ripples decrease due to the increasing of the speed of charging and discharging of the two capacitors, where this speed decreases the oscillation of the ripples while creating the current wave [49], [51]. The switching frequency of the circuit (shown in figure 6.17) is increased to 0.05ms (20 KHz) to see the effects on the current ripples.

Before increasing the switching frequency:

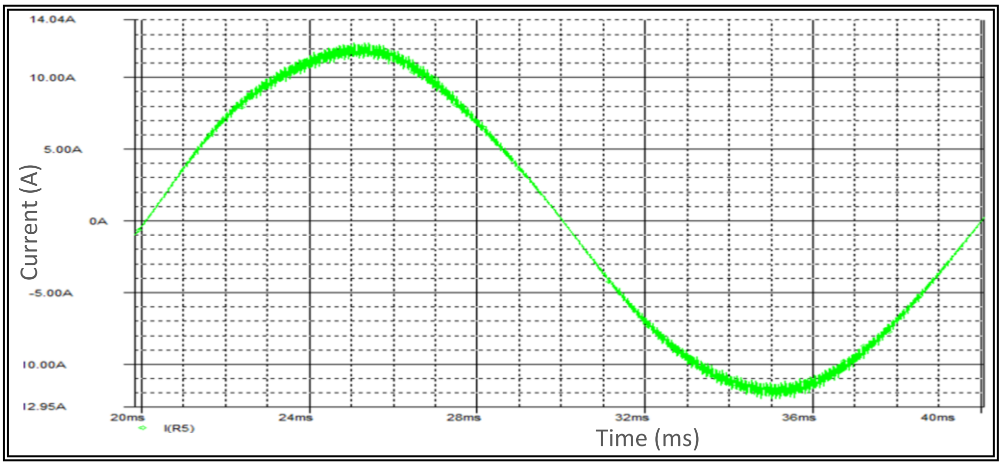


Figure 6.16: The current wave before increasing the switching frequency.

After increasing the switching frequency to 20 kHz:

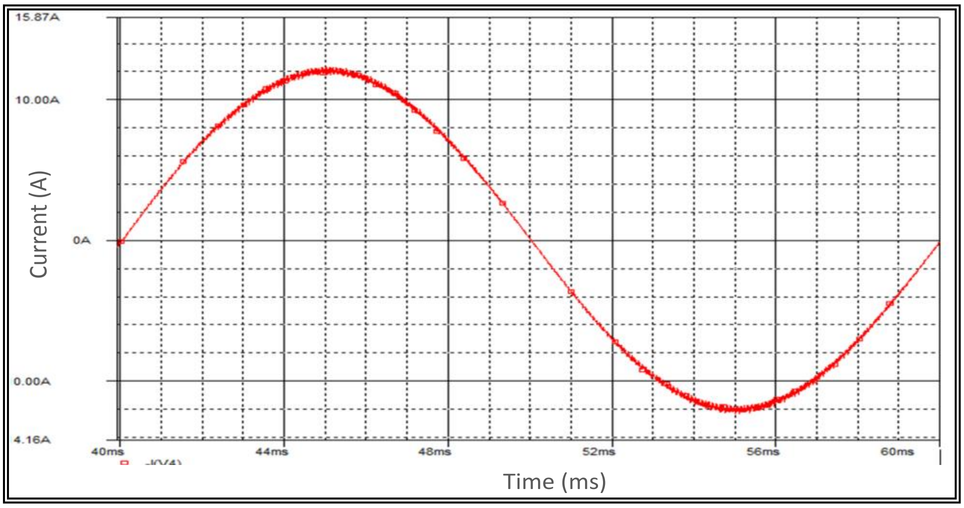
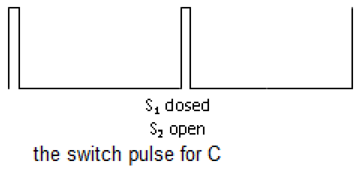
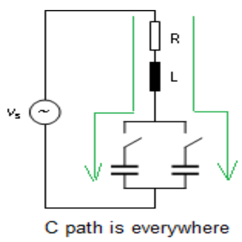
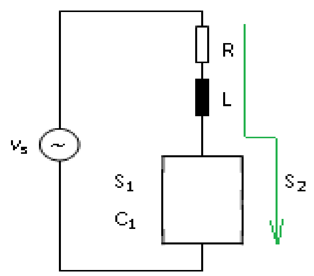


Figure 6.17: The current waves after increasing the switching frequency.

The 20 kHz frequency is too large and needs large heat sinks, besides decreasing the ripples in the current wave, increasing the switching frequency increases the higher order harmonics. These harmonics can be treated by using passive or active filters. The switching frequency used in the DSSC is 20KHz, which is more than that used in the DSDC circuit (10KHz) and this is because the current harmonics and noise that appeared in the DSSC were greater, so increasing the switching frequency overcomes this problem.

It is notable that the DSDC circuit is more stable and has less current noise in the case when the two capacitors values are equal (for example 100μF for both of them) due to both having the same ability to provide reactive power for every current path that the switches provide it. The curve of reactive compensation at every duty cycle of this case is drawn by excel and can be found in Appendix C. A comparison between the DSDC and DSSC shown in table 6.3:

Table 6.3: A comparison between the DSDC and DSSC.

DSDC	DSSC
Operates as a reactive power compensator for both leading and lagging behaviour. Has greater ability of producing leading reactive power than the DSSC due to the process of the double switches that distribute the pulses of the duty cycles on two capacitors, where all the current paths pass through a capacitor anywhere, as in the following figure.	The ability to produce lagging reactive power greater than the DCDC, which is due to the double switches that can create an inductive mode for the circuit when: • The switch of capacitor is open; • The duty cycle provides a mode that makes the capacitor invisible, as in the figure of the pulse below: 
Never goes to a 100% inductive mode. 	Could take this mode: 
The produced current distortions are less than for the DSSC	It produced current distortions and noise are more than for the DSDC

<table>
<tr><td colspan="2">The explanation for the above is that the DSSC circuit varies from being an inductive circuit to a capacitive one, even if the overall effect is capacitive. This variation of the current from lagging to leading so many times within one cycle causes distortion and hence, the harmonics. In the double switch double capacitor the current is always leading and hence there is less distortion</td></tr>
<tr><td>Can be used as an active filter better than the DSSC due to its harmonics.</td><td>Also has the ability to work as an active filter</td></tr>
<tr><td>The DSDC is not exposed to the series resonance. For any value of the duty cycle the capacitive mode is available, because all the pulse is shared between the two capacitors. Therefore, the capacitor cannot be invisible at point in the duty cycle.</td><td>The DSSC circuit is exposed to the series resonance. This is considered as a disadvantage, because a small duty cycle value on the capacitor, such as 0.01, increases the ability of the inductive mode. This could lead to following situation:
1) The inductor could tune with only capacitor
2) and tuning between L and C cancels their impedance (X_L equal and cancel X_C)
3) This cancellation of impedance will cause a high current path through the DSSC, which will damage the switches.</td></tr>
</table>

6.5 Automatic feedback for the controlled DSDC circuit– a closed loop approach

A circuit that returns a signal and carries one or more of the output characteristics to the input to change one or more of the input variables is called a feedback circuit. It is usually used to improve the performance of an electrical system automatically, which contributes to saving effort and money. This section deals with a system that improves the operation power factor correction of the DSDC circuit to achieve an automatic process. This feedback introduces a close loop that is undertaken according to the characteristics of the circuit parameters and the behaviour of the circuit at every load.

The open loop idea depends on a simple concept that takes the input of the system (reactive power) under consideration and does not react on the feedback that comes from the behaviour of the load to obtain the output value. On the other hand the closed loop system which is also referred as closed loop control system takes into consideration the condition of the load (the output) instead of the input and reacts according to the change of the load and its exact need for reactive power.

The open loop system supply reactive power (capacitive or inductive) depending on choosing manually the duty cycle that determines the value of supplied reactive power from the capacitors. The duty cycle modulation (on and off periods) for each of the capacitors in the DSDC circuit is chosen manually in order to supply the reactive power to the load which is considered an input in this case as seen in figure 16.18. On the other hand, the closed loop system choses the duty cycle for the each of the capacitors automatically by tracking the changes in the load value and phase angle in order to supply the load with its exact need of reactive power which contributes in correcting the power factor as seen ibn figure 6.19.

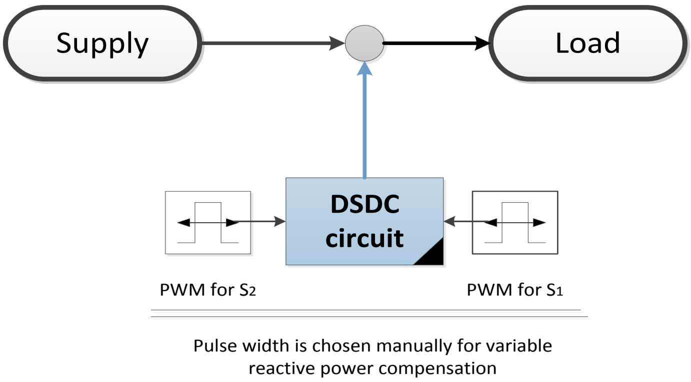


Figure 6.18: The concept of the closed loop DSDC system.

By using the closed loop system, the load is assured to not get extra amount of reactive power that could lead to further complications. Correspondingly the load will tracked at each second in order to update the control with its feedback that contributes in changing the operational duty cycle for the capacitors.

The operation of the closed loop feedback focuses on the idea of changing the duty cycle of the switches according to the change of the load. Every load value has its own reactive compensation amount and each of these has a specific capacitor value that provides it. This value of capacitance can be determined from the value of the duty cycle of the switches, where every duty cycle creates a new capacitor value. Instead of changing the duty cycle of the switches manually (such as in the open loop) for every change of the load an automatic change can be applied to them. This means that the load changing has a direct relation with the parameters of the switches. This relation is explained in the next subsections. The operation of closed loop DSDC is demonstrated in figure 6.19.

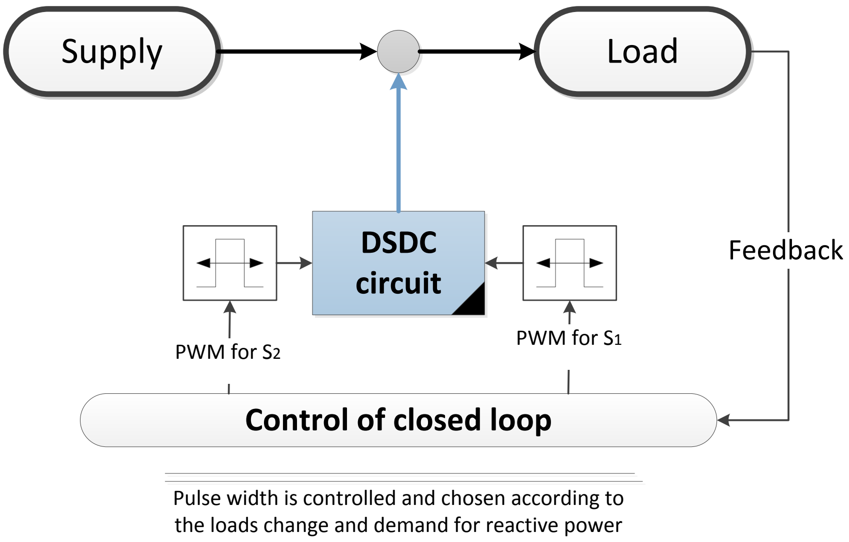


Figure 6.19: the concept of the open loop DSDC system.

The control idea depends on the curve of the C_{eff} that is provided for every duty cycle, whereby this curve should track the curve of the variable load values. The simulation is performed, using the DSDC circuit which, as discussed is believed to be more efficient and reliable than the DSSC circuit.

6.5.1 **The relation between the load and the pulse generator**

The switches are connected to a pulse generator that controls them according to the pulses, where '1' keeps the switch on for a period of time and '0' to keep the switch open for a specific period of time alternately.

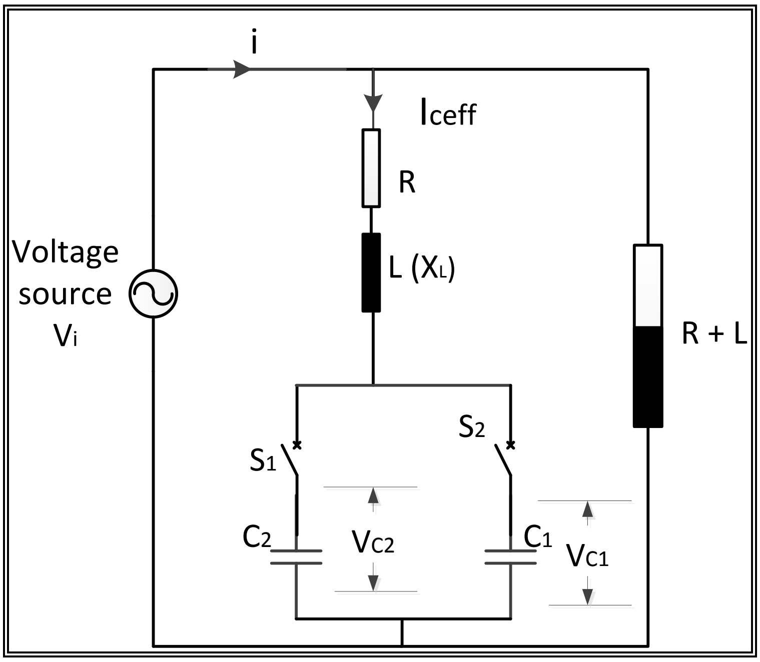


Figure 6.20: DSDC circuit connected with load.

By changing the load, four variables in the circuit of figure 6.20 change:

- The current that is absorbed from the load;
- The current that enters the DSDC circuit, $I_{ceff;}$
- The power that is dissipated in the load;
- A slight alteration in the load voltage.

The first three changes could be used as a reference and as a sign of the load change. These changes can be taken as being a technique for changing the duty cycle of the switches as those that were used in the DCDS circuit are voltage controlled switches. This means that the duty cycle of the switches changes according to the voltage pulse that they get from the source. Because the voltage pulse generator is an independent device that does not take any feedback and has to be changed manually, a controlled voltage pulse is needed to create the duty cycle of the pulses that are supplied to the switches regarding the change of the load.

6.5.2 System design

This simulation takes into account the following facts:

- The total load current increases by increasing the load;
- The load current is an AC current that can accept a Voltage Source Current Dependent VSCD.
- The comparator is a device that can be used to compare between two voltage signals to produce a square voltage signal according to this comparison;
- The AC voltage wave can be rectified to produce a DC voltage line;
- The switches are fed by square pulses in different duty cycles.

So according to these facts, the controlled pulse generator takes the following design procedures:

- A Voltage Source Current Dependant (VSCD) is applied depending on the load current value with a chosen value for the gain, which is discussed later;
- The voltage type is AC voltage and needs rectification, so a rectification circuit is applied;
- The rectified voltage is compared with a triangle voltage source (its characteristics will be discussed later) by using a comparator to produce a square voltage pulse;
- The produced pulse takes its duty cycle from the value of the rectified voltage. which takes its value originally from the load current change;
- The new produced pulse feeds the switch that is connected to the capacitor instead of being fed by a fixed voltage pulse source.

The feedback system that is applied to the DSDC circuit passes through the stages shown in figure 6.21.

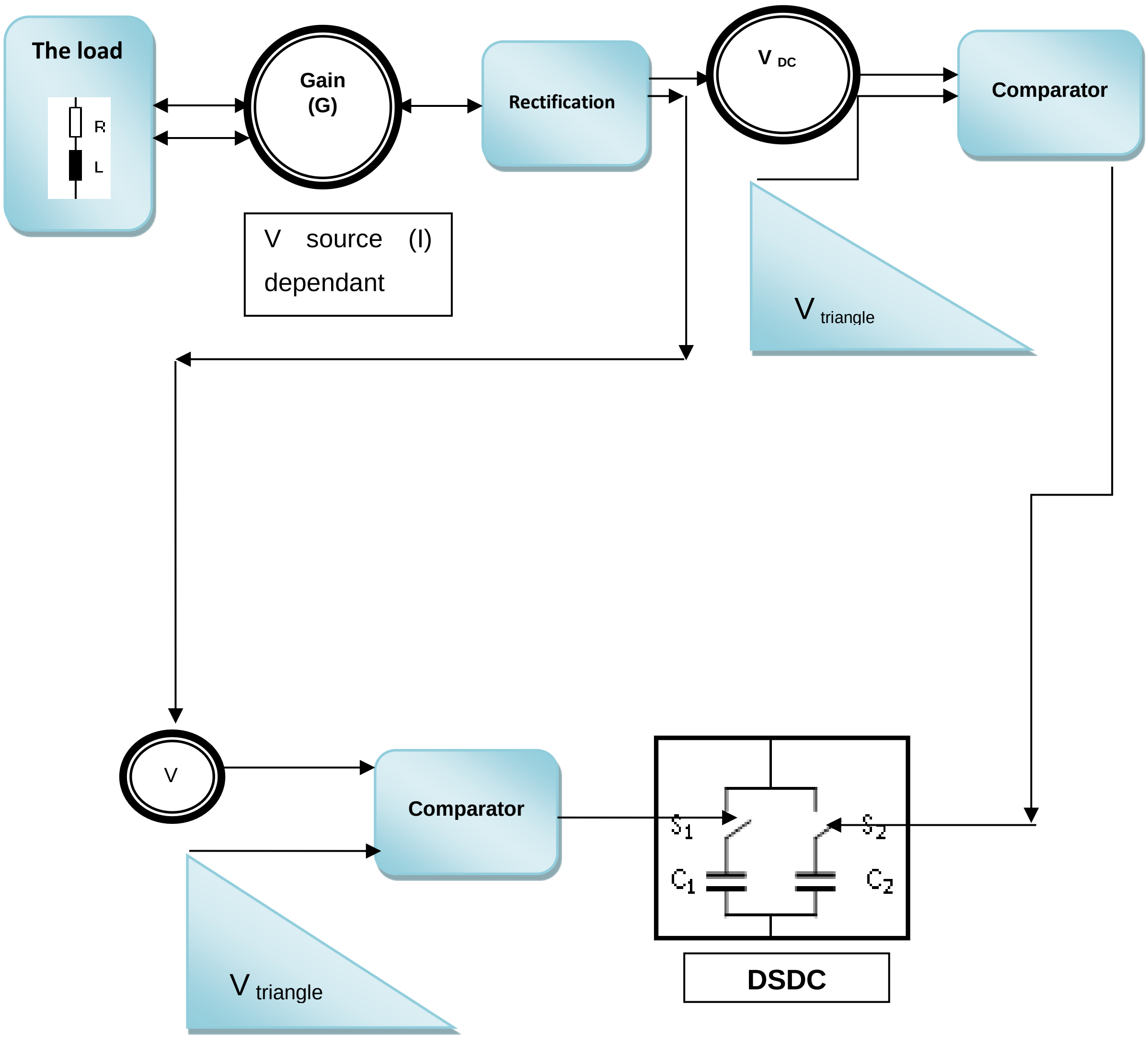


Figure 6.21: The design of feedback for a closed loop DSDC.

6.5.3 System design stages through PSpice and MATLAB

The system parts and design is discussed and demonstrated in this subsection for each part of the closed loop DSDC circuit. The control procedures for controlling a closed loop circuit are explained for each part in the design. The design steps are simulated and tested by using PSpice software and MATLAB.

6.5.3.1 *The Voltage Source Current Dependant (VSCD)*

A Voltage Source Current Dependant (VSDC) is connected to the load terminal to give a value that varies according to the load change. This source is available in the MATLAB and Pspice tools and can represent a voltage source with a sensor in the practical application. This VSCD produces the voltage according to its gain, where the output voltage value is the result of multiplying the load current by the gain.

$$\text{Output voltage} = \text{Load current} \times \text{Gain} \quad (6.16)$$

Equation 6.16 determines the voltage level that is required for comparing the comparator in the next stages, where choosing the gain plays a critical role in the balance of the automatic control, This is because the same gain is going to be used for every current change and choosing a suitable one means the following is required:

- Stability of the gradual change in the VSCD level;
- Proportionality between the voltage level that has been acquired from a specific gain value and the constant triangle voltage at the comparator stage, which contributes to producing a desired pulse.

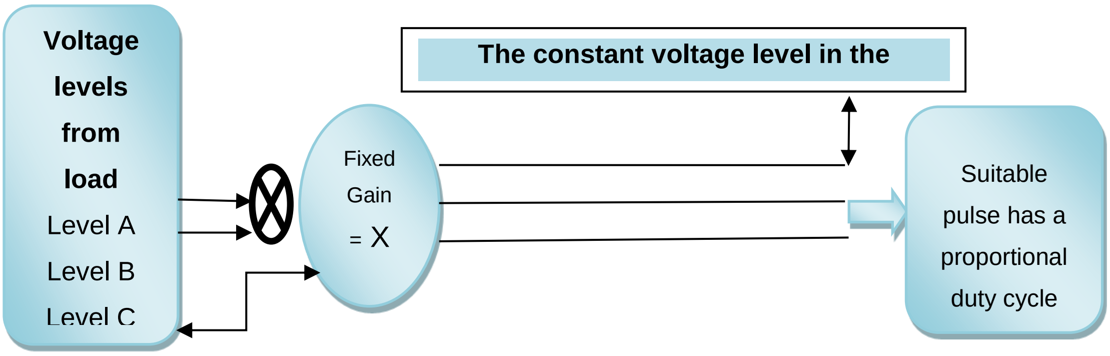


Figure 6.22: The function of the fixed gain in shaping the suitable duty cycle.

6.5.3.2 *The rectification circuit*

The purpose of using this circuit is to get a DC voltage line from the AC voltage source current controlled so it is suitable for comparing with a triangle voltage source that is connected to the comparator with this DC line. The full wave rectification is used in this simulation, as in figure 6.23 [141].

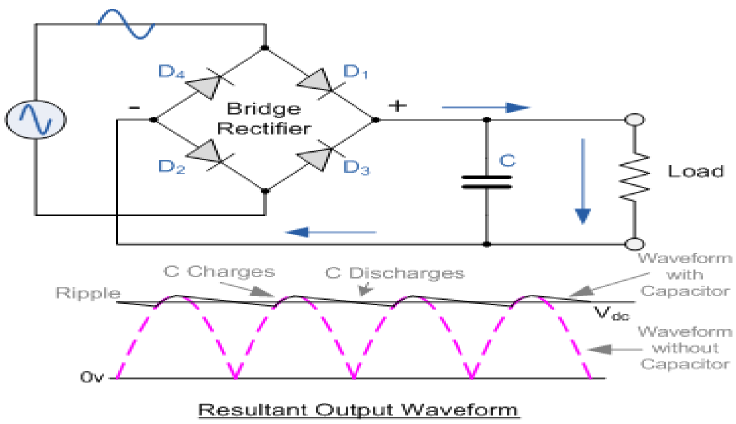


Figure 6.23: The used rectification circuit to get a DC signal.

The bridge rectifier consists of four diodes, as seen in figure 6.23, are connected in series, D_1 and D_2 conduct to rectify the positive half cycle, whilst D_3 and D_4 conduct to rectify the negative half cycle while D_1 and D_2 are off [141]. The value of the new rectified voltage is taken from equation (6.17) [141].

$$V_{dc} = \frac{2Vmax}{\pi} = 0.637Vmax = 0.9Vs \tag{6.17}$$

The purpose of the capacitor is to reduce the ripples in the rectified wave as much as possible by injecting or discharging voltage in the wave while it is going down. In other words it gives a smooth DC voltage. The value of the capacitor is chosen according to two considerations [141]:

- The capacitor operation voltage should be higher than the no load voltage
- The capacitance value, which determines the amount of discharged voltage.

6.5.3.2.1 *PSpice simulation*

To verify the efficiency of the rectification circuit, a load of 25Ω and 30mH is added to the circuit, as in figure 6.24. The rectification is for the VSCD with a gain that is calculated to get a 5V level from the AC load current.

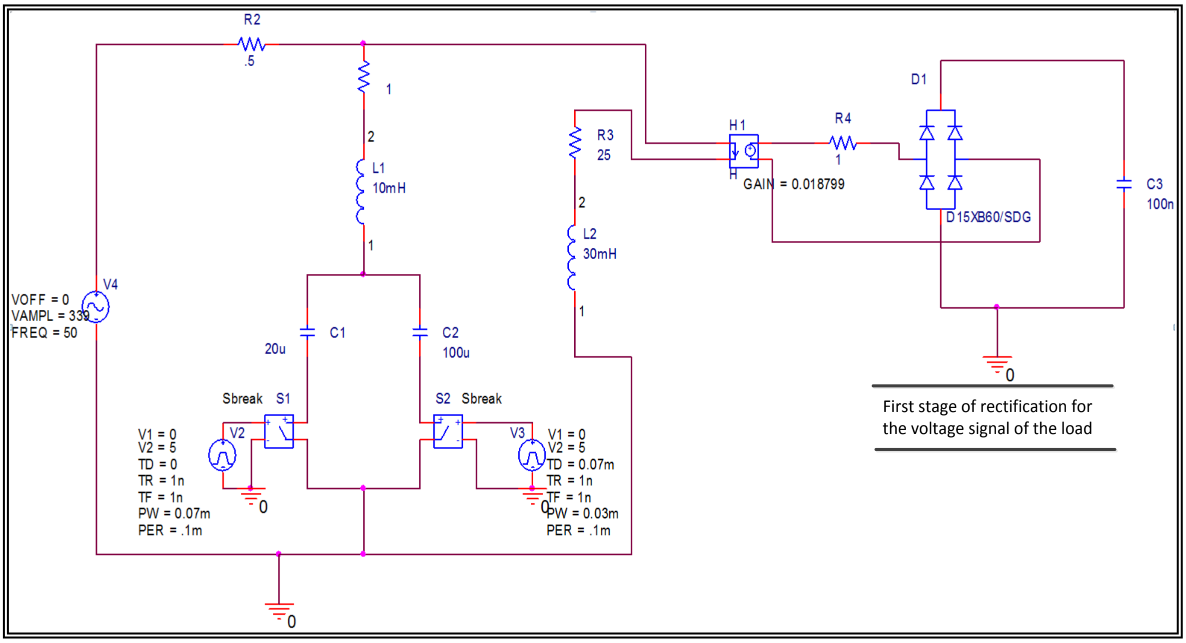


Figure 6.24: Rectification of the voltage from the Voltage Source Current Dependant (VSCD).

1. The voltage before rectification and after the gain

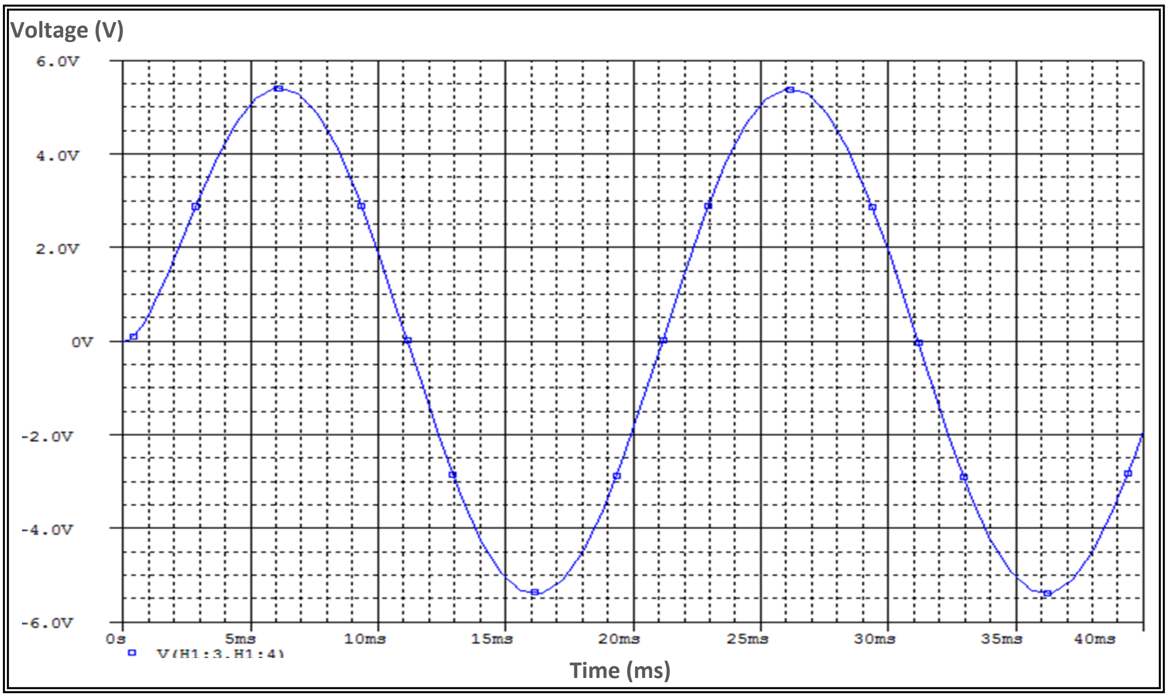


Figure 6.25: The AC voltage wave before the rectification for the Voltage Source Current Dependant (VSCD).

2. The DC output

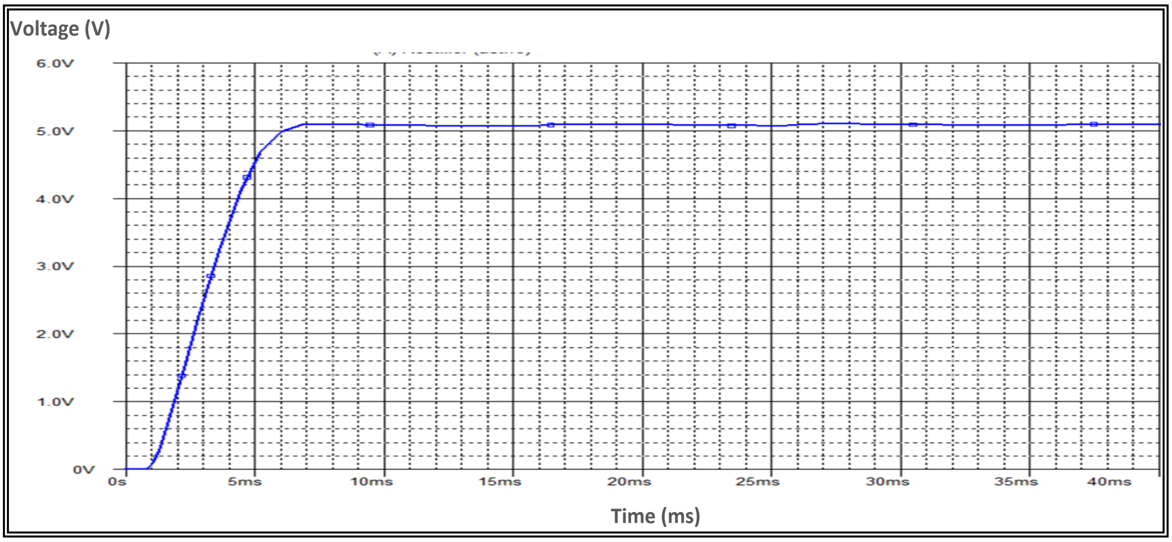


Figure 6.26: DC voltage wave after the rectification for Voltage Source Current Dependant (VSCD).

6.5.3.2.2 *MATLAB simulation*

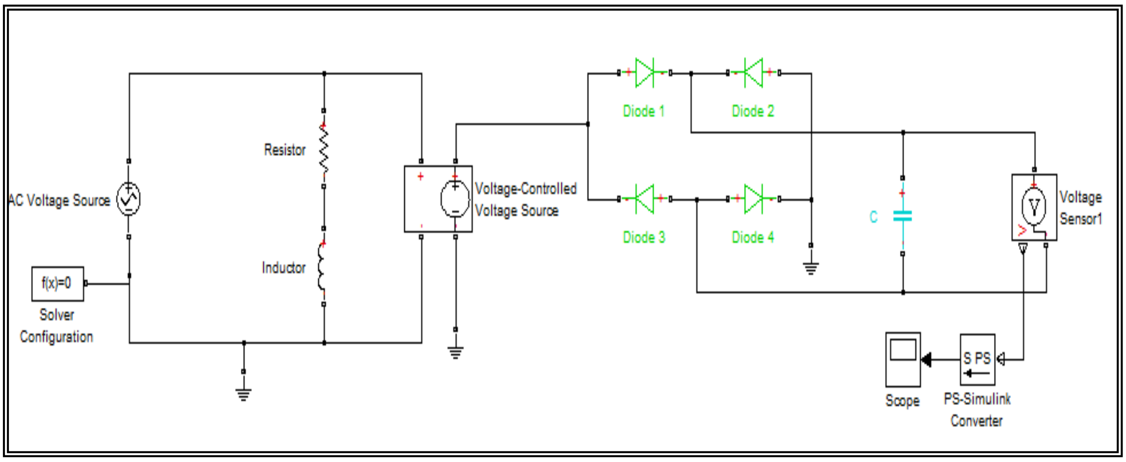


Figure 6.27: MATLAB rectification for VSCD.

The results of MATLAB simulation is shown in figure 6.28 and 6.29 for the voltage before rectification and for the voltage after rectification stage.

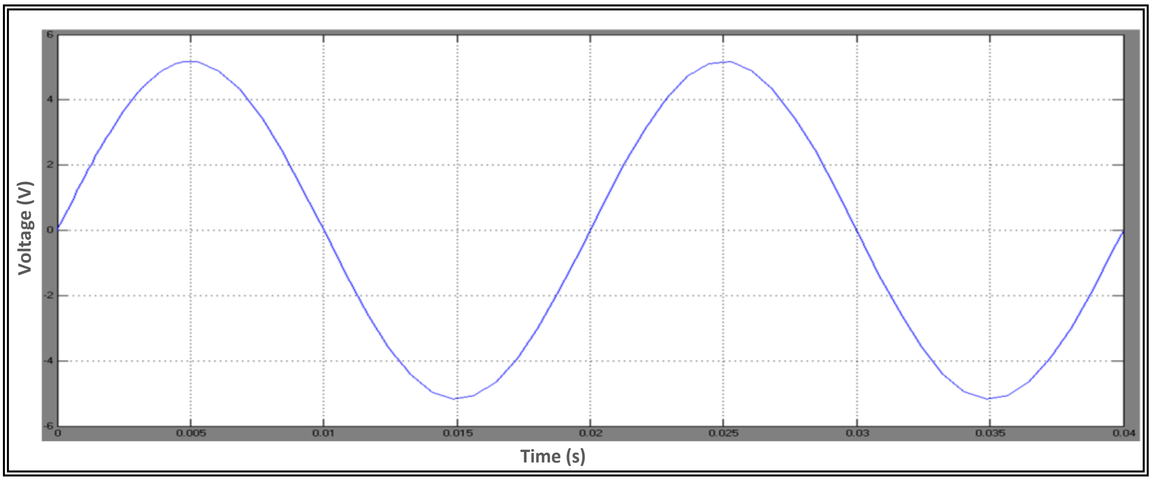


Figure 6.28: Voltage before rectification.

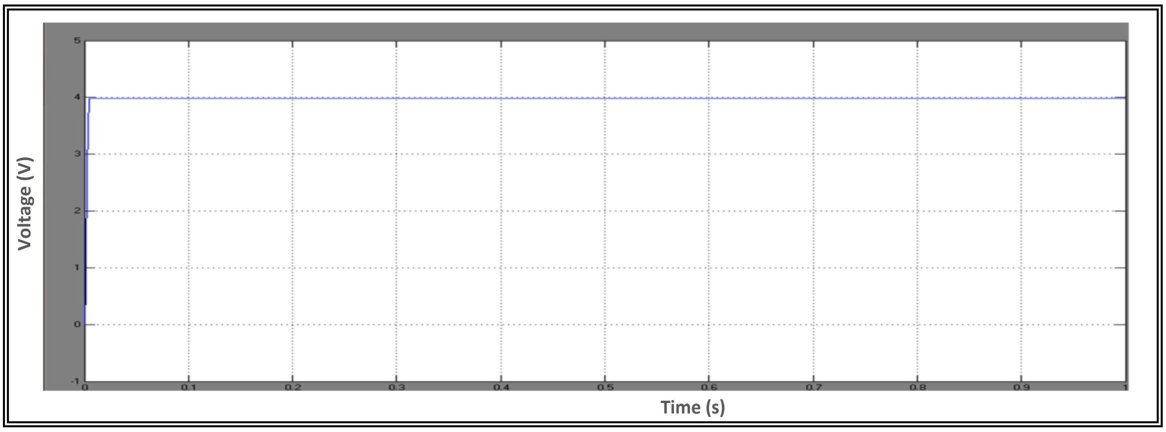


Figure 6.29: Voltage after rectification by using MATLAB.

6.5.3.2.3 *Discussions and comments*

In the Pspice simulation a DC voltage line is brought in after using a 50μF capacitor to smooth the triples of the voltage wave. The DC line takes 7ms to reach the straight line stage, which is the desired period that is needed for the comparator operation. In the MATLAB simulation, the DC voltage line appears straighter and has fewer ripples than the PSpice simulation. This is due to the theoretical technique that the MATLAB uses to solve electrical circuits, whereas in Pspice the components are closer to the practical electronics components that produce noise during operation.

The gain is initially determined according to the following assumptions and calculations and the MATLAB simulation is used for further confirmation:

- ✓ The level of the desired duty cycle at this value of load and capacitance compensation is 0.8 and the required gain for this percentage is Z;
- ✓ The fixed triangle voltage in the next stage (comparator stage) is equal to 5V;
- ✓ By measuring the voltage after rectification, a DC value is obtained and equals X= 339;
- ✓ The percentage here is Y= X/5 =339/5= 6780%= 67.8;
- ✓ The required percentage is 80%, so Y× Z = 80%;
- ✓ Then gain is Z= 0.8/Y= 0.8/67.8= **0.011799**
    - o To achieve the desired duty cycle, the gain should be 0.01179941.

6.5.3.3 ***Comparator stage***

The comparator is used here to create the pulse that is required for achieving the desired duty cycle for the specific gain.

The comparator takes two input voltages:

- The rectified voltage wave (DC line) from the previous stage;
- A triangle voltage wave that has modified parameters to give the shape of a saw tooth.

The process of creating the pulse is explained in figure 6.30

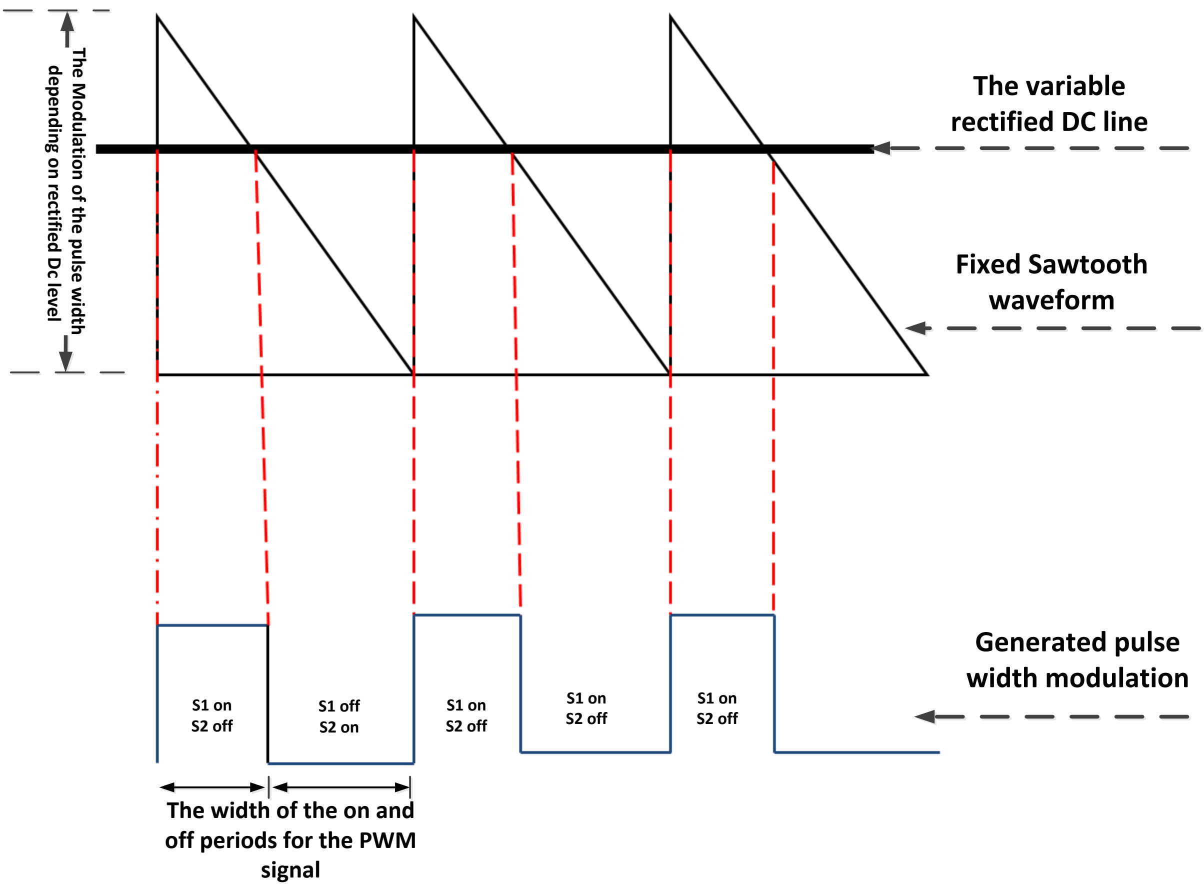


Figure 6.30: The function of the comparator.

The comparator gives a longer distance regarding the pulse for the 'on period', when the rectified voltage (DC voltage) decreases, because the base of the saw tooth triangle is longer than the top. So, according to this comparison, decreasing the load increases its current, which will lead to increasing the VSCD and this, in turn, increases the rectified voltage, thereby decreasing the 'on duty cycle' of the pulse, as demonstrated in figure 6.31.

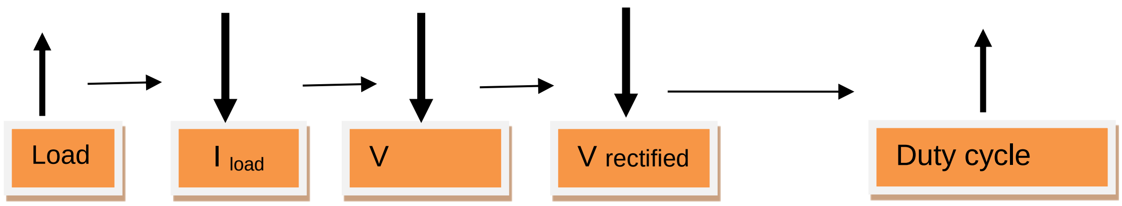


Figure 6.31: The relation between the load and the duty cycle.

6.5.3.3.1 *PSpice simulation*

The following comparator circuit is simulated to verify its efficiency before using it in the system.

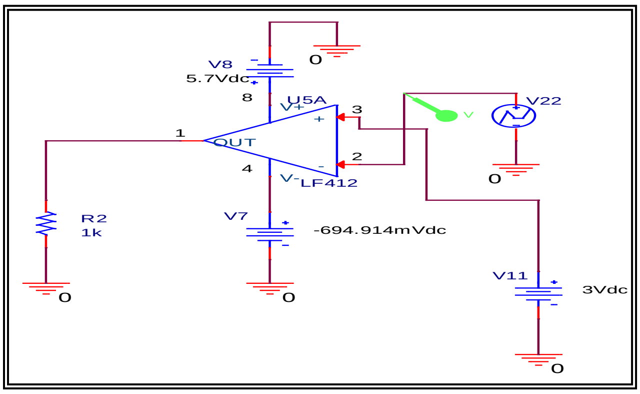


Figure 6.32: PSpice comparator.

1) The saw tooth output voltage, V=5

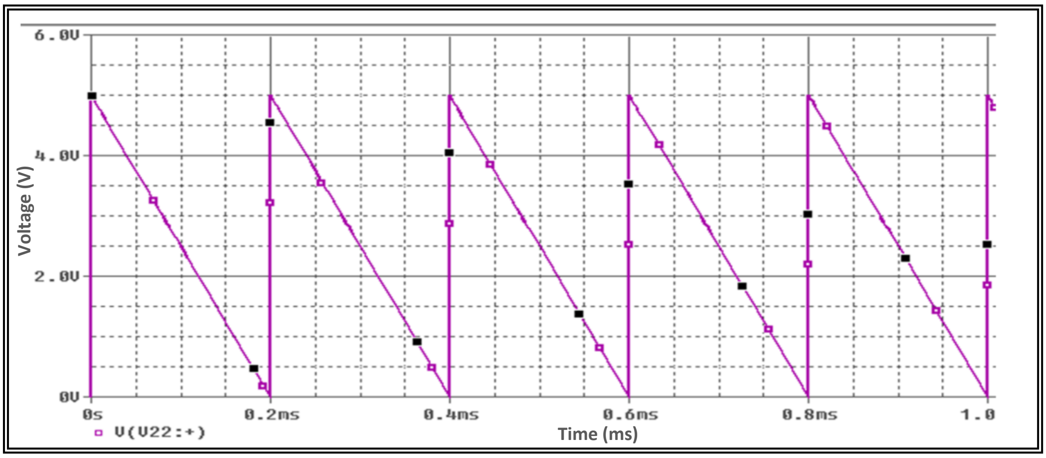


Figure 6.33: Constant saw tooth voltage.

2) DC voltage of 3V

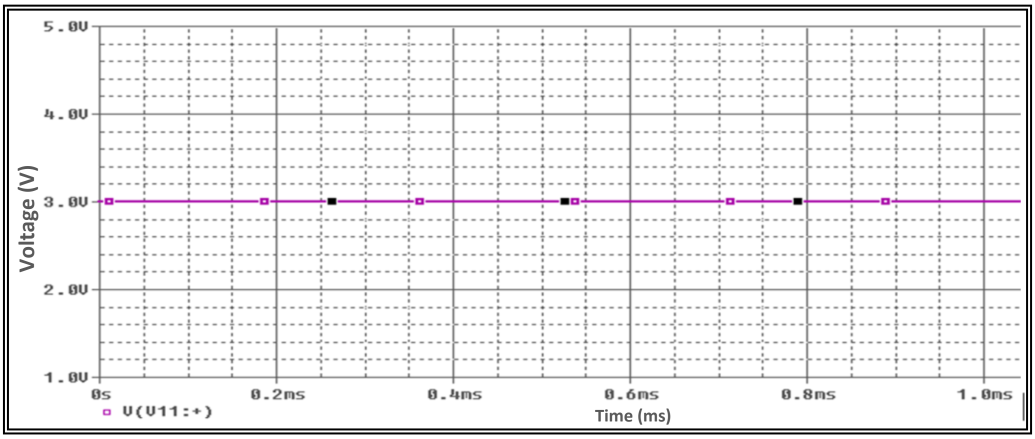


Figure 6.34: DC voltage is 3V.

3) The output voltage of the comparator

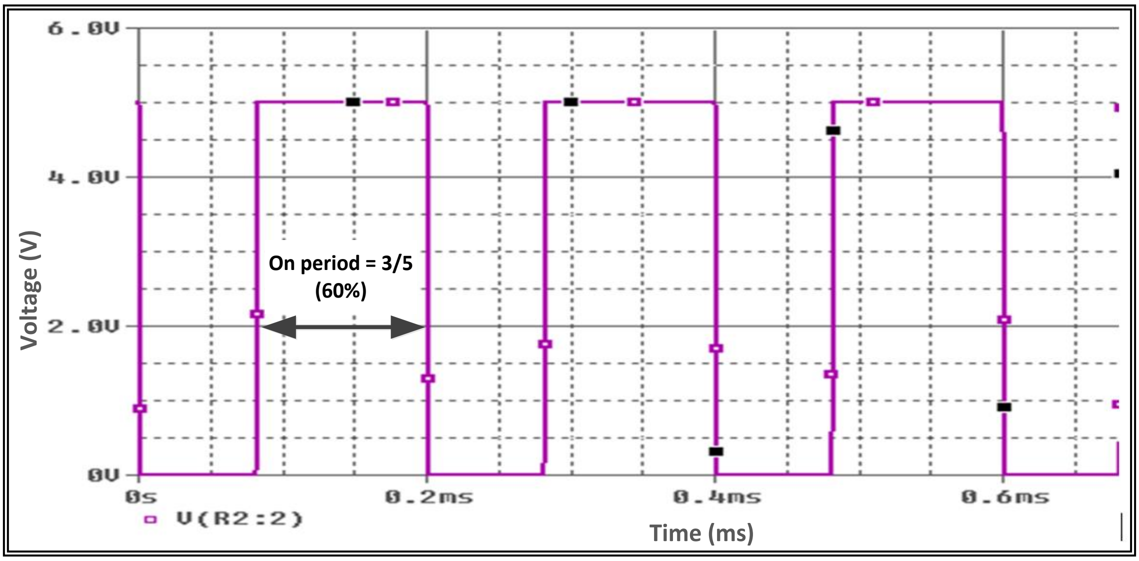


Figure 6.35: Generated pulse of the comparator, D=0.6.

6.5.3.3.2 *MATLAB simulation*

The same circuit that is used in PSpice is deployed here with a 5V fixed saw tooth voltage compared with 4V DC voltage in the comparator with a frequency of 5KHZ.

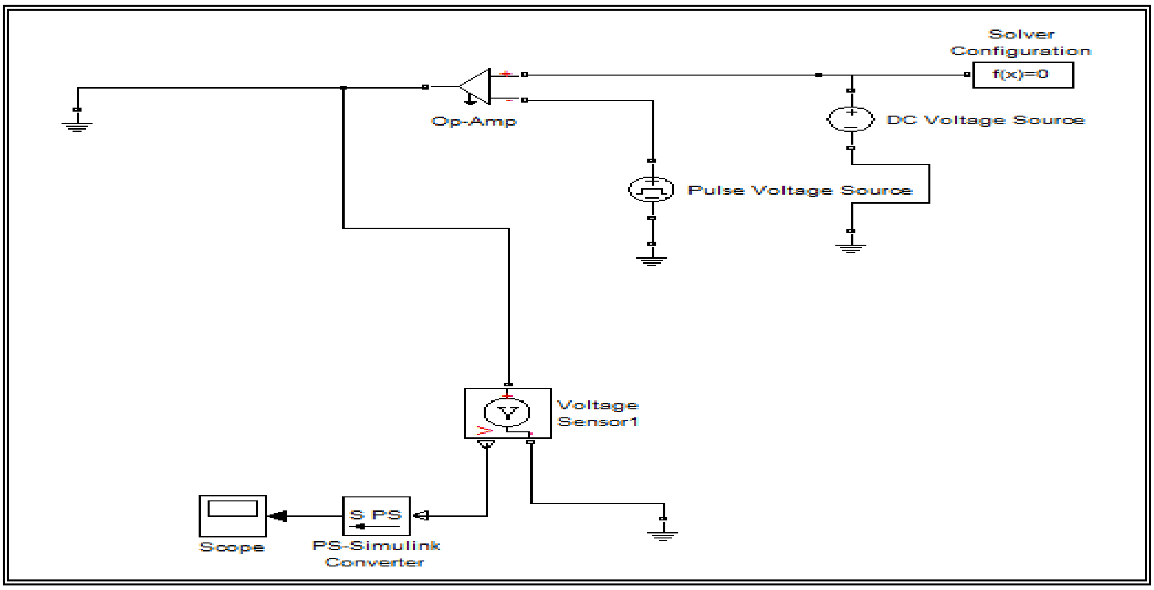


Figure 6.36: MATLAB comparator circuit.

The saw tooth output V=5V

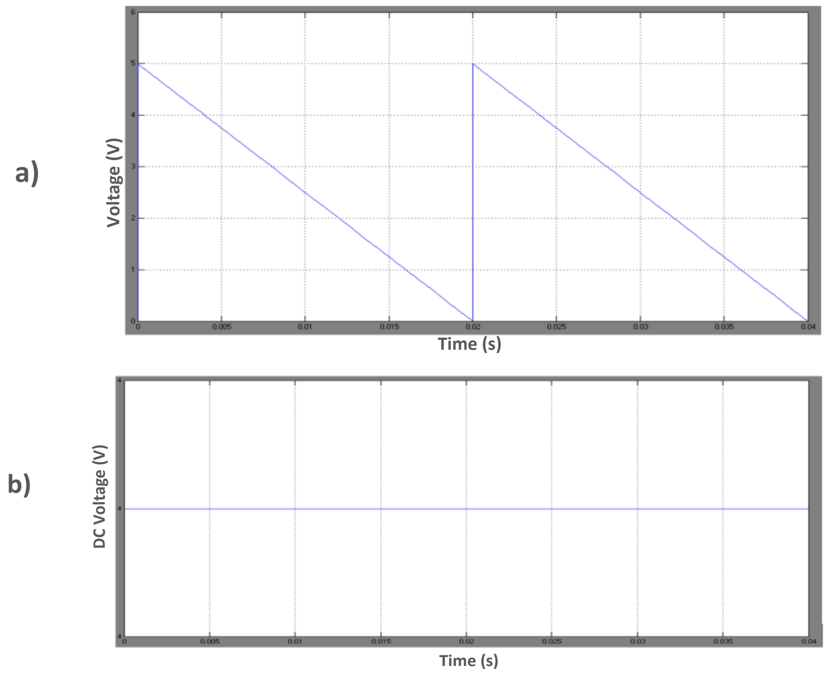


Figure 6.37: a) The saw tooth voltage with frequency = 5 KHz. b) the DC output = 4V.

1) The DC output that is compared with saw tooth voltage. The duty cycle of the pulse that is generated by the 4V DC is 0.8.

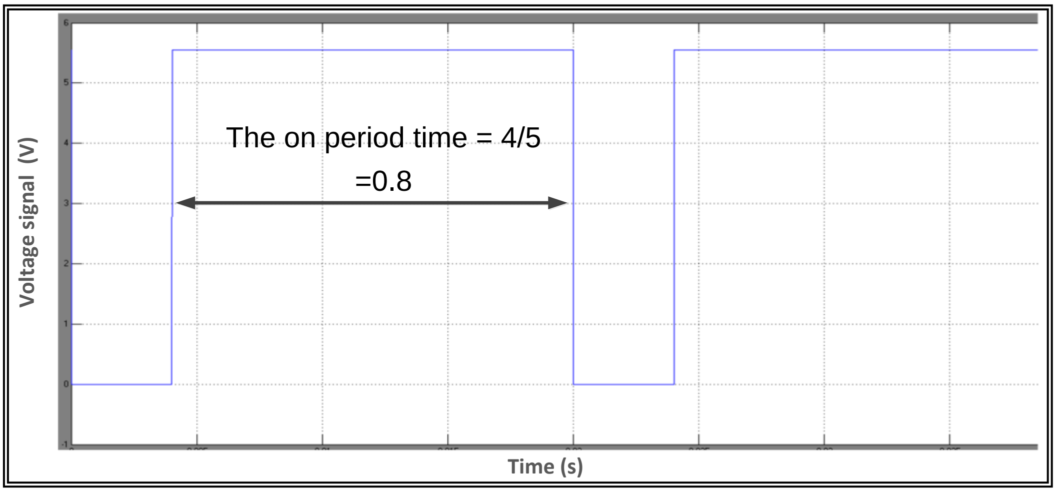


Figure 6.38: Duty cycle of the generated pulse.

6.5.3.3.3 *Discussions and comments*

The duty cycle of the PSpice simulated pulse is smaller than that of the MATLAB simulation, which is due to the smaller DC voltage level that is connected to the comparator. The MATLAB simulation is used to provide more confirmation of the results from the theoretical perspective, as discussed in the previous subsection. Two comparators are used in the automatic feedback and their operation is anti-phase, which means that when one of them gives an 'off' pulse the other gives an 'on' pulse. This can be achieved by inverting the connection of one of them to give the opposite operation of the other.

6.5.3.4 *Gain calculations*

The design of the automatic feedback depends on and is influenced by a suitable VSCD gain (G), which represents the accuracy of the desired duty cycle for every change. This gain is calculated according to several steps that track the loads behaviour depends on its value and degree changes between voltage and current. The steps of Gain estimation and calculations ate illustrated in the following subsections.

The final system appears in figure 6.39 below, where the two compartors are antiphase connected, as discussed previously. The full and clear figures are attached in Appendices E and F, where all the components values and specifications are visible.

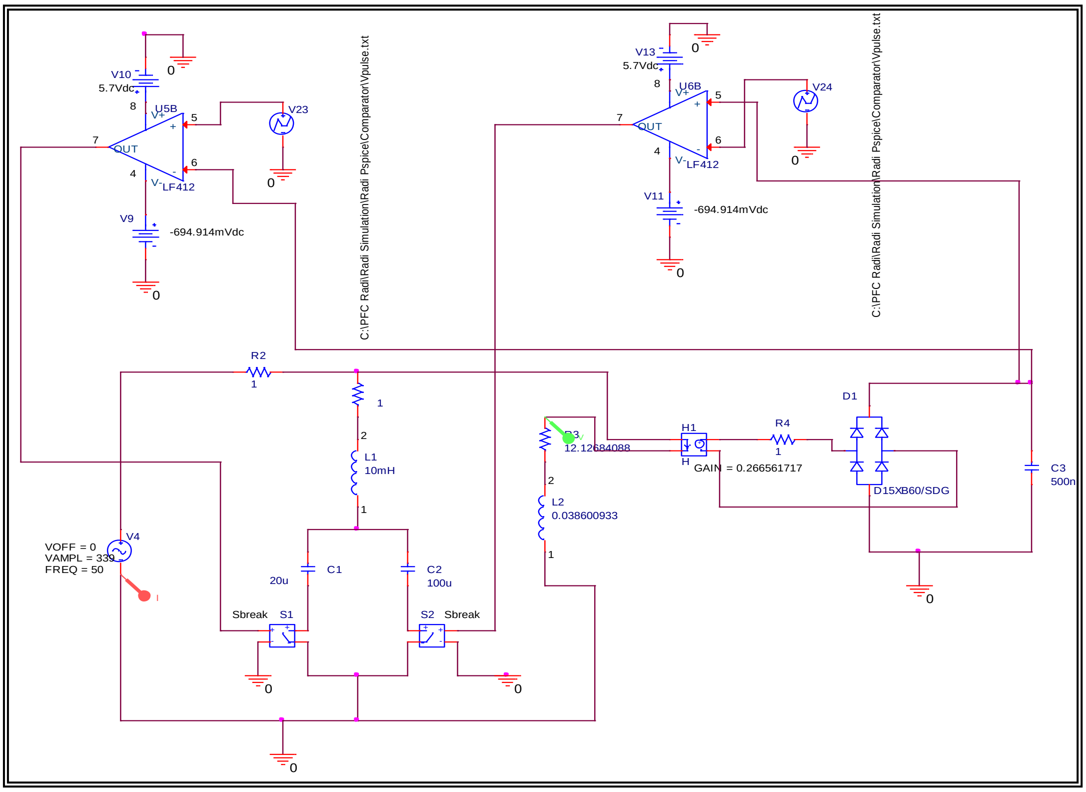


Figure 6.39: DSDC automatic feedback system.

The fixed suitable gain is calculated through the following procedures in the following subsections.

6.5.3.4.1 *Choosing suitable capacitor values for the DCDS circuit*

The effective capacitance value curves against the variable duty cycles for the DSDC circuit should be investigated and chosen in the correct way. A suitable curve is the one that shows a C_{eff} decrease by increasing the duty cycle (inverse relationship), because there are two kinds of duty cycle: the normal duty cycle and the I_{Load} duty cycle, as explained in figure 6.31. The I_{Load} duty cycle has an inverse relationship with C_{eff} in the case of inverting the comparator connections, as shown in the chart of figure 6.40. So, both of the duty cycles have the same inverse relationship by choosing that curve.

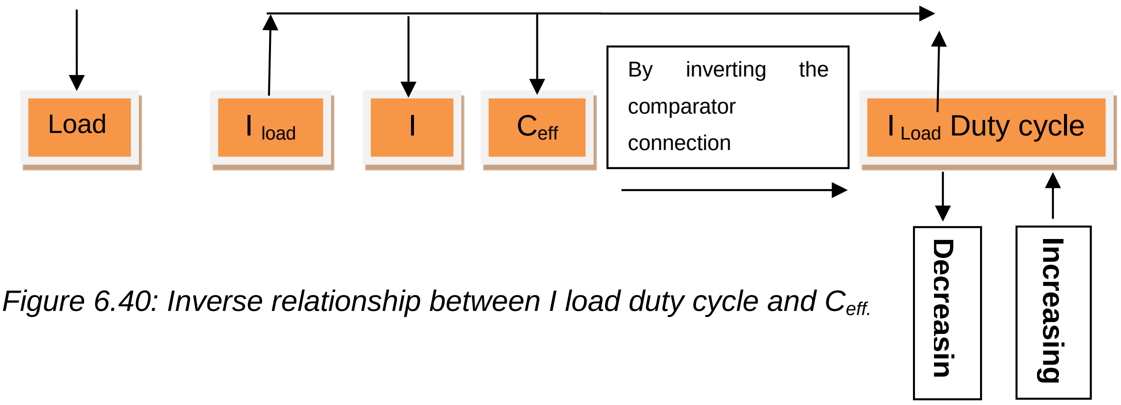


Figure 6.40: Inverse relationship between I load duty cycle and C_{eff}.

So the second curve and table from the calculated C_{eff} in Appendix C is chosen as it appears below in figure 6.41 where C_1 =20uF and C_2 =100uF

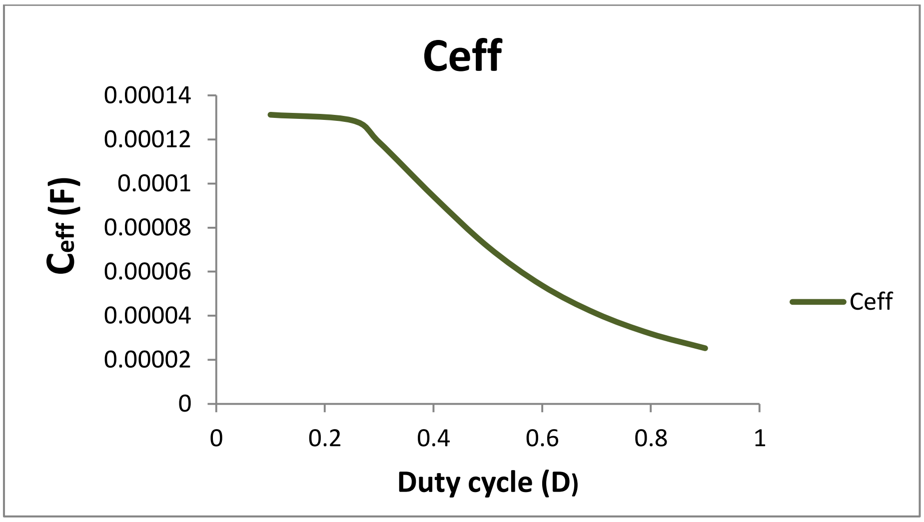


Figure 6. 41: The curve of C_{eff} for the 20μF and 100μF capacitors in the DSDC circuit.

Table 6.4: C_{eff} values for 20F and 100µF capacitors in the DSDC circuit.

Duty cycle (D)	C_1 (µF)	$K = \frac{C_1}{C_2}$	D^2	1-D	$(1-D)^2$	$D^2 \times (1-D) \times K$	C_{eff} (µF)	X_c (Ω)	X_L (Ω)	X_{eff} (Ω)	C_{eff} (µF)
0.1	30	0.30	0.01	0.90	0.81	0.25	118.58	26.84	3.14	23.72	134.17
0.2	30	0.30	0.04	0.80	0.64	0.23	129.31	24.62	3.14	21.50	148.07
0.3	30	0.30	0.09	0.70	0.49	0.24	126.58	25.15	3.14	22.03	144.51
0.4	30	0.30	0.16	0.60	0.36	0.27	111.94	28.44	3.14	25.31	125.75
0.5	30	0.30	0.25	0.50	0.25	0.33	92.31	34.48	3.14	31.36	101.51
0.6	30	0.30	0.36	0.40	0.16	0.41	73.53	43.29	3.14	40.16	79.26
0.7	30	0.30	0.49	0.30	0.09	0.52	58.03	54.86	3.14	51.72	61.54
0.8	30	0.30	0.64	0.20	0.04	0.65	46.01	69.18	3.14	66.05	48.20
0.9	30	0.30	0.81	0.10	0.01	0.81	36.90	86.26	3.14	83.13	38.29

6.5.3.4.2 *Calculating the loads that need the C_{eff} values in table 6.4*

To ensure that the automatic feedback system gives the required C_{eff} and automatically, the loads -resistances and inductors- that need these amounts of capacitances in table 6.4 are calculated by the following procedures, that are subsequently simulated:

- $X_{Ceff} = \frac{1}{2\,\pi\, f\, Ceff}$
- $I_c = V_{eff}/X_c$
- $I_{RL} = I_c/\sin\Phi$
- $Z = 240/I_{RL}$
- $X_L = 240 \times \sin\Phi$, and $R = 240 \times \cos\Phi$
  Where $L = X_L/2\,\pi f$

All the results (loads) for all the C_{eff} in table 6.4 are listed in table 6.5.

Table 6. 5: loads values that are tested for the automatic PF correction.

C (μF)	θ degree	X_c (Ω)	I_c (A)	θ (rad)	I_{RL} or VSCD (V)	Z (Ω)	R (Ω)	XL(Ω)	L (mH)
131.24	45	24.25	9.90	0.79	13.99	17.15	12.13	12.13	38.60
128.71	45	24.73	9.70	0.79	13.72	17.49	12.37	12.37	39.36
118.78	45	26.80	8.96	0.79	12.67	18.95	13.40	13.40	42.65
94.18	45	33.80	7.10	0.79	10.04	23.90	16.90	16.90	53.79
71.34	45	44.62	5.38	0.79	7.61	31.55	22.31	22.31	71.01
53.72	45	59.26	4.05	0.79	5.73	41.90	29.63	29.63	94.31
40.96	45	77.72	3.09	0.79	4.37	54.95	38.86	38.86	123.69
31.83	45	100	2.40	0.79	3.39	70.71	50.00	50.00	159.15
25.24	45	126	1.90	0.79	2.69	89.16	63.05	63.05	200.69

The results of different loads values-X_L and R- are taken in the process of the gain calculation at phase angle =45^o and V_{eff} =240, with a duty cycle that varies from 0.1 to 0.9.

6.5.3.4.3 *Evaluating the average gain before rectification*

Calculating VSCD max for every duty cycle by using the equation: I_{Load} max or VSCD max= VSCD $_{(in\ table\ 6.5)}$ ×√2, as shown in table 6.6

Table 6.6: I $_{Load}$ maximum.

Duty cycle	VSDC Max (V)
0.9	19.79
0.8	19.41
0.7	17.91
0.6	14.20
0.5	10.76
0.4	8.10
0.3	6.18
0.25	4.80
0.1	3.81

The gain is calculated as follows:

$$\text{Gain} = \frac{5\times Duty\ cycle}{\text{VSCD max}} \tag{6.18}$$

Equation (6.19) is used in table 6.7 to get the gains for the duty cycles from 0.9 to 0.1.

$$I_{\text{load duty cycle}} = \frac{\text{VSCD after rectification}}{5V\ (\,the\ fixed\ triangle\ voltage)} \qquad (6.19)$$

Table 6.7: The gains at several duty cycles.

Duty cycle	calculated gain	VSCD after gain (V)	average gain	D of the controlled current
0.9	0.23	4.51	0.23	0.90
0.8	0.21	4.42	0.23	0.88
0.7	0.20	4.08	0.23	0.82
0.6	0.21	3.24	0.23	0.65
0.5	0.23	2.45	0.23	0.49
0.4	0.25	1.85	0.23	0.37
0.3	0.24	1.41	0.23	0.28
0.25	0.26	1.09	0.23	0.22
	0.23			

The average of the gains in table 6.7, is **0.2278302527**

6.5.3.4.4 *Evaluating the average gain after rectification*

It is noticed that after rectification, the level of the voltage is reduced slightly, so to keep an accurate gain, this reduction is estimated after measuring the rectified voltage level after rectification at 17% of the voltage level before rectification. The following Excel table is derived

Table 6. 8: The gains after rectification.

Duty cycle	max voltage after rectification (V) tolerance 17%	new gain after rectification	Average gain	VSCD after gain (V)	D of the controlled current
0.9	16.43	0.27	0.27	4.38	0.88
0.8	16.11	0.24	0.27	4.29	0.86
0.7	14.87	0.23	0.27	3.96	0.79
0.6	11.79	0.25	0.27	3.14	0.63
0.5	8.93	0.27	0.27	2.38	0.48
0.4	6.72	0.29	0.27	1.79	0.36
0.3	5.13	0.28	0.27	1.37	0.27
0.25	3.98	0.30	0.27	1.06	0.21
		0.27			

The same calculations that were made in table 6.8 are repeated here, but with a reduction of 17% for the non-rectified voltage (max).

$$I_{\text{load duty cycle}} = \frac{\text{VSCD after rectification}}{5V\ (\mathit{the\ fixed\ triangle\ voltage})} \qquad (6.20)$$

The average gain that is to be adopted in the simulation, according the Excel table calculations, is **0.266562**.

A comparison between the duty cycles that are created from the change of I_{Load} and the normal perfect duty cycles (0.1 to 0.9) is shown as two lines in figure 6.42. The first line represents the linear change of the manual duty cycle and the red line represents the change of the duty cycle that is created from changing I_{Load} after choosing the suitable gain for the chosen DSDC circuit (20μF and 100μ).

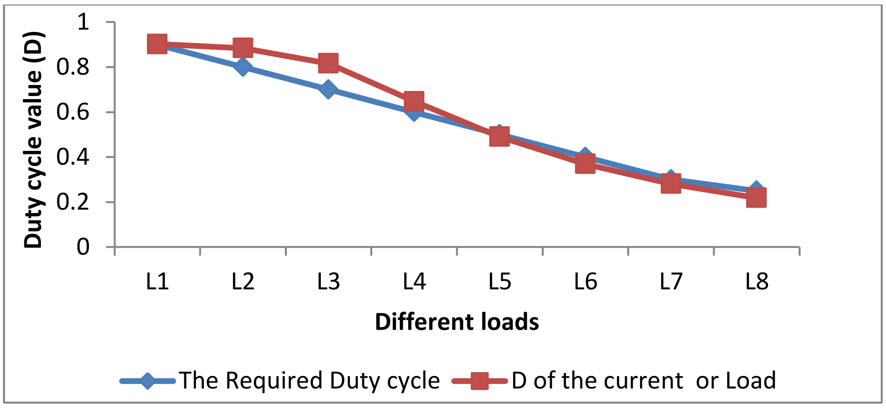


Figure 6.42: VSDC duty cycles after the gain calculations and before rectification.

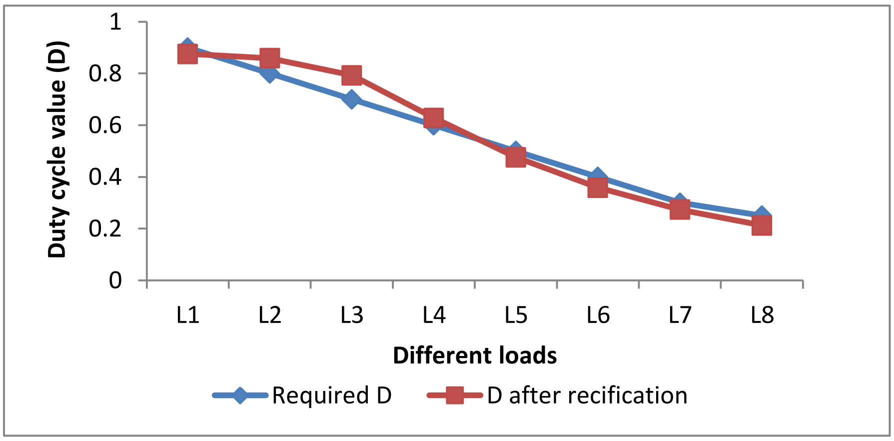


Figure 6.43: VSDC duty cycles after the gain calculations and after rectification.

As can be seen from figures 6.42 and 6.43, the line that is created from the automatic duty cycle is close to the perfect linear line of the manual duty cycles.

6.5.4 Full design and results through PSpice and MATLAB

The final design for the automatic feedback depends on and is influenced by the following:

- Suitable VSCD gain (G), which represents the accuracy of the desired duty cycle for every change;
- Interacting of the DSDC circuit with the new pulse generator;
- Interacting between the load change parentage and the produced C_{eff} change percentage;
- Suitable capacitor values that give a stable gradual C_{eff} change for every duty cycle and the curve of C_{eff} can be chosen from Appendix C.

The following DSDC feedback system is simulated by using PSpice and MATLAB simulations in order to improving the displacement power factor automatically, whereby the results are illustrated in the following subsections of PSpice and MATLAB simulations.

6.5.4.1 *PSpice results*

The required capacitance for the 3 values of the loads is listed in table 6.5:

6.5.4.1.1 *Constant phase angle =45o*

- At load R=12.12684088 Ω and 0.038600933H the difference phase angle is almost 0

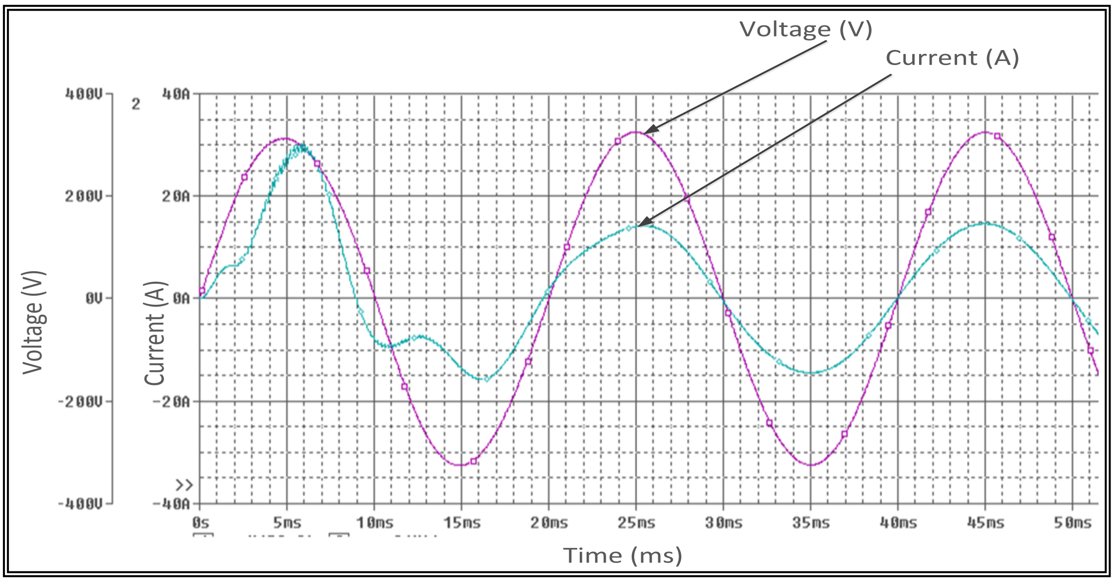


Figure 6. 44: The difference phase angle at load R=12.12684088Ω and 38mH.

- At load R=13.39910056 and L= 0.042650662H

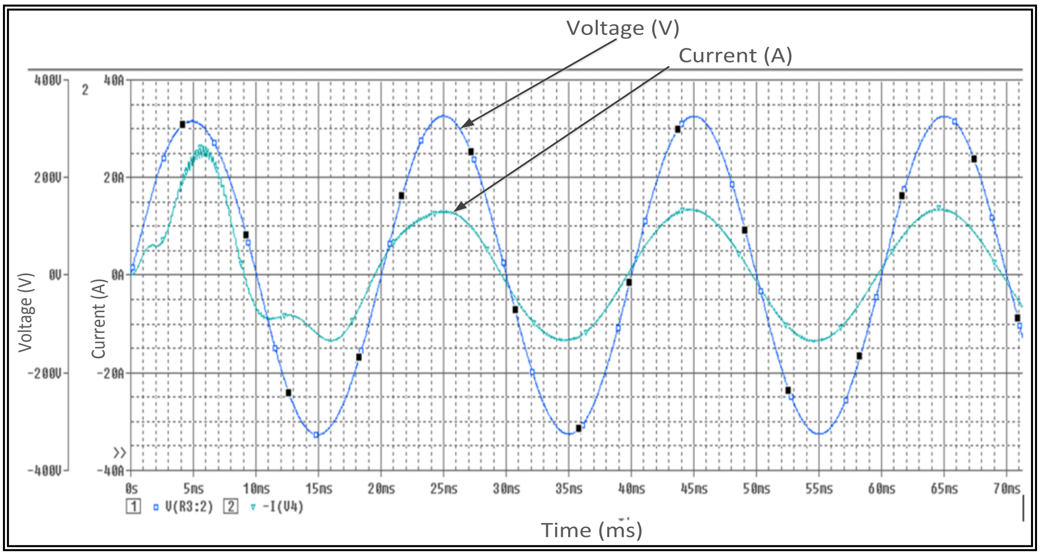


Figure 6. 45: The difference phase angle at load R=13.39910056 and L= 0.042650662H.

- At load R=63.04809321 and L= 0.200688314H

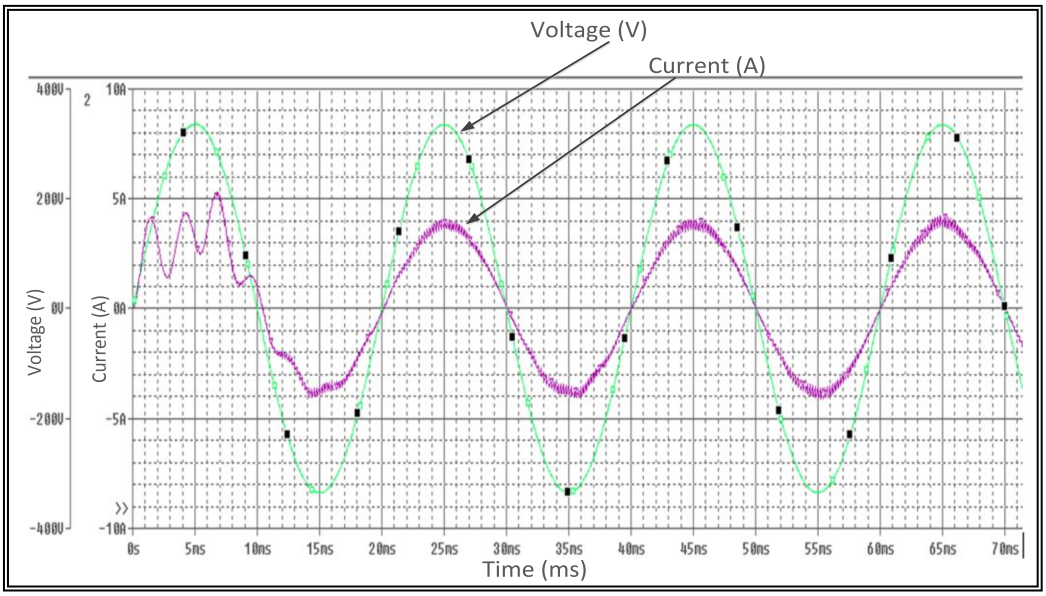


Figure 6.46: The difference phase angle at load R=63.04809321 and L= 0.2006H.

The previous loads where taken at different values, but constant phase angle (45^o) between $X_{L\text{ and}}$ R, where they showed a slight different phase angle that is almost zero.

6.5.4.1.2 *Different phase angle value*

The next result is for a random load that is taken at different random phase angles to verify the automatic compensation for the closed loop system.

- At load R=40 Ω and L=400mH, the phase angle is tan inverse (X_L /R) = **72.343°**

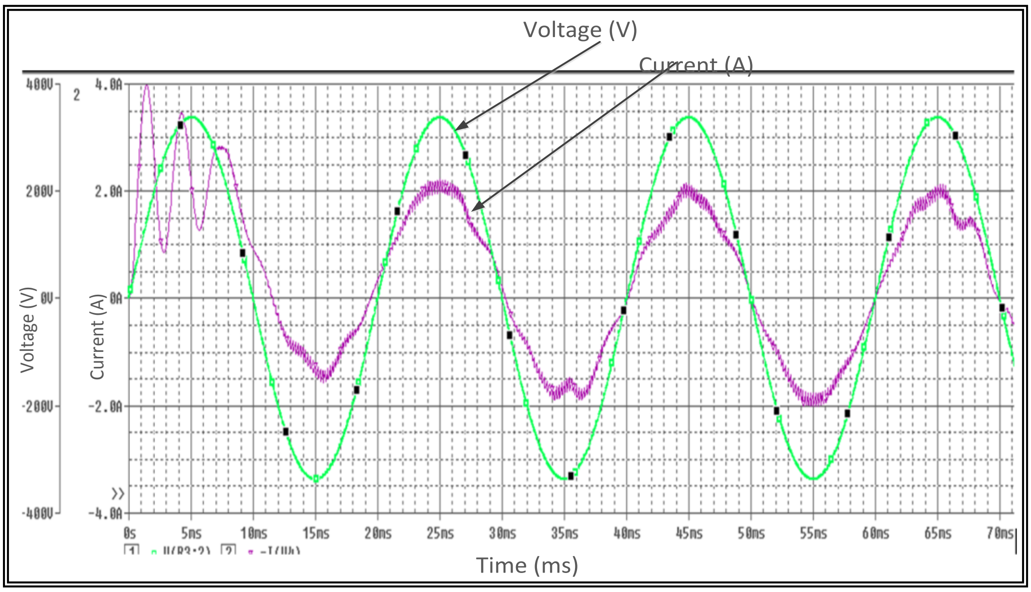


Figure 6.47: Power factor corrections at different phase angle between X_L and R.

6.5.4.2 *MATLAB results*

The results of testing the 3 loads that are listed and calculated in table 6.5. Two of them are different than the PSpice simulated loads.

6.5.4.2.1 *Constant phase angle=45o*

At the load R=12.12684088 Ω and 0.038600933H

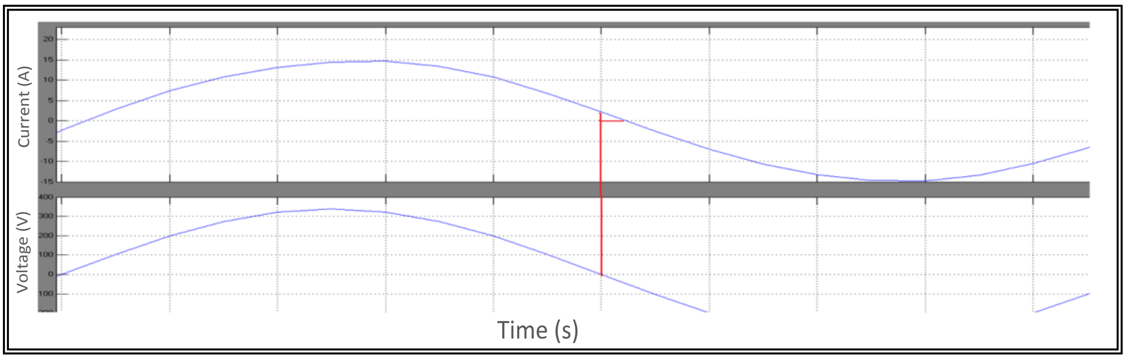


Figure 6.48: The phase difference between V and I in the first result of MATLAB.

After amplification of the wave, it is noticed that there is a minor difference in the phase angle between the voltage and the load, but the power factor is improved and the phase difference is much smaller than before.

- At load R=22.3080492 Ω and L= 071008726H

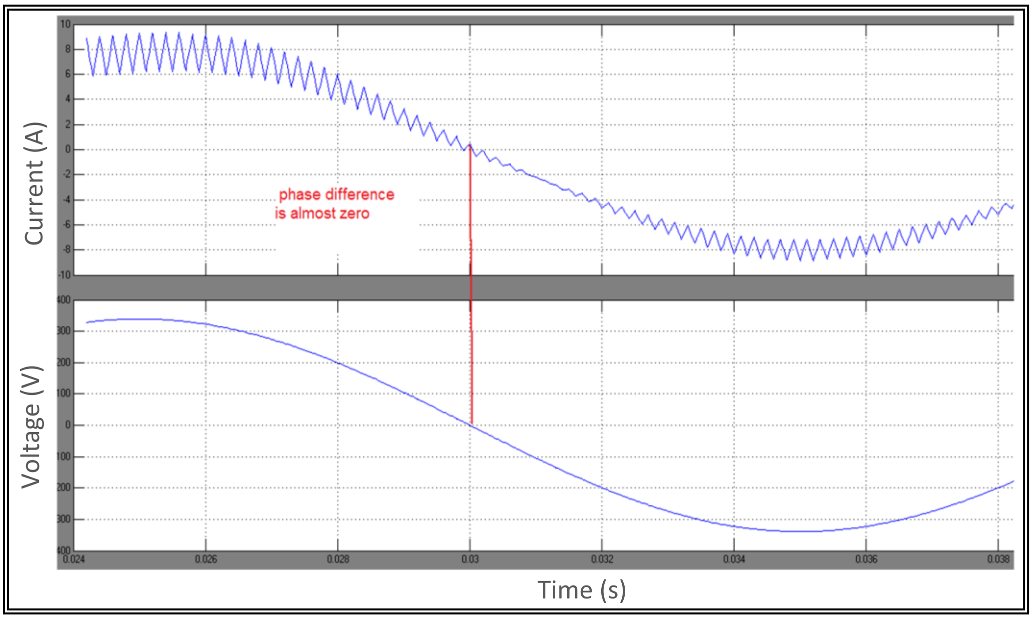


Figure 6. 49: The phase difference between I and V for a load that needs a 0.5 duty cycle.

- At load R=49.9979054 Ω and 0.159148276H

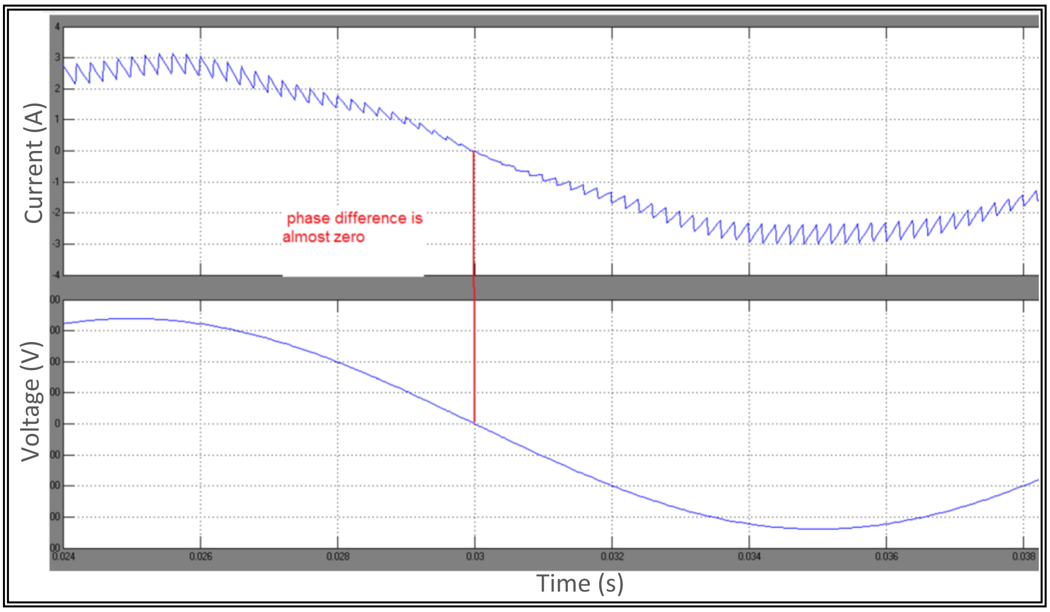


Figure 6. 50: The displacement power factor correction in MATLAB.

6.5.4.2.2 *Different phase angle value*

The load is R=40Ω and L=100.6mH, tan inverse (X_L /R) =**38.132°**

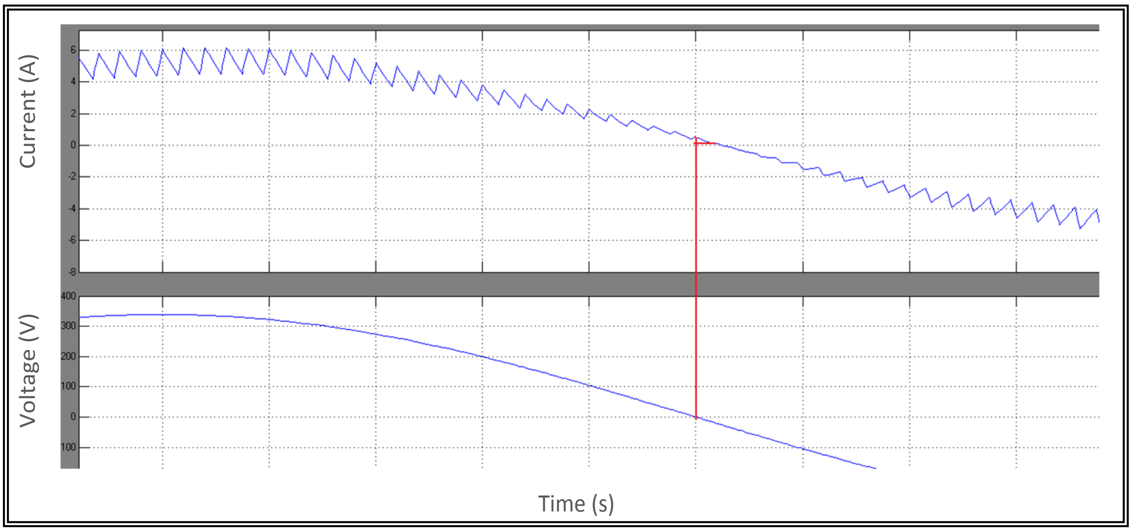


Figure 6. 51: The displacement power factor correction at a different phase angle.

As seen above in figure 6.51, the phase difference is too small when a different load with a new phase angle between X_L and R. As mentioned previously, the system doesn't give perfect displacement power factor correction at some loads, but it does reduce the phase difference as much as possible.

6.5.4.3 *Discussion and comments*

The simulations contents and discuss the DSDC circuit that has the 20uF and 100uF capacitors, where it is chosen according to its advantages over the DSSC circuit. After choosing the DSDC circuit, the challenge is to choose the most preferable capacitor values in the circuit. These were chosen according to the curves that achieve an inverse relationship between the given effective capacitance and the duty cycles of the switches, which is the same relationship between the duty cycles that are created from I_{Load} change and amount of capacitance compensation.

For the PSpice and MTALAB simulations two types of tests simulation were applied to the system to verify the automatic compensation process

- Different loads with a fixed phase angle between X_L and R.

At these kinds of loads the gain is chosen to achieve convincing results by decreasing the phase angle between V and I as much as possible. The current passes through a transient period at the beginning of its wave, which was not more than 18ms in the three loads simulation where it is normal in the case of switches existence. The process of switching in the circuit and of charging and discharging the capacitors creates the distortion that is seen in the current of the three loads. It increases when the load value is increased, and that due to the increase in the amount of capacitance compensation that is required for a larger load, which leads to an increase in the periods for charging and discharging the capacitors.

- Test for a different phase angle between X_L and R

The results in figures 6.47 and 6.51 verified the operation of closed loop DSDC in the conditions of changing the load at any value or any phase angle for the chosen circuit (20uF and 100uF capacitors).

The MATLAB result is less accurate than PSpice, and the difference phase shift between V and I is slightly greater in the case of load = R=12.12684088 Ω and 0.038600933H. This is due to different types of components that are used in MATLAB and PSpice regarding switches, comparators and diodes. That is, the components and parameters of PSpice are close to real and practical ones, MATLAB's are closer to the computational calculations relating to the theoretical background in the electronic circuits solution. The difference between the two programs creates slight differences that are unnoticeable at other loads.

This system could be a simple system that replaces the complex control systems found in rural areas where the changes in load are slight. These areas could have simple and cheap automatic power factor correction systems that contribute to the overall power factor correction in the network. The value of the capacitors in the DSDC circuit can be selected according to the expectation of the load demand in every area.

6.6 Conclusions

Reactive power demand varies between loads, which means that some loads depend mainly on consuming reactive power, such as in a factory that uses several induction machines. In this case injecting reactive power close to the load is a necessity more than an option. The switched capacitor operation was introduced for the purpose of capacitance compensation by Marouchos [50] and then by Darwish as an active filter in 1985 [51]. This approach is used for automatic reactive compensation for the purpose of power factor correction in inductive loads. The compensation process depends on providing the load with its exact need from reactive power, which means fewer losses and no waste in the released energy from the capacitors.

The DSDC and DSSC circuits have the ability to act in lagging and leading mode. The previous simulation uses the leading mode to compensate for the reactive power for a load that operates in the lagging mode. The capacitor switching circuit components, such as capacitors inductors and resistance, have been explained in the analysis. Every part has its role to play. The mode of the circuits is controlled by varying the values of X_c for the capacitors and X_L for the inductors. The circuits are also defined by using differential equations of V and I in both modes of the switches (S1 closed and open). The C_{eff} calculations were introduced in this chapter for both methods, manual and computational, by using PSpice, where both of the values were too close to each other.

The simulations proved that the DSDC circuit is efficient in power factor correction, whereby it can give several values of C equivalent by just changing the duty cycle value of the switches instead of replacing the entire capacitor bank in the case of load change. Owing to this efficiency the DSDC circuit was chosen to be simulated in MATLAB for further confirmation. A comparison between the DSDC and DSSC was introduced regarding to the operation of each circuit. This comparison showed the advantages and disadvantages of the two circuits in relation to their components and the strategies of each circuit when operating as a reactive power compensator.

In this chapter a full design for the DSDC circuit was introduced and its operation explained at each of the following stages:

- The purpose and operation of the VSCD.
- The rectification stage to get a straight DC voltage line;
- The comparator operation comparing between the DC voltage and the saw tooth voltage;
- The generated pulses for every load value.

This gain in the voltage source that takes its value from that of the load current is designed and calculated to give the closest duty cycle behaviour. This gain is the most sensitive stage in designing the system, because it contributes to producing the wanted pulse at every change. A chart was introduced to illustrate the idea of the feedback.

The simulations were performed using MATLAB and PSpice to verify and test the system at three loads sharing the same phase angle between X_L and R, where their amounts of reactive compensation had already been calculated. Also, the simulations included different loads with a different phase angle to verify the effect of the circuit at the change of the impedance phase angle. A comparison was made between the results of the MATLAB and PSpice to show the effect of using different electronics components in the system and for further confirmation. The system showed reliable behaviour that could be adopted as a simple and cheap system in simple electrical networks that don't have complex systems and facilities that are characterised as having unexpected consumption, where this system treats the displacement power factor.

7 Conclusions and future work

7.1 Conclusions

This chapter presents the main conclusions and highlights the possibilities for future research. The research outcomes in the earlier chapters are summarised in this chapter to introduce a general idea regarding reaching the main aims and objectives of the research and contributing to existing knowledge. Probable further modifications and possible improvements are introduced for future work that could enhance the research towards the proposed knowledge and research methodology.

The research considered the issue of power electronics intervention in electrical networks and studied the latest developments in terms of applications in electrical networks such as transmissions networks. The literature review investigated the main problems in LV networks subject to voltage and control problems besides the related challenges behind addressing those two main issues. Some studies addressed PE technology as a solution to approach the problems in LV network depending on the current case and the expected future scenarios for LV networks, whereby several approaches have adopted PE converter to meet challenges in LV such as voltage, reactive power, frequency and control issues. It also identified several challenges regarding the application of PE in LV network and real practical difficulties experienced in convincing investors in the electrical filed to adopt PE as a solution.

PE approaches in LV are innovative, and their adoption faces the barrier of investor concerns about potential cost of implementation and operational losses; however, these barriers are common to all new technological solutions. Power quality is a wide term that could be defined according to the requirements from the system and the outcomes from losses, technical sides, customer satisfaction and cost perspectives. Therefore, it could be conceivable for investors to support any approach in LV network by making a balanced comparison between the required level of power quality for a specific system, such as LV network, and the technical returns from one side, and the business benefits on the other (as concluded by this study, long-term benefits can be expected in both functional and cost dimensions).

It has been found that there are serious challenges to applying PE in LV in order to solve existing challenges, which makes it a closed circle dilemma requiring a novel approach in order to be able to surmount any technical barriers or cost obstacles. The literature review chapters expounded upon the technical challenges to applying

PE functions in LV networks from technical and cost perspectives, besides highlighting several projects amenable to PE adoption in LV networks.

The latest PE technology was investigated and its control ability analysed, whereby several improvements introduced recently by research communities illustrated the high potential of PE converters. Control abilities and flexibilities exist in solid state switches' functionalities and ability to perform several converting operations such as AC/DC/AC, which could be used in many solutions. This investigation of the function of PE enhances strategical thinking towards choosing the right converters implementations and control topologies depending on the case of the handled issues, in terms of voltage regulation and reactive power control, which have been found to be major problems in LV networks in terms of power density and quality constraints, highlighting current challenges and foreboding a highly problematic future if suitable equipment to solve these problems is not adopted. Therefore, the consideration of voltage regulation term and reactive power control in this research demonstrated the efficacy of intervening in LV networks using PE approaches and solutions.

PE intervention for LV was considered in this research for the purpose of voltage regulation and reactive power control in light of designing new approaches that possess the advantages of low losses and cost, without decreasing the functionality and flexibility of PE converters' operation. Cost and losses are the main concerns of investors in considering the adoption of PE solutions in LV networks. Therefore, this research introduces a new strategy by introducing PE approaches and their control techniques according to the exact needed function. The approaches are applied in unusual areas such as the last mile of the network with new ratings, which provides the last mile of the network with new abilities and functionalities that were previously neglected.

The investigated area in the network (LV) was chosen according to its necessity for current improvements in the context of future expectations, whereby approaches treating current and future problems can give the network a taste of monitoring, communication and flexible reactions towards poor network infrastructure without digging every pavement in the last mile to upgrade and develop current systems, which saves immense time and resources.

The last mile of the network status and problems were investigated regarding voltage regulation problems in several scenarios, whereby LV network was simulated and tested under a variety of loading conditions. The voltage behaviour was tested and obtained using MATLAB in light of the distance between loads and substation, equal feeders and phases, unequal loaded feeders and phases, power factor corrections, losses and types of load (constant current, constant power and constant impedance loads).

After verifying the problem by simulation and through reviewing pervious research, an approach was introduced to solve the problem depending on enhancing the LV network gradually with PEs, according to the exact need. The hybrid distribution transformer is introduced as an approach that has the potential to upgrade the operation of the new LV substation to a new level, with low PE losses due to using fractionally rated PE producing less condition and switching losses than the full rated PE switches. In addition, schematic diagrams for HT topologies were introduced wherein every topology addresses specific functions according to the arrangements of PE converter attached with LV transformer. The functionality of the back to back converter was addressed through simulation to verify the potentiality of the introduced approach for PE in the last mile of the network. Two different control topologies were applied in order to reach a high level of controllability: a vector control for the purpose of fixing the DC voltage level at the DC link, and PR control to efficiently track the grid voltage behaviour for each phase separately. As explained in chapter four, voltage regulation was detected in the last mile and a solution was introduced comprising partial rated PE switches attached partially with the winding of LV transformer.

Reactive power compensation or Var control challenges were addressed as a second form treated in LV by PEs. The second approach that the thesis handles was applied according to the reviewed problems in the LV networks. Providing the ability to control the RP in distribution networks is considered a feature for todays' distribution substations and a requirement for future demand. This kind of ability was introduced in this thesis an extra function provided by LV transformer in partial form as an approach to mitigate the effects of transferring reactive power through the transmission networks. The same design used to regulate voltage was utilised to provide partially reactive power with small modifications undertaken in the control topology and the design itself. Conceptual schematic diagrams for the possible PE solid state switches arrangements were presented to demonstrate several abilities and functionalities according to the requested demands. The attached solid state switches of the converter were designed at fractional ratings (around 20-30%) of the total windings of the LV transformer, which are the ratings needed to control the voltage regulation interval and to cut from the total power (S). The same converter (back-to-back) used in regulating voltage was used in the approach of reactive power, but with using power balance control topology to control the flow of the power between the rectifier attached partially with the windings of the transformer and the inverter attached with the LV grid lines. This kind of control has the advantage of keeping the DC voltage level constant, with minimum variations.

This HT design for reactive power injection was considered as a first step towards further modified designs that are better able to provide the whole demand of reactive power using more equipment such as energy storage techniques for reactive power. This amount could be increased in the future by depending on more reliable PE switches proportionate with the increase of future demand.

Reactive power demand varies between loads, which means that some loads depend mainly on consuming reactive power, such as factories that use several induction machines. In this case, injecting reactive power close from the load is a necessity more than an option. Providing the loads with a high amount of reactive power is believed to be more efficient in the case of supplying beside the load. Therefore, the form of PE intervention takes another path by the technique of switched capacitor. This new strategy is used to support the load with its exact need from reactive power, whereby the control strategy is designed according to the consumption behaviour of the load, depending on analysed study conditions regarding the slope of loading or consumption. The new proposed control strategy is simple and could be achieved by using a simple low cost programmable integrated circuit.

The abilities of switched capacitors were introduced in two forms, double switches double capacitors (DSDC) and double switches single capacitor (DSSC). Utilising switched capacitors contributes towards the saving concept, as it decreases the amount of injected reactive power according to the exact need; therefore, there is no waste for the stored energy in capacitors. The capacitor size and types represents an important issue regarding the cost and lifetime of the device, so any loads requiring this approach should take into consideration the size of the capacitor depending on its consumption behaviour, whereby every load has its own characteristics and design ratings. The technique was simulated using the software programs MATLAB and PSpice to verify and test the system in several conditions; the results were discussed and analysed for each step of the control design.

7.2 Future work

The conducted research identified some points able to undergo more modifications relying on improved strategies and synchronisation with advanced techniques over a proportional timeframe. Moreover, each chapter was designed to approach a specific object in order to reach the main aim of deploying PE in LV networks. However, these approaches are capable of being utilised for more purposes subject to further modifications for two main issues: the proposed designs, such as modifying the design of HT and the control topologies; and further modifications regarding the provided functions in LV network. Future work could consider the following strategies.

7.2.1 7.2.1 Utilising higher ratings

The research could take another route in case of relying on more advanced findings regarding solid state switched performance in PE approaches, such as less losses in the conducting and switching process. In this case, the 20-30% ratings used can be increased and more reliance on PE could be achieved, achieving more flexible results and contributing more towards required functions such as voltage regulation and reactive power control.

7.2.2 DC link

There is an important potential behind using the ability of DC link to act as source for a limited DC networks or loads. Utilising more advanced control techniques and more efficient capacitor or energy storage techniques could make this approach real. This kind of research enhances the prospects of utilising DC loads or networks, which is considered an important current research area. This function will provide the substation with more controllability and flexibility rather than being a mere voltage step-down point.

7.2.3 Multiport and multifunction transformer

Several studies have been conducted to explore the use of PE converters as a multiport approach serving bidirectional power flow, but due to high costs and switches losses, these approaches have not been deployed in practical applications. Therefore, using a hybrid transformer with less losses and cost in serving bidirectional power flow could address an important solution for such challenges, including distributed generators and the intervention of renewable energy in LV networks (such as PV cells). This approach addresses several challenges that should be taken into consideration such as frequency control. Both voltage regulation and reactive power objects could be achieved at the same time by reaching a common functional algorithm between both of them that enables voltage regulation through reactive injection.

7.2.4 More verified results

More verified results could be applied by demonstrating practical field experiments in labs with high capability of simulating the real status of LV network before actual adoption, such as simulation with winding transformers able to address the exact behaviour of the LV transformer in dealing with partially rated switches. This research focused on the possibility of design and controllability from an approachable side more than a technical one.

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