Comparative Evaluation of Different Power Quality Issues of Variable Speed Wind Turbines

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DECLARATION

I, Ibrahim Ahmed, declare that I have written this thesis and it is entirely my work. I also certify that this thesis work has not before been submitted for a degree for any other academic Association.

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ABSTRACT

The generation of wind energy deliberately becomes a significant part of generated electrical power in developed nations. Factors like fluctuation in natural wind speed and the use of power electronics present issues related power quality in wind turbine application. Following to the fact that there have been remarkable increase of wind energy in the electrical energy production worldwide, the effect on power quality and power system stability caused by wind power is considered significant, and hence the evaluation of this effect is crucial and obligatory. In order to examine and evaluate the characteristics of power quality of grid-integration of wind power in a persistent and authentic manner, several guidelines were introduced and established. One of the widely used guideline to define power quality of wind turbine is IEC standard 61400-21. Moreover, power system operator demands wind turbines to tolerate a certain voltage dip in some countries.

The wind turbines concepts such as doubly-fed induction generator wind turbine and the direct driven wind turbine wind turbine with a permanent magnet synchronous generator are considered as the most promising concepts among other wind turbine types since they can operate in wide range of wind speed.

The major goal of this PhD work is to examine the power quality character aspects of these wind turbine concepts. The power quality problems were calculated according to that devised by IEC- 61400-21 and then compared afterwards. The research includes the evaluation of the following power quality characteristics: voltage dip response, current harmonics distortion, control of active and reactive power and voltage flicker. Besides the IEC-standard 61400-21, the study also looks into the short-circuit current and fault-ride through with specifications provided by some grid codes, as power system stability is greatly influenced by these aspects.

In order to achieve the research's goal, a reliable dynamic model of wind turbine system and control are required. Thus a complete model for both wind turbines systems was developed in PSCAD/EMTDC simulation-program which is the fanatical power system analysis tool, which can achieve a complete simulation of the system dynamic behaviour from the wind turbine. Two controllers are adopted for wind turbine system, converter control and pitch angle control. The converter controlled by a vector control in order to regulate the active and the reactive power whereas the pitch control scheme is put to function to limit the aerodynamic power in high wind speed. The ability of providing adequate state steady and dynamic performances are what wind turbine assures, as examined by simulation results, and

via this, problems related to power quality caused by integrating wind turbines to the grid can be studied by wind turbine model.

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List of Abbreviations

DFIG	Doubly-fed induction generator
PMSG	Permanent magnet synchronous generator
PCSAD	Power System Computer Aided Design
EMTDC	Electromagnetic Transients including DC
IEC	International Electrotechnical Commission
MW	Mega watt
WT	Wind turbine
GSC	Grid side converter
RSC	Rotor side converter
Ref	Reference
EMF	Electromotive force
MMF	Magnetomotive force
THD	Total harmonic distortion
SVPWM	Space vector pulse width modulation
SPWM	Sinusoidal pulse width modulation
HCC	Hysteresis current control
PLL	Phase-locked loop
VSC	Voltage source converter
d-q	direct-quadrature
MPPT	Maximum power-point tracking
IGBT	Insulated Gate Bipolar Transistor
GTO	Gate turn-off thyristor
FRT	Fault Ride through
DC	Direct current
ESS	Energy Storage Circuit
SCC	Short circuit current
WRIM	wound rotor induction machine
AC	Alternative current
r.p.m	Revelation per minute
RFPM	Radial flux permanent magnet

AFPM	Axial flux permanent magnet
TFPM	Transverse-flux permanent-magnet
RRF	Rotor reference frame
PWM	Pulse width modulation
FOC	Field-oriented controller
DTC	Direct torque controller
DPC	Direct power controller
PI	Proportional-integral control
SVRF	Stator voltage reference frame
PCC	Point of common coupling
MVA	Mega volt ampere
SFRF	Stator flux reference frame
STATCOM	Static synchronous compensator
MV	Medium volt
HV	High voltage
KHZ	Kilo hertz
DFT	Discrete Fourier Transform
sec	second
TSO	Transmission system operators
m-sec	millisecond
RMS	Root main square
Kv	Kilo-volt
m/sec	meter per second
VSI	Volt-source inverter
MVAr	Mega volt ampere reactive
KA	Kilo Ampere
FSWT	Fixed-speed wind turbine
SCIG	squirrel cage induction machine
WRIM	Wound rotor induction machine

List of Symbols

P_{tur}	Aerodynamic power
P_{st}	Short-term flicker
P_{lt}	Long-term flicker
k_{ψ}	Grid impedance angle
p.u	Per unit
ρ	Air density
r	Turbine radius
C_p	Power coefficient
V	Wind speed
λ	Tip speed ratio
β	Pitch angle
W_{tur}	Turbine rotor speed in radians
J_{Gen}	Generator inertia
J_{tur}	Turbine inertia
D_{shaft}	damping coefficient
K_{shaft}	Shaft stiffness
K_{gear}	Gear box ratio
Θ	shaft angular position
θ_{Ref}	Pitch angle reference
V_{shadow}	equivalent wind speed due to tower shadow
V_{sheer}	wind shear component
a	tower radius
θ	azimuthal angle
X	Blades-tower distance
α	wind shear empirical
H	rotor hub height
Ψ_{PM}	the flux linkage
$\underline{E}$	Induced voltage
X_s	Stator winding reactance
R_S	Stator winding resistance

P	Pole number
I_S	Stator current
ω_{gen}	Generator angular speed
ω_e	Electrical angular frequency
$\underline{Vs}$	voltage at stator terminals
V_{qs}	Quadrate component of stator component
V_{ds}	Direct component of stator voltage
i_{qs}	Quadrate component of stator current
i_{ds}	Direct component of stator current
Ψ_{qs}	Quadrate component of induced flux linkage
Ψ_{ds}	Direct component of induced flux linkage
T_e	Electromagnetic torque
L_d	Direct inductance
L_q	Quadrate inductance
L_s	Stator inductance
X_d	synchronous reactance
$X`_d$	Transient reactance
$X``_d$	Sub-transient reactance
m	modulation index
C	Capacitor capacity
S_n	S_n Nominal power
V_{DC}	DC link voltage
V_{AC}	Nominal generator voltage
ΔV_{DC}	Acceptable ripple in DC voltage
T_{ref}	Optimal torque reference
V'_r	Rotor voltage referred to the stator
I'_r	Rotor current referred to the stator
I_m	Magnetising current
$R_{r\sigma}$	Rotor resistance referred to the stator
$X'_{r\sigma}$	Stator leakage reactance
X_m	Magnetizing reactance
S	Generator slip
P_m	Mechanical power

P_r	Rotor power
P_s	Stator power
ω_s	Stator angular frequency
ω_r	Rotor angular frequency
Ψ_{qr}	Quadrature component of rotor flux linkage
Ψ_{dr}	Direct component of rotor flux linkage
L_r	Rotor inductances
L_s	Stator inductances
L_m	Mutual inductances
$L_s\sigma$	Stator leakage inductance
$L_{r\sigma}$	Rotor leakage inductance
$C(\Psi_K, V_A)$	Flicker coefficient
S_K	Short circuit ratio
S_N	Wind turbine nominal power
Ψ_K	Grid impedance angle
V_A	mean wind speed
N_{WT}	Number of wind turbine
E_{PSTI}	Short-term flicker limit
E_{PLTI}	Long-term flicker limit
$k_{f\ (\psi k)}$	Flicker step factor
$ku_{\ (\psi k)}$	Voltage change factor
U_{max}	Maximum o RMS of the phase-to neutral voltage
U_{min}	Minimum RMS of the phase-to neutral voltage
U_n	Nominal phase-to-phase voltage
N_{10m}	Maximum number of switching operations within a 10 min period
N_{120m}	Maximum number of switching operations within a 120 min period
T_p	Transient time period of a switching operation
d	Relative voltage change (%)
I_N	Rated current
β	Exponent associated with summation of harmonics
I_h	harmonic current distortion
n_i	Ratio of the transformer at the i'th wind turbine
$P_{0.2}$	Maximum measured active power (0,2 sec average value)

P_{60}	Maximum measured active power (60 sec average value)
P_{600}	Maximum measured active power (600 sec average value)
$P_{current}$	Actual active power measured
$P_{t=0}$	Power measured just before the fault
$U_{current}$	Measured voltage during fault
$U_{t=0}$	Voltage before the fault
I_Q	Reactive current
I_{Q0}	Reactive current before the fault
U_0	Voltage before the fault
U_n	Rated voltage
$T'_{r.CB}$	Transient time constant
R_{CB}	Equivalent crowbar resistance
ΔT	Time of the first peak
T'_s	Stator transient time constant
T'_r	Rotor transient time constant
i_{max}	maximum rotor fault current
f_{DC}	Harmonics frequency at DC converter's sides
f_{AC}	Harmonics frequency at AC converter's sides

Chapter 1 Introduction

The public debates carried out in recent times place a lot of stress on the traditional means of energy generation that rely on fossil fuel sources. In the traditional electrical energy generation, CO2 is usually released, which has a detrimental effect on global warming. In addition, even though there are limited fossil fuel resources, it is likely that there will be a high demand for energy, particularly by the countries that have recently become industrialized, for example, China and India. This is why European countries are using renewable energy sources to a larger extent. One of the most widely used renewable sources of energy is wind power, which is being used to a large extent in different countries like China, USA and Germany [1]. It was found in [2] that there was a large increase in the wind power installed all over the world in the past few years. It was shown that the amount of power generated increased from 23,900 MW in 2001 to 486,749 MW in 2016, signifying an increase in installed wind power capacity by almost twice in the past 15 years. It was found that China had the largest wind power capacity at 33.6%, followed by USA (17.2%) and Germany (10.45%). In addition, it is evident that comparatively high degree of wind energy penetration within the electricity grids has been attained by the European countries [3]. It is also expected that there will be further wind power installation offshore with greater number, such as in the European coasts. This prominent rise in the wind power capacity is because of the greater number of installed wind turbines, and because of the increased size of the wind turbine. In the previous three decades, there was a significant increase in wind turbine size with respect to turbine power and rotor diameter, from 15m to 160 m [4]. In the present times, the usual power of wind turbines is between 1 MW to 3 MW, and the rotor diameter is over 60 m. In addition, 5 MW wind turbines are already installed, suggesting that even greater units can possibly exist.

The first wind turbines generation is fixed speed where the wind turbines operate in very narrow range of wind speed, however those of last generation function with variable speed can accomplish an optimum aerodynamic efficiency over a wide range of wind speeds. Variable speed wind turbines have a complex electrical system in comparison to fixed peed wind turbine. They are typically equipped with power converters which control the generator power. The use of variable-speed wind turbines has several advantages such as: less mechanical stress on the wind turbine, improved power quality and increased energy capture. The drawbacks are the cost and the loss of power electronics.

The existing PhD thesis considers mega-watt class wind turbines with 3 MW rating power, having the turbine's rotor radius of 45m, as these are indicative of the latest wind turbine design.

1.1 Problem Statement

By nature, wind energy is a fluctuating source, just like majority of the renewable power sources. Therefore, it has a distinct function in the power station in comparison to the traditional power generation units. Due to the fluctuating wind, variation is brought about in the active power from WTs, causing a fluctuation in voltage. This may lead to what is known as flicker. In addition, harmonic emissions are considered to be a power quality issue for contemporary variable-speed wind turbines due to the existence of power electronics. In addition, WTs are normally connected to the grid at remote terminals, which is at a distance from central loads or traditional generation. This is causing the utility companies to show be hesitant in injecting that type of power with unpredictable behaviour and to examine the related power quality aspects. In addition, because of the large share of wind power in utility grid, additional difficulties are created for power system operators, as they need to make sure that there is a reliable and consistent grid system in place. As long as just small and single wind power units are set up in the power system, the wind power has no effect on the working of the power system and it is easy to integrate it. Nonetheless, when a considerably high level is attained by the wind power penetration and traditional power production units are replaced, it becomes difficult to make sure that grid integration can occur without any issues. This means that WTs should have the ability to exhibit the same behaviour during grid failure as that shown by confidential generator units. Therefore, the way wind power affects the power system becomes evident and should be dealt with.

Keeping in view the significance of WT power quality aspects and the need to have stable and replicable recording of the power quality features of wind turbines, several directives were issued, for example the IEC 61400-21. In these directives, a typical process to carry out power quality assessment of wind turbine needed for grid-connected functions are given. The different power quality factors are included in various groups, as per the time frame of the event being tested. In addition, in those countries that have a huge amount of wind power, grid codes are being added by power system operators, and these define the required capability of the wind turbines to remain connected during fault which well identified as fault ride-through. They mainly address the way wind turbine controller and the turbine's protection mechanism should be developed such that the wind turbines stay coupled to the network, even when there are grid faults.

The question that should to be highlighted is how the wind power is going to contribute to power quality and how to affect the power system stability. It has been found in different published research pertaining to this subject that the WTs integrated into distribution networks can have an impact on operations in these networks in various ways. It has been found in these studies that the embedded generators: i- contribute to power quality issues, ii- cause problems to power system stability, iii- may raise the fault levels to an extent that makes it necessary to reinforce, iv- need new protection practices so that the network can be protected from abnormal conditions like faults and islanding conditions.

Contemporary wind turbines are likely to be variable speed wind turbine that have power electronic interface that raises the control possibilities and makes wind turbines provide active support to the grid. The power quality's guidelines that establish wind turbine requirements make it important to assess and determine the way variable speed wind turbine can affect power quality.

1.2 Scope of Research

The objective of this thesis titled "Comparative Evaluation of Different power Quality Issues of Variable Speed Wind Turbines" is to examine and contrast the power quality features given by IEC-61000-21 standard pertaining to variable speed wind turbines. This study includes two promising variable speed wind turbine concepts, i.e. the doubly-fed induction generator and the multi-pole permanent magnet synchronous generator wind turbine concepts. The current research is important for practical purposes because of the significance of power quality study and the fact that these wind turbine concepts accurately signify the latest generators for variable speed wind energy conversion systems. With respect to the typical perspective, it is important to measure and assess each power quality feature in specific condition so as to provide reliability. Hence, it is vital to precisely simulate the WTs and examine how they interact with the grid. For this simulation, modelling and control of WTs for power system is needed, including electrical and mechanical aspect of WTs system.

1.3 Aim of Research

The present research seeks to measure and contrast power quality issues for variable speed wind turbines that are installed with DFIG and PMSG, as per the IEC 61000-21 standard. In addition, it also evaluates the significant problems associated with each kind of the wind turbines specified in case a fault takes place, as well as the fault ride-through abilities of every wind turbine according to some grid codes. The short-circuit current contribution of different wind turbines types is also taken into account.

1.4 Research Objectives and Methodology

To carry out valid power quality measurement and its effect on power system, it is vital to have a proper modelling and controller for the wind turbine. Hence, three key problems arise from this research work: modelling, control, and power quality measurements.

- **Modelling**

To determine the effect of wind turbines on power quality, precise model of wind turbines is need to employ dynamic simulation. This model should correctly signify the dynamic behaviour of the wind turbines so that critical operation conditions can be determined on one hand, and the dynamic performance can be enhanced on the other hand. Therefore, wind turbine models must be created and executed in particular power system simulation tools so that the study pertaining to the wind turbines' relationship with the power system can be facilitated. Power system software tools develop the foundation for power system simulations and permit consistent state load flow assessment, in addition to dynamic computation of the system. In these kinds of power system simulation software, power system aspects like bus-bars, cables, lines, transformers or traditional generation units are usually built-in. On the other hand, new renewable power generation units such as wind turbines are usually not included in the all power system simulation software tools. Therefore, this present work seeks to create complete dynamic simulation models that can be incorporated into the power system tool so that the effect of the wind turbine's power system can be precisely tested and evaluated. In this research, the simulation tool that has been selected is the dedicated power system tool "PCSAD EMTDC". The idea of the pitch-regulated variable speed wind turbine with power with power-electronic interface is mainly adopted in contemporary wind turbines. Greater control abilities are provided by this concept, which permits the wind turbine to offer power system ancillary functionalities. The variable speed wind turbine with doubly-fed induction generator (DFIG) and the multipole permanent magnet synchronous generator (PMSG) have been chosen for this study as they represent variable speed wind turbine ideals. A modular structure is adopted for the modelling, which suggests that certain turbine elements are individually modelled. The mechanical system model can be adopted for the two concepts, whereas the electrical system and its embedded control are separately modelled for every concept. The turbines' dynamic behaviour can be examined using the comprehensive simulation models. The control strategies are designed on this basis, (vector control) to study the variable speed wind turbines' dynamic performance and the way they interact to the power system.

- **Control**

In this study, the fundamental control strategy for normal uninterrupted operation is to make the wind turbine's energy production optimal at different wind speed operation. In addition, the controller is required to subsidise the grid during critical condition by providing reactive power. In the present times, wind turbines are needed to take part in the power system as active components, which is just like the traditional power plants. This problem involves different aspects, however, in this project, the behaviour of wind turbines when there is a dip and fault in voltage is examined. In addition, fault ride-through deals with the regulation and protection of the turbine when grid faults occur, so as to ensure the wind turbine stays linked to the grid in case of grid faults.

- **Power quality measurements**

According to the guideline 61000-21, power quality measurements are needed for wind turbine in various operations, on the basis of the power quality characteristics. Various grid impedances are used during voltage flicker to validate the wind turbine flicker emission during strong and wear grid. In addition, the voltage dip issue necessitates connecting the wind turbine to an impedance to cause a decrease in the terminal voltage as required by the standard. Therefore, various case studies are performed to which the wind turbine models are connected.

1.5 Main Contributions to the Knowledge

Integrating of wind turbine to power system affects the power quality and stabilities of the utility grid, the fluctuating source of wind speed and power electronics are the main cause for poor power quality.

Several studies addressed a few power quality problems caused by wind turbine. It was proven that flicker is most issue of fixed speed wind turbine whereas the harmonics distortion is the main drawback of variable speed wind turbine. However, none of these studies covered the all power quality issues of modern variable speed turbines. This research is the first to study, evaluate and compare the power quality issues of variable speed wind turbine with permanent magnet synchronous generator and doubly-fed induction generator wind turbines according to the standard 61400-21.

A comprehensive study, modelling and a series of simulations have been done to determine these issues and to investigate how every wind turbine type contribute to every power quality aspect.

The contributions of this PhD research to knowledge are highlighted and concluded as following:

- It was revealed by this work that both PMSG and DFIG have low flicker emission during continuous operation in compliance to flicker limit stated by the standard IEC61000-3-7. DFIG has advantage of lower flicker emission to PMSG. However, during switching operation, PMSG has better performance during switching operation because of complete-isolation from the grid which results to lower voltage step factor and flicker step factor.

- The results demonstrate that both wind turbine emit current harmonics, In contrast, DFIG causes higher harmonic distortion than PMSG.

- This study reveals, that PMSG and DFIG can follow a given set points of active or active power as specified by IEC 61400-21 very quickly and precisely.

- It was proved by this work that PMSG has a smooth performance when it exposed to a voltage dip, this because the inverter achieves fully isolation between the generator and the grid and can control the current to a certain value. On the other hand, FFIG has a large inrush and reactive power consumption during voltage dip as a result of direct connection between the stator winding and the grid.

- It was demonstrated by this work that PMSG has much less short-current contribution of WTs when it exposed to sever symmetrical three-phase fault, the inverter decouple the wind turbine from fault. In contrast, DFIG has much higher fault current because of direct connection of the stator to the grid. The magnitude of DFIG fault current depends mainly on leakage inductance of the stator and rotor, the stator and rotor transient time constants determine the time of fault current decay.
- This study reveals that PMSG and DFIG are capable of being connected to the grid during voltage dip defined by the British, German and Danish grid codes and they are compliant to FRT defined by theses grid codes. However, DFIG cannot support the reactive power stated by British and German codes because of protection scheme whereas PMSG can supply reactive power during fault as it independent function of the inverter.

1.6 Outlines of Thesis

This PhD research is structured as follows:

Chapter 2 presents a literature review of selected studies. These studies concentrate on the various power quality issues claimed by IEC-61000-21 and short-circuit current. In addition, the chapter presents a summary of the problems pertaining to Simulation and Modelling.

Chapter 3 presents the various marketable wind turbine concepts applicable and their distinct features in. The mechanical systems of variable speed wind turbines comprise of the aerodynamic and drive-train, which were also explained in the Chapter.

Chapter 4 presents the electrical system and control of variable speed permanent magnet synchronous generator wind turbine concept along steady state and the dynamic theory.

Chapter 5 presents the variable speed wind turbine with doubly-fed induction generator including the theory of generator’s steady state and dynamic performance.

Chapter 6 explains the power quality issues in conformance to the IEC-61400-21 standard that pertained to wind turbines and their assessment. In this chapter, seven issues linked to power quality that arose due to wind turbine integration were discussed, i.e. flicker; existing harmonics; voltage drops; active power; reactive power; grid protection and reconnection time. In addition, the process needed for measuring and evaluating these issues was also presented. Consequently, the roles performed by short-circuit current and the requirements for fault ride-through ability for wind turbines were introduced. Finally, the requirements for FRT ability which involved British, Danish and German grid codes were discussed.

Chapter 7 explains the various parameters used in the simulation model in the earlier sections. These comprised of drive-train system, aerodynamic system, back-to-back converters and their regulations and the standard for grid synchronization. The case study used for the simulation model and the program was briefly presented. Consequently, the simulation outcomes for both wind turbines during standard operation were presented to verify the control mechanisms as given in Chapter 4 and 5. Finally, the simulation findings for power quality aspects given in Chapter 6 were performed and explained.

In Chapter 8, “Conclusions” and a summary of the overall thesis is given, including recommendations with respect to future research and studies.

1.7 Author’s Publications

[1] I. A. Ahmed, A. F. Zobaa and G. A. Taylor, "Power quality issues of 3MW direct-driven PMSG wind turbine," *2015 50th Int Universities Power Engineering Conf (UPEC)*, Stoke on Trent UK, pp. 1-6, 2015.

[2] I. Ahmed, A. F. Zobaa. "Comparative power quality study of variable speed wind turbines." *Int. J. Energy Convers (IRECON)*, Vol. 4, no. 4, pp. 97-104, 2017.

Chapter 2 Literature Review

The wind energy has already a huge penetration in the electrical power generation, especially in certain developed countries i.e. China, U.S and Germany. With the growing awareness and use of wind power generation in the power system it is becoming significant to address problems related to integration of this energy source. In the past decade, the part played by the wind power in the electric power generation has completely evolved. Nowadays the large wind power units (megawatt class) are linked straight to the utility grid replacing the conventional generation units from distribution system. There is a need to make adjustments in the large wind farms so that they can undertake the tasks of the conventional power stations, for example active and reactive power control, Harmonics, voltage flicker and ext. The power quality standards and grid codes were established by transmission system operators for how to carry out control responsibilities of wind turbines integrated to the grid. For ensuring the compliance with the power quality standards and grid codes for assessment and improvement of grid integration of wind power, modelling wind turbine in power system simulation tools are required to assess the dynamic behaviour and the effect on power system.

The power quality problems based on IEC61400-21 standard and the issues of integrating wind turbines are the main focus of this chapter; the power quality problems of wind turbine mentioned in IEC61000-21 are elaborated along with a summary of short-circuit current. Other factors effecting wind turbine modelling in operational power system simulation software are also discussed in this chapter.

2.1 Power Quality Aspects of Wind Turbine

With the growth of wind power industry and installation of larger units, the wind power has evolved to a better position in power systems. The traditional setting of wind turbines where they were connected to the utility grid has been discussed before. Now, wind farms with large number are coupled to the power system directly, emerging as a powerful and convenient alternate for the traditional centralised power plants. This advancement has positively influenced the power system operation and power system stability. Thus far, due to their negligible effect on power system stability and voltage quality, low scale wind power units were directly integrated to the transmission system. But with larger wind farms (several 100

MW) influence on the power system has also increased; therefore, they are now being connected to the transmission system. Listed below are some reasons behind such measures [5]:

- ❖ Installation of larger wind turbines in larger units including offshore wind farms. Thus, wind power has become more important.
- ❖ Installation of wind power far from the transmission lines which makes a weak grid connection, for instance offshore wind farms at seaside parts in long distance from the customers.
- ❖ Wind power mainly depends on the prevailing wind and it can fluctuate based on the conditions; therefore, must be balanced.
- ❖ The gap between generation and demand is the main reason for the variation in the node voltage and current, which must be adjusted properly.

IEC61000-400 is most commonly followed guidelines for the power quality of wind turbine and according to these guidelines the power quality depends on following factors:

Flicker

Due to dependence on the weather and prevailing wind, the wind turbines may experience fluctuations in the output power. The voltage fluctuations and flicker with the deviations in the produced power of the wind turbines flowing into the grid are mentioned in Ref [6]. The wind gradient, the wind speed fluctuation and the effect of tower causes the fluctuations in the output power, which is responsible for the flicker produced by wind turbines in normal operation [7]. The drop in turbine's power will occur three times per single rotating cycle for wind turbine with three-bladed (this frequency is known as $P_{3)}$ because of the combined effect of the wind gradient, the wind speed fluctuation and the effect of tower . The resistance to the wind flow due the wind turbine tower is known as the tower shadow effect and it causes disruption in the flow of wind equally in up and down direction. The speed of wind remains constant at significant distance from the tower, it increases when approaching the tower and upon coming closer to the tower it starts to decrease. This shadow effect can be illustrated by the help of a Fourier series with harmonic multiples of p_3 frequency. When the blades of the wind turbine are downwind of the tower the tower shadow effect will be of greater significance. The wind speed gradient along the height of the area swept by the blades produces oscillations in the output torque of wind turbine, this phenomenon is known as wind shear. The wind speed gradient might be described in polar coordinates centred at the hub elevation by the binomial series [8]. The wind profile is treated like a periodical fluctuating function of the time which has harmonic multiples of p3 frequency by the rotor. The frequency domain is used for the evaluation of the output power of grid-integrated wind turbine [9, 10]. Along with the significant periodic component p_3 other p_6, p_9, p_{12} and p_{18} components are also visible in the results. Appearance of the p1 component can be correlated with the possible unbalanced rotor or that the torque produced by one of the blades is greater than the others. There is also a presence of tower resonance frequency which may be initiating from a side-ways oscillation of the turbine.

The level of flicker varies from wind turbine type to another. The variable speed wind turbines produce lower flicker compared to the fixed speed wind turbines [7]. The flicker levels can be lowered up to four folds by using a wind turbine having variable speed operation [11]. For the fixed speed wind turbines the flicker contribution from the p_3 component is rather substantial. The p3 pulsations in the output power are also reduced by using variable speed wind turbines [7].

The flicker emission in relation to variable speed wind turbine during continuous operation have been the focus of many studies, where the factors affecting the flicker, including the features of the wind like mean wind speed and turbulence intensity, and the conditions of the grid such as short circuit capacity, grid impedance angle are discussed.

The flicker level of PMSG WT is directly related to the rise in the wind speed until the wind speed reaches the rated value, which is when the wind turbine reaches its maximum power. When the wind speed increase beyond the rated value, the pitch control will smooth out the variation in output power and, the flicker will be reduced consequently [12-16]. Many researchers have focused their studies on the flicker emission of DFIG WT, wind speed increases is also directly related to the flicker emission until it reaches rated speed [7, 17-21], then it reduces a little [7, 13, 18, 19].

The flicker emission of wind turbines is considerably effected by the turbulence intensity and with increase in the turbulence intensity for PMSG WT [10, 12, 17] and DFIG WT [7, 13, 18] the flicker level increases as well.

The flicker emission is also influenced greatly by the short circuit capacity such that the higher short circuit capacity ratio is, greater will be the strength of the grid to which the wind turbine is coupled. The PMSG and DFIG has been studied by the authors [12, 13] and [7, 13, 18] respectively under different capacities of short circuit. The wind turbine produced greater flicker in weak grids in comparison to that in the stronger grids as it was anticipated and it can be said that flicker level has an inverse relation with the short circuit capacity the wind turbines is connected.

The importance of grid impedance angle can be assessed by the fact that the changes in voltage from the active power flow have the potential to be cancelled out [7]. A unity power factor is when no injected nor drawn reactive power from the grid. Usually variable speed wind turbines are operated with unity power factor, in this case, the resistance parameter of the grid impedance acts as the determining factor as it has a significant influence on the wind turbine flicker emission. The operations of DFIG WT at unity power factor and different k_{ψ} from 0 to 90 degree have been discussed by [7, 17, 22]. The results suggested that flicker is decreases with increase in the k_{ψ} till it reaches 90 degree. Similarly, the PMSG WT flicker emission decrease with increase in $k\psi$ as well [12-14, 16, 23].

Many other authors have also invested their research in comparing the flicker emission of PMSG and DFIG WTs. In [22], the P_{st} of two different wind farm was calculated, where one has PMSGs and FSIGs with capacity of 200.25 MW, the second wind farm has the DFIG with capacity of 49.5 MW. The P_{st} calculated from the first farm was 0.16, which is relatively lower in comparison to the DFIG wind farm having 0.35 P_{st}. The P_{st} of PMSG and DFIG with same nominal power (1.5 MW) was compared by the author of [24], and the DFIF had lower P_{st} emission. Another author [25] calculated both PMSG and DFIG (with 2 MW) to have approximately equal P_{st} emission.

Harmonic Distortion

The variable-speed operation of wind turbines was made possible with the advancement of the power electronics and their use in wind energy extraction. The doubly fed induction generator (DFIG) or full-power converter is used alternatively with the variable-speed wind turbines. A major concern with modern variable-speed wind turbines is the harmonic distortion. It is fundamental to evaluate and analyse the harmonic emitted from variable-speed wind turbines in order to predict the effects of this harmonic emission on the electrical grids where they are connected.

Variable speed wind turbines emit higher harmonics emission than fixed speed Wind Turbines [26]. The characteristics and the control of the Wind turbine power converters and the harmonic filters used are the factors that determine the shape and frequency range of the spectrum [27].

The harmonics appears on both stator and rotor currents in DFIGs [28-43]. The harmonics and inter-harmonics are produced by GSC, RSC and the machine itself, by the simple act of turning on the power electronic devices [37]. The performance of DFIG is considerably affected by distortion of the stator and rotor terminal [33]. The DFIG harmonics emission is also effected by the supply harmonics [35].

Ref [34] claimed that there are two causes for the rotor harmonics, EMF induced in the rotor by stator driven airgap field, and rotor excitation. Additionally, the harmonics in the rotor side are caused by the core saturation and non-sinusoidal flux distribution [39]. The bad quality of RSC can be linked with rotor circuit harmonics. The design of the converter and modulation method used can be held responsible for the poor quality [33]. The switching of the grid-side converter can also be linked with the rotor circuit harmonics according to author [28]. This depends upon the technique with which the amplitude acts as a determining factor for the magnitude of every discrete frequency. The amplitude generating techniques include the switching instant (hysteresis, triangle, space vectors, etc.), converter topologies (two or three level) and switching scheme (polar or unipolar) [37]. Harmonics field will induce EMF in the rotor winding; this as a result will be responsible to originate range of rotor driven harmonics field in the rotor coordinate system [36]. The rotor harmonics can also be linked back to the wind turbine operation, the variation in slip is associated with the variations in the speed of the generator, and there is an inverse relation between the slip and the overlap angle whereas that between the slip and the current harmonic of the rotor is direct, in other word, as the slip increases, the overlap angle decrease and the harmonics in rotor current increases [38].

The operation of the rotor-side converter in DFIG is relevant to the stator current harmonic, however, the operating slip of the generator is used to modulate the frequency because frequency component will transfer from rotor side to the grid side [31]. The interaction between the stator and rotor interaction causes the frequency in the stator harmonics. In the stator circuits non-integer harmonics are induced by the rotor converter owing to the operating slip of the machine [37]. The 3^{rd} harmonics is sequence of nonlinear magnetisation characteristic of the iron core, which appears in the DFIG stator voltage [30]. For removing the third harmonic and its multiple the three phase rectifier bridge is employed in DFIGs [28].

Author of [39] has discovered in addition to those mentioned above, there are some other source for stator harmonics including flicker, unbalanced voltage and voltage distributed during fault. A sub-harmonic current in the stator (and supply) is induced due to the interaction between the airgap flux and rotor current harmonics, this current is non-integer multiple of the nominal frequency [44]. The MMF space harmonics are caused by the none-sinusoidal distribution of the stator and the rotor winding [37].

Scientists [34, 38, 40, 45] have provided evidence supporting that harmonics of lower order are the dominated in DFIG current harmonics; and the values of the 5^{th} and 7^{th} harmonics are relatively high [40]. The voltage drop over the power devices, the distorted voltage of PWM converter caused by output voltage transition slope, turn on/off time and voltage drop the active switching and freewheeling diodes are some of the reasons for the generation of low frequency harmonics generation [33]. The magnetic saturation with machine may also cause the low order frequency 3^{rd}, 5^{th} and 7^{th} generation [34]. Author [38] states that when modulation index exceeds 1, low harmonics are generated given that the network voltage is unbalanced and dead-time to avoid short circuit transaction. It is undeniable that several problems arise due to these harmonics, however, it is also important to note that they are also responsible for the production of the pulsating torque to synchronous speed particularly 7^{th}, 11^{th}, and 13^{th} [38].

In DFIG current the chances of having a high-order harmonics are greater as the PMW technique is involved [28]. When the sub synchronous mode was compared with super-synchronous mode high, the harmonics content was higher in the former due to the extensive use of the converter [32]. A low-pass filter can be used to remove the noise in high-frequency band this can be done utilizing the principle that noise frequency and nominal frequency are separate [33].

The THD of DFIG was discussed in the reference and it was discovered that THD is high when the current is low [42]. In case of distorted supply voltage, the chances of worse THD are greater [43]. Ref [41] however claimed that by the use of Active filter The THD can be considerably reduced, in his research the THD was mitigated from 24.86 to 8.08% by the use of Active filter for 5^{th} and 7^{th} order.

When the PMSGs are being considered the grid-side convert is responsible for the production of harmonics. The grid-side convert is typically a six-pulse inverter. The harmonic and inter harmonic currents can be linked back to the operation of power electronic switching devices. The topology of the converter and switching strategy used during operation without any disruptions are the factors on which the characteristic harmonics depend. The distinctive harmonics in a six-pulse converter are of the harmonic order 6n ±1, in which n represents a positive integer [27, 46, 47].

Many researchers have studied and discovered that the low order frequency 5th and 7th harmonic is subjugated in PMSG current while the values of the 5th order are higher [27, 46-48]. A wind farm up to 10MW with PMSG was studied by [46] and it was discovered that 3rd harmonics has a non-negligible value (1%) in comparison to the 5th (1.5%) and 7th (1.2). The current harmonics of a 1.5 MW PMSG were studied by [27], which led to the discovery that 11th and 13th appear with 5th, 7th in PMSG with higher 5th (3%). Ref [48] measured the harmonic current of 2MW PMSG Wind Turbines at rated current and the results showed that the low order harmonics had following values 5th (0.4%), 7th (0.3%) and 11th (0.47%).

The current harmonics of PMSG for the same generator and different converter topologies and control strategies were compared with another author. When the PMSG Wind Turbines used a current-source inverter higher low-orders harmonics were obtained in comparison to when voltage-source inverter was used 3rd (2%), 5th (8%) and 7th (8%) [47]. Melicio et al [49] conducted an all-inclusive simulation study on three different topologies of power converter: multilevel, two-level and matrix to study their fractional-order control strategy for the variable-speed operation of PMSG Wind Turbines. In this study 3rd harmonic and THD under different wind speed of different power converter topologies and control strategies were compared with one another. The results from the studies showed that the multilevel converter and the fractional-order control technique improve the harmonics emission relatively compared to other converters using a conventional integer-order control strategy.

Ref [50] addressed the total harmonic distortion of PMSG wind turbine, the authors investigated and compared three different techniques used to control the back-to-back converter, which are: hysteresis current control (HCC), space vector pulse width modulation (SVPWM) and sinusoidal pulse width modulation (SPWM). Moreover, DC ink voltage has been used to make comparison between SVPWM and SPWM. The results of these studies concluded that the efficiency of SVPWM is better than that of HCC and SPWM control technique where the THD was 3.6% and the others were 4.68% and 4.95%.

A study was conducted by Tsai el al. [49] where the current THD of PMSG equipped with diode converter was studied, this study differed from other studies such that it did not focus on back to back convert utilised, PMSG equipped with diode has distinguished high level of THD where it reached 35%. It has been discovered that addition of an active filter reduces the THD significantly somewhere between 1.6-4.9%.

Two-variable speed wind turbines were compared in a study on the basis of their harmonics emission. The current THD of two different wind farm fixed and variable speed at rated power is analysed by [50] and the results revealed that fixed speed (1.9%) gives lower values than variable speed (5.6%). DFIG has higher THD when compared to PMSG wind turbine, due to the presence of inter-harmonics [29]. The THD of PMSG and DFIG for different power range were compared by [27] and the results showed that were somewhat equal having a difference of 1%.

Active Power Control

Wind turbines take active part in the grid operation control through regulation of their active power output. In the IEC 61000-21 and grid codes the active power regulation consist of active power control modes, which are responsible for limiting the maximum active power, balancing the active power output, and defining the ramp rates in the upward or downward direction.

The frequency converter controls the variable-speed wind turbine; this frequency converter responds fast to the reference signals. When the fluctuation is reduced through regulation of the generator speed variable speed WTs can operate at maximum power point as the amount of energy captured, efficiency and the power quality are all improved consequently.

There are several control strategies for variable-speed wind turbines. Given below is a classification of these strategies:

- Indirect control strategies: these are managed through torque/speed of the Wind Turbine's generator by d-and q-axis stator currents I_d and I_q in the rotating reference frame.
- Direct control strategies- there is a direct management by torque/speed of the Wind Turbine's generator controlled of stator flux linkage and torque in stator reference frame.

The controllers applied to variable-speed wind turbine systems have been the focus of many studies conducted over the years. A grid-side converter (GSC) controller algorithm was put forward by [51] for a grid connected PMSG. Vector control algorithm is used in the GSC, whereas for compensation of phase difference in voltage between GSC and grid, a PLL algorithm is used. For the verification of operation of the system, the system was simulated where varying active power signals applied to inverter which having differing reactive power operation. The generated active power successfully tracked the applied reference values of active power when the reactive power set to zero. The reactive power is also assumed to have a non-zero value. In these circumstances, the generated active powers can still be successfully follow the various reference active power values having very little and short-term oscillations in active power.

Ref [52] claimed that the delay in PMSG active power and the current response can be enhanced by using a three-phase voltage-source-converter (VSC), the converter is controlled by adopting vector pulse-width-modulation (SVPWM) with current-predictive control approach. Active and reactive current were adjusted such that in the d-q rotating coordinate system that unity power factor is obtained. With the application of the proposed switching algorithm the simulation results revealed that with changes in wind speed are between 12m/s and 14 m/s the active power also changed from 0.6 to 0.8 in just less than 1 sec. It can be concluded that the converter can be controlled with wide input differences that guarantee the stable operation against various disturbances.

Ref [53] introduced an enhanced technique of control of active power for PMSG wind turbine in order to improve damping capability and inertial response in transitory time. The optimized power-point tracking (OPPT) Works by regulating the operating point of the wind turbine from MPPT mode to so-called virtual inertia control (VIC) mode which usually represent by a curve regulating with frequency variation. The stored kinetic energy is estimated by OPPT and then it provides dynamic frequency to improve the grid. The influence on power oscillation-damping capability caused by the VIC can be theoretically evaluated. This control scheme showed faster response of inertial and provided enhanced system damping capability at transient events when it compared to the traditional supplementary derivative inertia control.

The application of direct power control for PMSG, the performance of the controller was verified by MATLAB software is presented by [54]. The reasonable simulation has been achieved showing conformity between measured and reference quantities. The results showed when the reference of active power change from 0.5 p.u to around 0.3 p.u the measured power tracked its reference very fast and great performances with no overshoot fluctuations in the steady state.

Ref [55] has presented a new scheme for vector control, which is based on the vector control rotor-flux-oriented. In the new strategy, the commonly used stator flux oriented vector control is compared against the one that controls the DFIG. It was found that both vector control strategies depend on the estimation of stator-flux, and rotor-flux have been tested on the rotor-side converter (RSC) for controlling the stator active power produced by the generator. MATLAB/SIMULINK was used for modelling and simulating the complete system. Simulation results revealed when power signal shows variation between 0 and 0.7 p.u, the measured power tracked the reference in less than 0.1 sec in both control strategies. By using the rotor flux oriented vector control strategy, the ability of wind turbine to track the active power reference was more accurate than that with the stator flux oriented-vector control technique.

A DFIG wind turbine controlled by direct current vector control technique was introduced by Ref [56], this method established integrated control strategy for all controllers in wind turbine. To validate the efficiency of the developed control method, a simulated system by the aid of Sim-Power System was assembled. Compassion has been performed between the conventional and the proposed control for DFIG wind turbine during stable and fluctuating wind circumstances. The simulation showed by using direct control vector control technique, a better performance can be achieved.

The variations between direct and indirect control of DFIG was done by ref [57]. The results showed that the working produced by direct control is much better than that of the indirect control. It is also much appropriate and is simpler for usage. The disadvantages of the indirect method include its complexity in implementation but are also very useful in giving a realistic approach towards the integration of the rotor current regulation loop which may allow for us to set restrictions on the current by protecting the device that is not allowed by the direct method. Additionally, control loop rotor current can also be controlled by it, since it is rather simple to restrict the greatest quantity of current machine when load is shifting suddenly or in transient.

A new power control for DFIG wind turbine was given by [58] using space vector modulation in order to manage the active and reactive powers replaced between the DFIG stator and the grid, for the confirmation of operating the wind turbine in optimum power point and decrease the Powers and Torque ripples significantly. The SVM control is adopted for rotor-side converter to achieve the active and reactive power control and for voltage regulation of wind turbine. For validating this approach MATLAB-Simulink software was used for modelling and simulation, the results demonstrated a good performance of the proposed control in which the active and reactive power can track accurately the given references.

Ref [59] investigated a vector control with PI (with stator-flux-orientation) controllers for DFIG in which the writer made comparison for the working of the open-loop and closed-loop control of the powers at the voltage drop. The simulated results clearly indicate that the working of the closed-loop power control is much improved at the voltage drop, and it still can track the reference power. This helps in giving consistency to the generated power during the stator voltage drop through wind energy applications and may have lesser control complexity and low cost implementation.

A detailed comparison between the voltage-oriented control and stator-flux oriented strategies for DFIG is put forth by [60]. It was found by the simulation that by using voltage-oriented and stator-flux control, DFIG can achieve a fast-dynamic response and accurate control of stator reactive power and generator torque.

Reactive Power Control

The power quality can be improved and the grid during critical situation can be stabilized with actual reactive power control. However, the reactive power has yet failed to deliver any actual practical benefit, it is found application in voltage adjustment, thus, it can be used to maintain desired voltage level.

Ref [61] suggested a novel strategy to enhance reactive power of PMSG grid-side converter with a matrix converter. Both generator-current (active and reactive) contribute to the proposed method to control the grid-side reactive current. The simulation results by using this given technique for a case study showed that there was increment in all wind speeds by grid side reactive power.

Ref [62] presented that the PMSG active and reactive powers are able to successfully follow the references of both active and reactive power at different operating circumstances, for instance at different rotor-speed and different references of active and reactive power. This study also provided evidence that the wind turbines improve the grid because of its ability of independent control of active and reactive power according to specified references.

Ref [63] addressed the capabilities of both DFIG converter sides to produce reactive power. The authors also proposed new method for the calculation of the reactive power of stator's terminals while the crowbar is engaged a. Following measure must be taken for avoiding this inductive reactive power consumption: (1) a appropriate dc-chopper can be installed to decrease the active probability of crowbar; (2) the stator's reactive currents should be balanced by GSC. The results of stimulation are validated the viability for this proposed control scheme during various operation of reactive power to show the effectiveness of employing dc-chopper, A 1.5-MW DFIG system was simulated. It has been proved that during voltage drops the control of reactive power has a fast dynamic response; moreover DFIG does not draw reactive power from the stator terminal. The importance of the dc-chopper is also shown by comparing the conductance of reactive power.

The reactive power limit of DFIG was calculated by [64] and a novel coordinated control strategy was proposed where that the main reactive controller be used as the grid-side converter and the rotor side converter as auxiliary, after which the current reactive power control schemes of DFIG are given which unify power factor and voltage control through RSC are achieved. In another study three methods employing the two converter's sides regulate the reactive power supply and voltage are evaluated and compared. MATLAB/SIMULINK was utilized to model the controllers according to the results when the WT works at 50% and voltage dip of 50% occurrences, the success of the given control scheme is clear by giving almost 0.55 p.u of reactive power to grid whereas the supply by conventional control is just 0.2 of reactive power.

Ref [65] also examined the capability of DFIG to control reactive power. A DFIG dq Model was built in synchronous coordination system by applying the stator-flux-oriented vector control, whereas the PSCAD/EMTDC simulation software will be used to examine the ability to deliver the reactive power to utility grid. The working of the DFIG system may help in taking part in the system voltage profiles regulation and to give a reactive power to the system.

Ref [66] proposed a new method of voltage control for DFIG. The authors also compared the new method to other conventional voltage controls. Detailed models built in Dig-SILENT Power-Factory Simulations to show how the performance of DFIG during steady state and disturbance situation will be affected by these controllers. Both RSC and GSC controlled the voltage independently or in combination for all types of disturbances. Additionally, the study Verified that during critical situation, the voltage profile was seriously affected by grid impedance angle (X/R) and power control. When both converter parts utilised to regulate the voltage control but without coordination, there is a possibility that one of converter sides might takes the action, this however eventually leads to consuming reactive power by the other converter side. At disturbed situation the crowbar usually restrict or totally block the rotor circuit excitation. Supplying the reactive power form GSC and stator improve PCC voltage and decreases the RSC reactive power demand. However, it is more productive to regulate the reactive power by RSC because will be multiplied by generator' slip at stator terminals.

The reactive power of PMSG and DFIG during fault was analysed and compared by [67, 68]. According to the simulated results the DFIG can enhance the grid voltage throughout disturbance situation, however it is inadequate. Conversely, PMSG has better flexible controllability and consequently is a good fit for filling these requirements

Response to Voltage Dip

During a voltage dip in the grid, the active power which can be injected is affected by this drop and limited. Consequently, a surplus of active power is experienced. Under these conditions, WTs can get disconnected from the grid. According to IEC61400-21, a defined voltage that indicates a restricted profile of voltage dips should be applied for a WT, the WT should operate without disconnecting and supply a reactive current. In case of disconnection from wind farm due to fault conditions, the grid voltage will deeply decrease. The grid voltage can also be improved if a reactive current can be provided by the WT.

The structure of variable-speed wind turbines is different and so is the connection to the grid responsible for making them behave in different ways to voltage dip, for PMSG wind turbine, the full-scale converter decouples the generator terminals from the grid. For improving the performance of PMSG during voltage dip different methods have been proposed in light of previous studies.

The employment of Pitch-angle control in wind turbine system is to avoid the over-speed of the generator's rotor which can be achieved by turning the blades to reduce the power coefficient of wind turbine. The response of pitch angle control are greatly restricted when the wind turbine connected to weak grid because of the great dynamic power causing from backing up the power throughout fault despite the fact that pitch control mechanism can quickly turn the blades to its maximum values[69].

During a voltage reduction the excess power can also be resolved by DC link capacitor sizing. Ref [70] establishes a direct relation between the required capacitor power and the dip voltage such that the essential size of capacitor will rise if the time of reduced voltage increases. There is a need to resize the fully rated converters. However, the capacitor sizing technique is not a cost-effective and practical solution.

For improving the wind turbine performance during voltage dip, a crowbar can be used on the DC link. To decreasing the extra power and balance the power between the GSC and RSC, a resistor is added in the dc circuit for. The semiconductor switches used by the active crowbar are GTOs or IGBTs which are rather costly [71]. For voltage dips spread over long period of time there is high dissipation of power and active crowbar method might be combine with Pitch angle control for decreasing the aerodynamic power by regulating the blade angle and so that the difference between both the input and output power of the converter will be mitigated as well as reducing dissipating power from braking resistor [69].

Addition of a battery based ESS at DC-link bus is a new method for PMSG is DC Bus Energy Storage Circuit (ESS), this method consume the extra power from DC link or transmit the power to the grid which leads to smooth operation and enhance the capability of FRT [72]. However, ESS method has the potential to be prone to the severity of fault rather than fault type, thus an extra dc-converter can be used for protection as well as adequate sizing of the RSC [73, 74].

Converter control is also can be used for improving the performance of PMSG. According to details in [70] a control of generator-side rectifier is illustrated: the power of generator decreases suddenly in this type of power control by decreasing the generator torque when the voltage at DC bus gets to threshold value. This decrease in the generator torque results in de-loading droop characteristics that must be very quick for discharge a high wind turbine's power in very short time (milliseconds). When the voltage at DC link decreases, The GSC control decreases the current of wind turbines causing a drop in the wind turbine active power, consequently the generator speed is managed to keep up at optimum value.

According to [75] the grid-side converter also plays a part in improving the voltage dip, usually the controllers are made such that they can work in a particular operating range points therefor if grid voltage decreases under the rated values, the point of operation might divers form the designed range which creates a sudden reaction causing the currents to increase and exceed the limitation. A complicated control techniques are applied to GSI to enhance the FRT ability as it has limited ability.

It is stated in Ref [76, 77] that a control strategy which is managed by RSC of PMSG controls the DC link, the grid experienced an intentional fault which is the why voltage drops to 50% and last 0.1s, the results showed neither torque nor rotor speed had remarkable change. With decrease in the terminal voltage the active power reduces also decreases and consequently, the rotor speed is increased and the time 0.1 sec is not enough to react.

The voltage dip issue of PMSG equipped with diode rectifier and presented magnetic amplifier topology for improving the performance during fault has been analysed in [78]. It had discovered that by application of the magnetic amplifier to DC link in order to decrease the number of magnetic elements. The results provide the necessary proof that magnetic amplifier at the DC side is very successful and also restricts the stress on power converter.

The disturbances on the grid can greatly affect the DFIG as there is a direct coupling of stator terminal to the grid. In absence of a protection system, the transient in the stator current is very high at fault because the stator terminals are straight coupled to the network which can affect the DFIG. The transient (from stator) is transferred to the rotor as a result of the magnetic coupling which links the stator to the rotor, the transmitted transient causes higher voltage and rotor currents at fault. It is consequently essential to protect the converter from overcurrent, the rotor winding and the DC bus from overvoltage. Many researchers have focused their work in finding methods for improving the performance at voltage dip for the DFIG.

The rotor crowbar method can be considered as a traditional solution to fulfil FRT requirements [79], [80]. This is the main procedure that is followed by majority of the manufacturers in order to achieve FRT. Even though the crowbar is not an expensive way for protecting both the generator and the converter in fault conditions, it brings some drawbacks that concern the researchers. There is one big issue which DFIG losses the control after the initiation of the crowbar, as a result of deactivation of the RSC. DFIG, in these circumstances, consume much reactive power from point of common coupling, resulting in additional disturbance to grid voltage. Moreover, the resistance of crowbar also must be measured precisely to supply adequate damping with less consuming energy.

Ref [81] gave another arrangement for crowbar in order to solve these problems such that the crowbar is connected to with the stator terminals in series. However, the losses in conduction of the bidirectional switches during normal operation are another concern. All these considerations must be kept in mind while designing the power electronics, to minimize these losses.

The DFIG DC capacitor sizing method is somewhat similar to the crowbar configuration, with the exception of protection form the IGBTs from overvoltage and Energy storage system were discovered by [82].

Ref [83, 84] investigated ESS-based method with the ability for controlling the generator during the fault. For allowing the currents during fault to go through the DFIG rotor circuit, the size of RSC has to be chosen adequately. There is need for additional energy storage devices which would increase the cost and complexity of this system.

Ref [85] suggest that braking resistor method to DC bus with either braking resistor or chopper might be integrated to the DC bus, this method function is similar to the crowbar used in RSC terminals. In this method DFIG transient has become smother and shorter. In case of a fault, rotor-side converter keeps coupling to the system whereas the rotor-currents are controlled twice as much the nominal value. The proper damping of torque oscillation and the peak of torque pulse is 1.5 folds greater than the nominal value which will be much less when done with a crowbar.

Another approach is proposed with modifications in hardware (e.g., chopper) and control schemes [86, 87]. The studies also presented a control strategy which utilizes feed-forward transient current for DFIG’s rotor side with crowbar. Other feed-forward transient compensation terms are injected within the output received from a traditional (PI) current controller at the rotor side converter. This output will then be arranged in line with the transient induced voltage which will produce a least transient rotor current and least record of crowbar disturbance. This new control scheme requires additional computation skills in comparison to the traditional controller.

Ref [88] proposed a configuration which employs a parallel grid-side-rectifier along with a series grid-side-converter. A strong voltage-ride through can be achieved with the combination of these two converters. Just as it happens in the conventional DFIG, a DC bus is created by the rotor slip as it is recovered by the generator side.

Short Circuit Current Contribution

Other than the power quality issues given by the standard IEC 61400-21, one of the major characteristics of wind power plant impact on power system is the short-circuit (SC) current input of the plant for the transmission network under erroneous situations like single, two, and three-phase faults in various network locations,. The relation between the installed capacity of wind power farms and the effects of large-scale wind power integration on the power quality is proportional, as with greater wind power the wind power short-circuit current injected to the system will also be of greater amount. The effects of different types of wind turbines on the power grids vary greatly from one another, there is a need to conduct a study on the short-circuit current characteristics of wind farms. Many researchers have dedicated their research towards the effects of the short-circuit fault on wind farms and the short-circuit characteristics of different wind turbines.

The short-circuit current wave of the asynchronous constant speed wind turbine as compared to the DFIG was given by Ref [89], according to this comparison the short-circuit current from DFIG wind turbine depends on the rotor circuit breaker protecting settings of the rotor side converter. In an instance where the rotor is short-circuited by the rotor circuit breaker, the short-circuit current features of the turbine act as that of the constant speed wind turbine, and the short-circuit current dies out quickly.

The operation characteristics of the wind turbine during the three-phase symmetrical short-circuit fault condition were the main topic in Ref [90] and according the obtained results shows that when exposing PMSG wind turbine to a symmetrical three-phase short-circuit fault, the fault can efficiently be isolated by the of a the frequency converter and the short-circuit current can be injected in precise amount.

In Ref [91] the authors evaluated the fault features of the PMSG and DFIG wind turbine in the single-phase as well as in the three-phase short-circuit fault, this is done by the creation of an electromagnetic-transient model of the D-PMSG and DFIG wind turbine. According to the results the PMSG has the potential of delivering constant sustained fault current and reactive power support to the grids. The DFIG contrarily have the potential of delivering sustained fault current, however, attenuation characteristic of the fault current remain.

The contribution of DFIG wind turbine to short-circuit current was studied by Ref [92]. The author focused on calculating the maximum fault current of the conventional induction generator, a comparison of this generator and DFIG in term of short-circuit ratio was conducted by the study. The study included also a derivation of an estimate equation for determining the highest fault current of DFIG. A comparison was conducted between the values from the proposed method and time-domain simulation, the difference between the two values was roughly 15%.

Ref [93] in their study proposed a non-complicated approach for the calculation and understanding the behaviour of the SCC for different WTGs types. Analyses of different five types of WTGs were carried out. The peak and the settling time of the SCCs is defined and calculated. In view of the results from the variable-speed wind turbines, PMSG can restrict the fault current to a given values as it can be controlled by the inverter. A power converter for a PMSG with full converter based wind turbine is usually designed to limit the output current to 1.1 of the rated current. However, in case of a DFIG, two different crowbar resistance values can be used and according to the results there is an inverse relation between a crowbar resistance and peak current and AC component.

2.2 Simulation and Modelling Issues

This study states that within power systems with high penetration of wind energy, power quality is an important parameter. Proper power system simulation tools are required for the analysis of wind turbine, and there is a need to include wind turbine models into such simulation tools [94]. MATLAB, PSS/E, SIMPOW, PSCAD/EMTDC or DIgSILENT are examples of certain power tools that can be used in wind turbine simulation. Usually these tools have some built-in electrical components which can be employed for modelling wind turbine system. The time frame of the simulation determines the level of detail present in a model. In other word the simulated time frame is choosed according to the purpose of simulation. For instance, if the balancing power of wind turbines is conducted, a long-time frame must be considered for this activity (minutes), on the other hand, if the study focuses on the transient stability, then a small time frame is considered (m-sec). Another important contributing factor towards the power system operation and power flow at a wind farm is the availability of wind energy and the production forecast. These features are related to long term operation of wind turbines and can be seen in wind power contribution to one-days to several days. Nevertheless, the long time-frame is not studied since this study concentrate on power quality of wind turbine during fluctuating wind speeds and during grid faults, which demands much less time. Wind speed fluctuations last for a few seconds to few minutes. Therefore, the response time of wind turbine control for varying situations and their dynamics controllers span over a few seconds. When grid faults conditions and their effects on wind turbines are under consideration, the response time is very small , which spans over a few seconds or sometimes milliseconds is studied. A vigilant modelling of wind turbine performance on the basis of time frame of milliseconds must be done. Therefore, the time frame for the response of the electrical system of wind turbine to fault will also range between milliseconds and seconds after the fault, as the responding time of the mechanical system would be higher because of the larger time constants of mechanical components. In comparison to the grid fault duration, the wind speed fluctuations are slow thus it is important not to consider wind speed changes in grid fault investigations.

It is essential to choose the most appropriate powerful simulation software to properly find out how wind power influences the power system. For this purpose, PSCAD/EMTDC software has been selected for this work as it has been developed for purposes of modelling and simulating power system in recent years. A massive library is available at PSCAD/EMTDC package which contains lots of built-in of electrical components used in modelling power system such as machines (generators and motors), circuit breakers, dynamic loads and various other passive network elements as e.g. lines, cables, transformers, static loads and shunts, etc. Furthermore, PSCAD library contains some of wind turbine components such as: pitch angle and drive-train. Through the provision of the built-in models from the database library it is easier to create comprehensive dynamic wind turbine system.

2.3 **Summary**

This chapter is conclusively based on the problems of wind turbine that are related to its power quality following the standard IEC61400-21. The research has been done by performing many research works, statistics and many calculations about the recent conditions of wind energy. The results of this analysis indicate that research on the power quality of wind turbine is of increasing significance. In countries like China and USA, wind power has become a great part of the power system. This is why power quality guidelines and grid codes have been established which ensures that the wind turbines that are working actively in the network just like in all the other power plants. EC6100-21 has identified the most important power quality problems as voltage flicker, current harmonics, response to voltage dip, active and reactive power control. Therefore, several PhD works have been focused on these issues. For the analysis of the effect of wind power on power quality, a suitable power system simulation tools are also needed. Additionally, there is a need for developing a detailed dynamic simulation models of wind turbine and implemented in simulation tools. PSCAD/EMTDC can be used as one of the most suitable power systems and therefore we have explained the major parts of the system. The models to be developed must be developed on the basis of the time frame of the simulation. A proper time frame in the form of milliseconds has been achieved to evaluate the reaction of the wind turbine and the stability of power system when to disturbance in grid or fluctuation of wind occurs.

Chapter 3 Wind Turbine Technologies

Kinetic energy stored in the moving air is converted to mechanical energy with the help of wind turbine, to be converted once more by the wind turbines generator to electrical energy.
During the last thirty years so various ideas for wind turbines have been developed and presented. The classification of the wind turbine is done in various ways, which are their structure (direct-driven or geared), speed range operation (fixed speed, limited variable speed, and variable speed), power control (stall, pitch control, active stall) and orientation of the spin axis (vertical axis and horizontal axis).

3.1 Wind Turbine Concept

Initially two spin axis structures were present in the wind turbine, which were referred as vertical axis and horizontal axis. Fig 3.1(A) shows the configuration of vertical axis wind turbine that rotates vertically, which is highly beneficial as it irrespective of the direction of the wind would be effective [95]. Fig 3.1(B) shows the configuration of horizontal axis wind turbine that is operative with either three or two blades with upwind or downwind operation in the more recent times wind turbines [96].
In this thesis, the classification of wind turbine is based on speed range operation. There are four types of wind turbine concept that are more successful and they are the most predominant these days: a fixed speed wind turbine that is equipped with induction generator (FSWT), a limited variable speed with induction generator and variable rotor resistors (LVSWT), and variable speed wind turbine which can be equipped with induction or synchronous generator (VSDFIG). A doubly-fed induction generator equipped with partially power converter or a PMSG with full power converter are the most systems used in VSDFIG. However, wound rotor synchronous generator and squirrel cage induction generator also can be used in VSWT with full power converter.

(A) (B)

Fig 3-1: Vertical and Horizontal axis wind turbine [95, 97]

3.1.1 Fixed-speed wind turbine (FSWT)

This wind turbine concept is called fixed speed as it has very narrow rotor speed range operation (below 2% variation of rated shaft speed). Where the stator winding is integrated directly to the utility grid, a squirrel-cage induction generator (SCIG) comes in utility. The bales are changed during high wind speed from streamline flow to turbulent flow with the help of a stall regulated control that is usually used for the blades, to save the generator from overheating and the mechanical system from damage by decreasing the aerodynamic power. Rigidity, simplicity in maintenance, low price, robust and reliability are a few advantages this FSWT wind turbine has to offer. This stall control usage on the other hand has its downside as optimal power from wind can be captured by the wind turbine in the rated speed only. In order to operate the generator at two speeds the winding of the generator stator is often designed with two pole (e.g. 2 and 4-poles), which increases the captured aerodynamic power of the turbine when operating with higher wind speeds. The configuration of FSWT wind turbine is depicted in Fig 3.2.

Configuration of FSWT wind turbine is depicted in Fig 3.2, in which the generator speed is upped with the help of a gear box, and to couple the generator terminal to the power grid a step-up transformer is used. The reactive power is used up by the generator for which a capacitor is to be installed, in order to balance the usage of the reactive power. A large inrush current is formed when the wind turbine is started, as a result of the direct connection, to limit

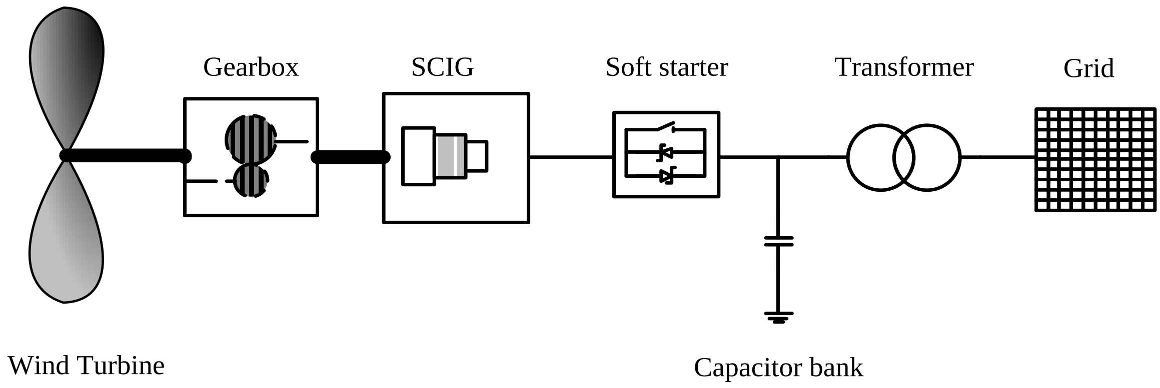

Fig 3-2: FSWT Wind turbine

This inrush current a soft-starter of two thyristors as commutation devices is used. This power electronic type is a cheap and simple.

3.1.2 Limited variable speed wind turbines (LVSWT)

LVSWT is a wound rotor induction machine (WRIM) in which its rotor winding is linked to external variable resistor, not very different from FSWT. The external variable resistor enables limited variable speed operation by increasing the slip to operate in higher range up to 10 %. A greater size capacitance is necessary as the loss is increased by these resistances, resulting in increased need for reactive power. The blades can be controlled by pitch or stall regulator, however the pitch control to limit the wind turbine power during wind speed can be opted as a better option. Fig 3.3 shows the configuration of LVSWT.

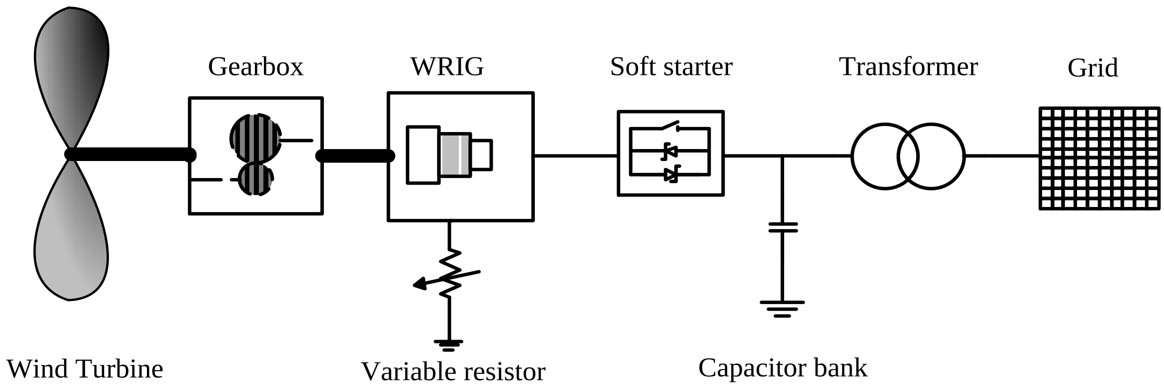

Fig 3-3: LVSWT wind turbine

A resemblance can be observed in the structure of LVSWT depicted in Fig 3.3 with Fig 3.2 which depicts FSWT. Here through a gearbox the generator rotor is coupled to the turbine shaft, the stator winding directly or by transformer connects to the grid, furthermore the rotor winding is shortened by means of variable resistor and a bank capacitor is essential to compensate the reactive power consumed by the generator [98].

3.1.3 Variable speed wind turbines with doubly-fed induction generator (VSDFIG)

In DFIG, a wound-rotor induction machine is used where stator windings are directly coupled to the network (as in types FSWT and LVSWT), the rotor windings are coupled to the grid with the help of fully controlled converter. Fig. 3.4 depicts the concept of VSDFIG.

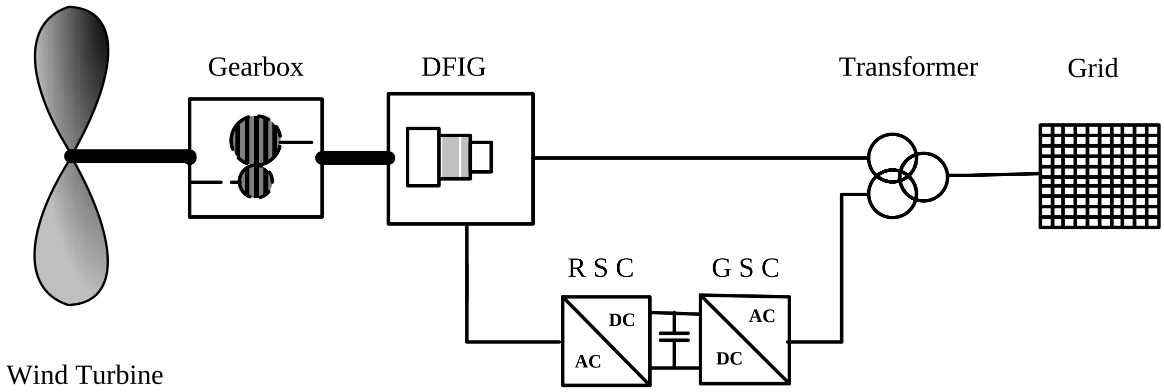

Fig 3-4: VSDFIG Wind turbine

In VSDFIC type the prim-mover shaft is coupled by a gear box (as done previously in types FSWT and LSVSWT). At high wind speeds conditions, this wind turbine has a pitch angle controller for aerodynamic power limitation. The converter regulates the active and the reactive power of the generator and variable speed operation is enabled, the speed operation of VSDFIG is found out to be around ± 30% of the generator synchronous speed. Since the reactive power is controlled, there is no need for the capacitor supply. The converter's is around 30% or less of the whole generator power, thus reducing the price and in turn this type is more attractive [99].

3.1.4 Variable speed wind turbines with full-scale frequency converters (VSWTFC)

For this type, a full-power converter is needed to transfer all the turbine power to the grid. SCIG or synchronous generator are used here, the wound rotor and permanent magnet both can be useful in case of synchronous generator, and lately the permanent magnet synchronous generator (PMSG), credit to its simple construction and DC excitation elimination is becoming highly popular. PMSG can be constructed with large number of pole, this however gives the advantage of omitting the gearbox. Wind turbine type VSWTFC equipped with direct-driven PMSG is shown in the Fig 3.5.

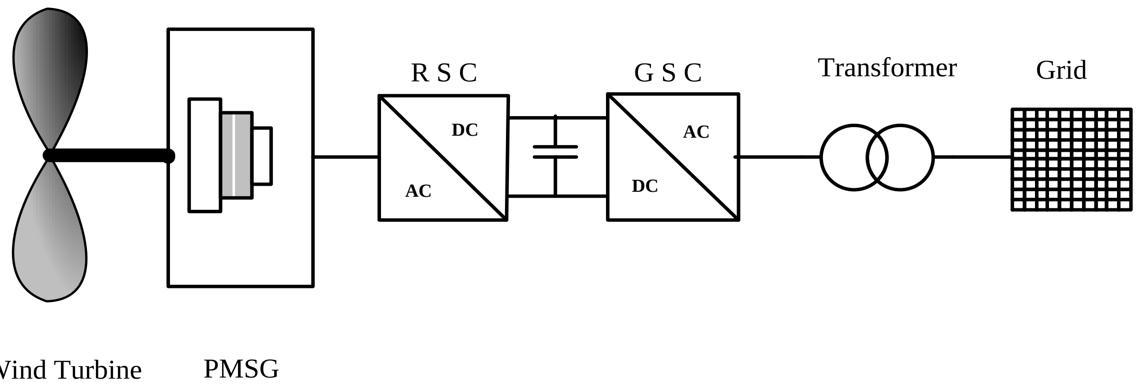

Fig 3-5: VSWTFC Wind turbine

In Fig 3.6 it can be viewed that the generator terminals are coupled to the converter and all the wind turbine power flows through the converter, thus it is deduced the convert size must be rated equal or a slightly above the wind turbine power nominal power. The blades are controlled by pitch angle and the converter fully regulates the active and reactive power control, then the wind turbine can then operate in wide range speed operation. This process however has its own disadvantage as the cost becomes high [100].

3.2 Comparison between Variable Speed and Fixed Speed Wind Turbines

The structure of variable and fixed speed was depicted well previously. The main benefit of fixed speed wind turbines concept is that are quite simple and robust, as standard asynchronous generators are used instead of power electronics thus leading to economic benefits and reduction in maintenance requirements. On the other hand consuming reactive power, narrow-range operation (result to low average power production) higher mechanical stress are its drawbacks [101]. Fixed speed is installed with stall control, and or pitch angle control system does not need to be used, thus adding simplicity and robustness. However, higher mechanical stresses are found in stall control, thus its blade, bearing and brake are needed to be stronger. A fixed blade angle may further result in losses in captured power, as the optimum point of maximum aerodynamic power is not feasible for any wind speed. For fixed speed wind turbines active stall control is used to accomplish power control at high wind speeds. The pitch angle is adjusted by a very slow control to higher angles in which the wind attacks the blades to reduce the aerodynamic power. Pitch control should not however be installed with fixed speed generators as it can cause large variations to the turbine power during high wind speed because of slow react of pitch mechanism during at severe fluctuating in wind speed. Alternatively, the pitch mechanism is most likely to be installed in variable-speed wind turbines. The variable speed operation assures, that the pitch control restricts the excess power, when a rapid power resulted from wind gust is stored the turbine.

Variable speed operation at partial load makes sure that optimum value of aerodynamic power can be captured for any wind speed from cut-in till rated. The pitch control changes the pitch angle during wind speeds higher than rated value, to limit the power to its rated value. In comparison, variable speed with pitch control accomplishes higher power than fixed speed in the two modes of operation.

The studies carried out concluded that a variable speed pitch control wind turbine is the most sought after wind turbine technology. In addition to better control, the other advantages are maximum power point operation, smooth tension of mechanical parts and less noisy [102]. However, a disadvantage for this type of wind turbine is additional loss due to additional components such as capital costs of the system increases with power electronics and pitch system. Further developments in the technology will ensure further reduction in the costs of power electronics.

Other factors are also influential in the wind turbine technology. The selection for wind turbine concept is very crucial in countries with high wind power share, while taking into account the wind power grid integration. Power control capability of wind turbines are taken care of by wind power grid integration, where wind turbines must have be able to regulate the output power in order to comply to power system demand. Also, power quality standards and transmission system operator in some countries necessitate the wind turbine to provide

reactive power and stay connected to a certain voltage drops. Hence, the wind turbine control will influence its development and compliance to grid demands and in the future.
The wind turbines used in type VSDFIG and VSWTFC, which represent the modern wind turbines, these concept using a fully controlled converter to allow variable speed operation, they are referred as the more popular technology in the future market, thus making its way for further research in this study. Wind turbines type FSWT and type LVSWT which do not utilise power electronics won't be considered in the present study as they are considered incapable of fulfilling grid code requirements. The study will be based on (I) wind turbine type VSWTFC with high-pole number permanent magnet synchronous generator and (II) wind turbine type VSDFIG.

3.3 Wind Turbine Elements

Wind turbine system consists of various elements. Each element in its own capacity will help in converting kinetic energy to electrical energy. The wind turbine system has three main parts which are as follows:

- **The mechanical part**

The mechanical part consists of turbine pitch mechanism, gearbox, drive-train.

- **The electrical part**

  Generators, power electronics devices including converter, soft starter, capacitor, and inductor, protection system including crowbar, breaking resistor and circuit breaker, transformer and cables are collectively referred to as the electrical part. But then it is observed that every constituent may not exist in all the wind turbine concepts.

- **Control system**

Converter controller and blade angle control are included in this system.
In Fig 3.6 the main elements of modern wind turbine can be seen; from left to right the first three elements (wind, turbine, drive-train and gearbox) of the mechanical part can be viewed. The electrical part consists of all the other elements [103].

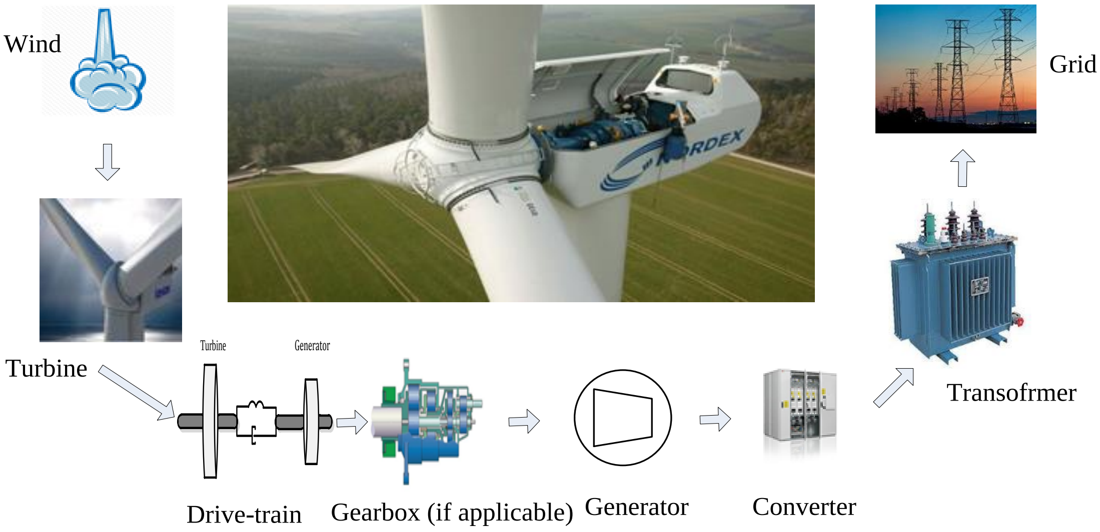

Fig 3-6: Variable speed wind turbine elements [104]

3.4 Mechanical System

The PhD study has focussed its investigation on the effect of power quality issues caused by variable-speed wind turbines, and to examine interaction between power system and wind turbine including the voltage disturbance during grid faults. Realistic models are imperative to conduct the study on electrical and mechanical system of the wind-turbine. The wind turbine's mechanical part comprises of several models include the aerodynamic, the pitch mechanism and the drive train. When studying power system wind turbine tower may be insignificant, but the aerodynamic torque affected by tower shadow has been taken into consideration in this work. Mechanical breaks are irrelevant to the operational states considered here; therefore they are not included in the study. Further, it is vital to coordinate both electrical and mechanical (pitch angle) system.

A description and modelling of pitch angle mechanism which can be developed in PSCAD package is presented in the following sections, where a control strategy and mechanical system model for the pitch angle mechanism is presented. Few components of the electrical and mechanical systems have built-in models in PSCAD, whereas the user himself has to build other models (such as tower shadow effect), the converter control also has to be modelled. Fig 3.7 gives an overview of the modelling scheme.

The investigation is carried on 3-MW variable speed wind turbines, their parameters are presented in the appendix. No specific manufacturer of pitch-controlled variable-speed wind turbines is included in the study, rather the wind turbine data is based on entirety. The mechanical model can be applied for both wind turbine concepts (PMSG and DFIG).

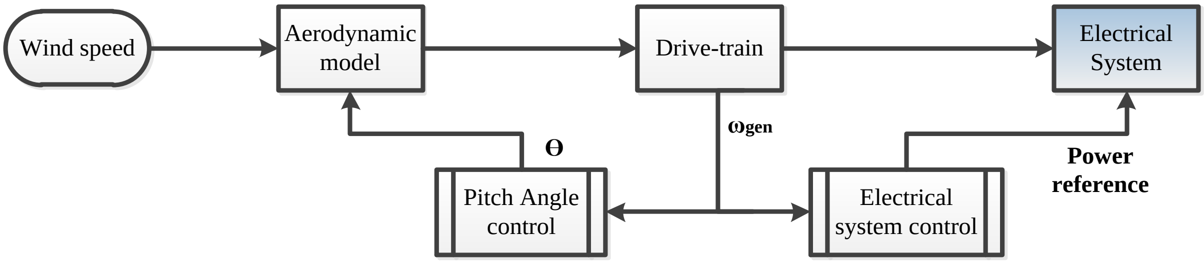

Fig 3-7: Schematic modelling of mechanical system

3.4.1 Aerodynamic power

The aerodynamic power generated by three blade wind turbines is given by Betz law as illustrated in equation (3.1); the aerodynamic of the rotor is sufficiently modelled. With the help of turbine's blades, the aerodynamic power is captured from the wind and then converted into mechanical power as given by formula [105]:

$$P_{tur} = 0.5\rho\pi r^2 \, C_P \, (\lambda, \beta) \, V^3 \tag{3.1}$$

where ρ is density of air, $C_P \, (\lambda, \beta)$ is turbine power coefficient and V is wind speed, the of pitch angle and tip speed ratio dominate the power coefficient. The power coefficient and tip speed ratio is determined using the following equations [106, 107]:

$$C_P \, (\lambda, \beta) = 0.22[\frac{116}{\lambda i} - 0.4\beta - 5] \; e^{\frac{-12.5}{\lambda i}} \tag{3.2}$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.3}$$

$$\lambda = \frac{W_{tur} \, . \, r}{V} \tag{3.4}$$

In the aerodynamic model as revealed in Fig 3.9 wind shear and tower shadow effect have been omitted to better understand the model, which will later be explained in detail. The aerodynamic model is illustrated through Fig 3.8

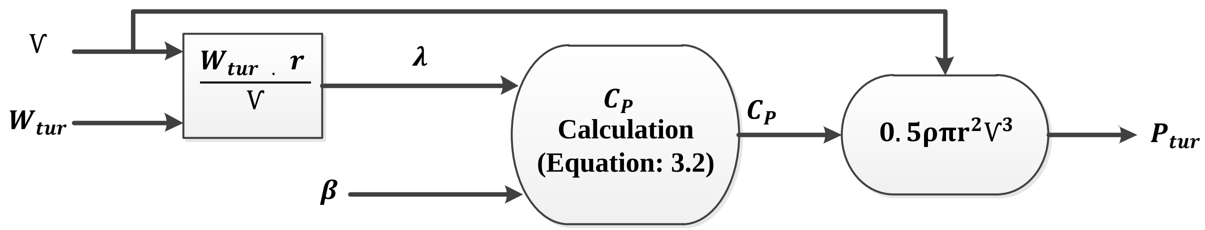

Fig 3-8**: Aerodynamic model**

The tip speed ratio is calculated in Fig 3.9 from wind and rotor speed, then to gain the power coefficient which is kept at its optimum level at or under nominal wind speed, it is used with pitch angle, to reduce the wind turbine mechanical power during high wind speed which is the key factor, this is achieved by adjusting the blades angle. The relation between λ and C_P when β = 0 is plotted in Fig. 3.9, when λ is between 6.1 and 6.5 the optimum value of is reached, thus, for maximum power point tracking is kept within this range. The maximum extracted power from wind for different wind speed and turbine rotor speed where the pitch angle is kept zero for optimal power coefficient is shown in Fig 3.10.

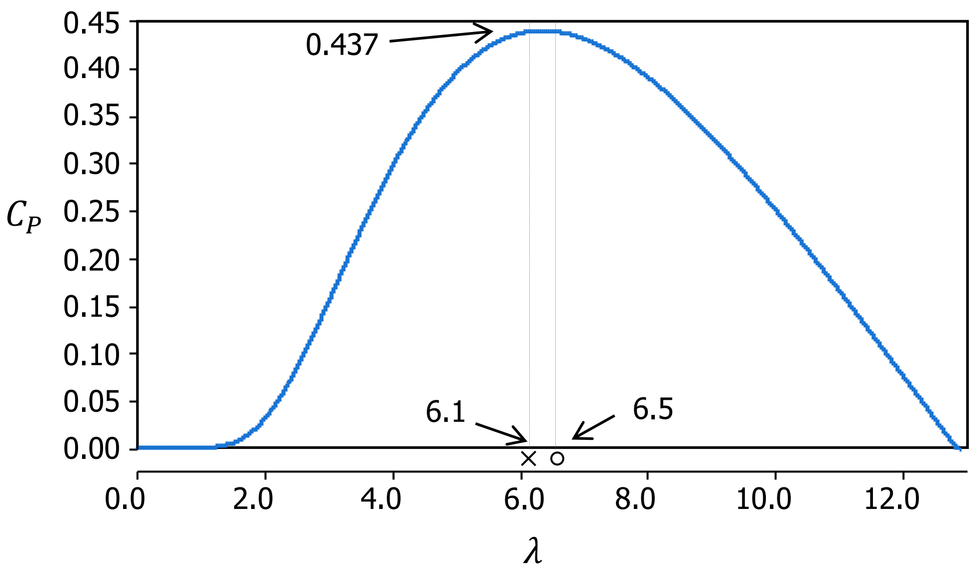

Fig 3-9 Power coefficient for different tip speed ratio

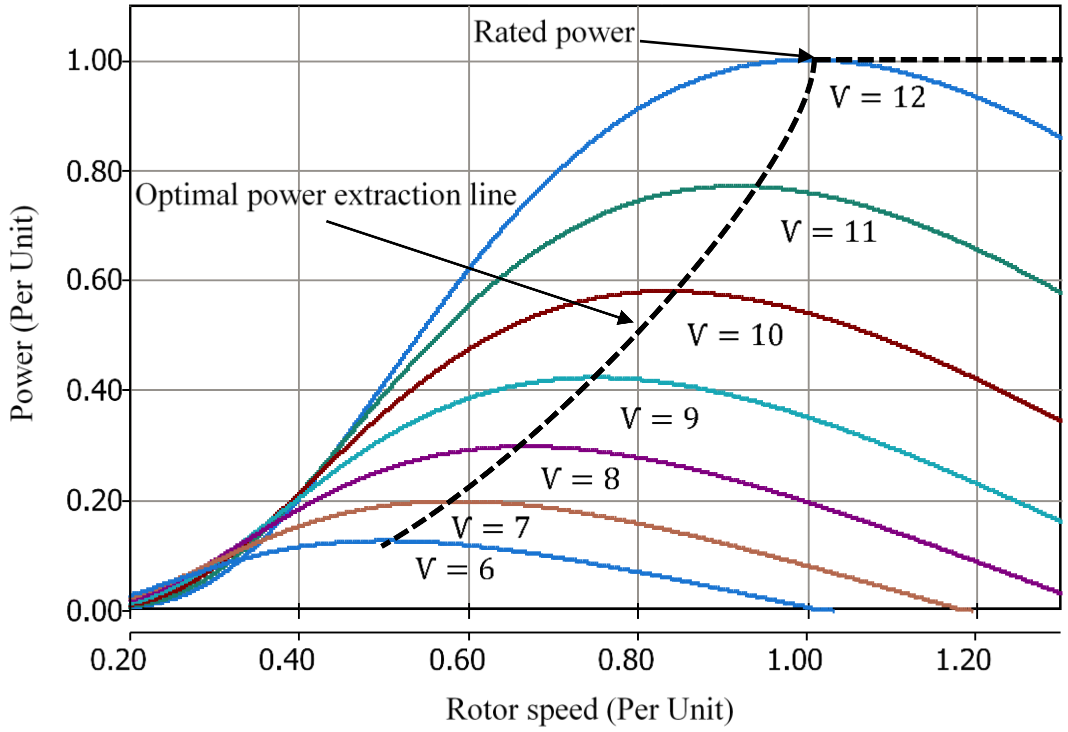

Fig 3-10: Turbine power at different wind and rotor speed

3.4.2 Drive train

Turbine blades, rotors of turbine and generator, gearbox (if applicable) and shafts (of high and low speed) are the constituents of a drive train of wind turbine. These components combined within, wind turbine drive train is usually modelled as one, two, three and six mass drive train model [108]. Fig. 3.11 shows the drive train model. When the electrical behaviour is observed during the study, the drive train is modelled as a range from one mass lumped till six mass drive train model, for reasonable results, this study a two-mass type was adopted.

As depicted in Fig 3.11 the drive train model represents 2 masses turbine inertia (J_{Tur}) as being the first and the generator inertia (J_{Gen}) as being the second mass. A flexible shaft couples both masses to each other and act like torsion spring between them. The two characters of this shaft are damping coefficient (D_{Shaft}) and stiffness (K_{Shaft}), the value of the characters is given per unit. The gearbox is presumed to be ideal when DFIG is modelled with exchange ratio1: K_{gear}. The damping and stiffness components are modelled at the side

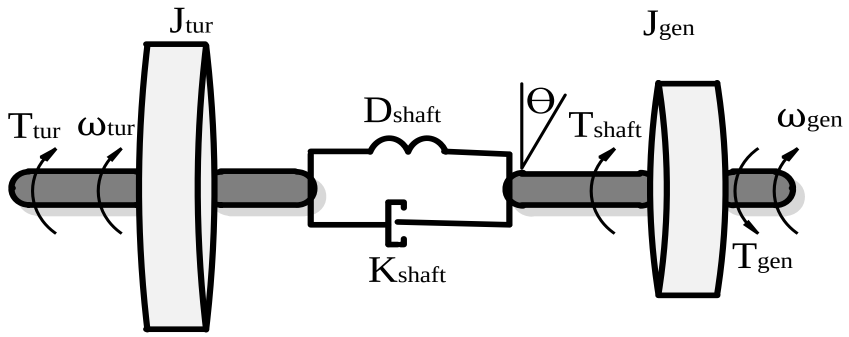

Fig 3-11: Two-mass model for wind turbine drive train

with low speed, as stiffness is observed at the high-speed shaft. PMSG and turbine are directly connected as the turbine has speed similar to the generator rotors in steady state operation since K_{gear} is equal to 1. Two-mass drive train model are represented in equation (3.5)-(3.7). Equation (3.5) describes the turbine rotor torque, equation (3.6) deduces the generator torque, and equation (3.7) calculates the twist angle between turbine and generator [109, 110].

$$J_{tur} \frac{d\omega_{tur}}{dt} = T_{tur} - K_{shaft}\,\Theta - D_{shaft}\,(\omega_{tur} - \omega_{gen}) \tag{3.5}$$

$$J_{gen} \frac{d\omega_{gen}}{dt} = K_{shaft}\,\Theta + D_{shaft}\,(\omega_{tur} - \omega_{gen}) - T_{gen} \tag{3.6}$$

$$\frac{d\Theta}{dt} = \omega_{tur} - \omega_{gen} \tag{3.7}$$

3.4.3 Pitch angle control

The pitch mechanism is employed in wind turbine system for aerodynamic power limitation to avoid rotor over-speed which may lead to mechanical system failure. As previously mentioned, the pitch angle is regularly set to zero in the range from cut-in to rated wind speed to gain maximum potential aerodynamic power from wind, whereas the control of the electrical system ascertains variable speed operation. In high wind speed and transient condition (wind gusts), the pitch angle must be adjusted to reduce the aerodynamic power. Fig 3.13 illustrates the schematic block diagram of pitch control [111].

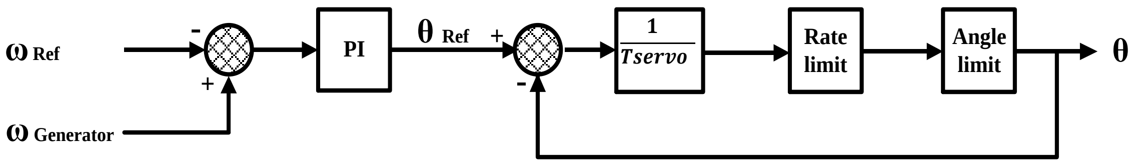

Fig 3-12: Pitch angle control scheme

The pitch angle control shown in Fig 3.13 has a speed controller using PI controller which regulate the turbine rotor speed to its reference, the resultant is a reference signal of pitch angle (θ_{Ref}). A servo time content is added to pitch angle control system to get a realistic response, the control scheme also must limit the pitch angle and its rate, these limitations are usually set to 30 degree and ± 10 degree for pitch angle and rate respectively. At grid faults condition, a limitation of the rate-of-change plays a key role to decide how quickly the turbine power is reduced to avoid the rotor's over-speed. The limitation of pitch rate here is usual set to 10 deg/sec. The reference and the actual pitch angle (θ_{ref} ,θ) are compared, the resultant error is adjusted by the servo mechanism.

The blades control is activated as the rotor speed exceed its rated value as mentioned earlier, and thus control the output power within its rated value. A maximum power point tracking (MPPT) here is employed to link rotor velocity and power to have a control of the electrical system. The MPPT determines at partial load a maximum aerodynamic efficiency operation and also specifying rated speed is only achievable at rated power. This infers that there is a well coordination between the controls of the electrical and mechanical system. The rotor speed of turbine and generator has slower response time of the mechanical system and thus they are controlled by the slower acting pitch mechanism. The quick response time of the electrical system determines the generator power, which is then controlled with the help of converter control. When compared to the electrical control, the response of the servo mechanism is slow, thus during high wind speed dynamic deviations occurs.The mass of all system rotating parts absorb sudden power caused by transient raise of wind speed, whereas the output power remains constant because of the electrical system control, the stress on the mechanical system is reduced [112].

Fig 3.13 depicts the effect of pitch angle to the aerodynamic power as in equation 3.2

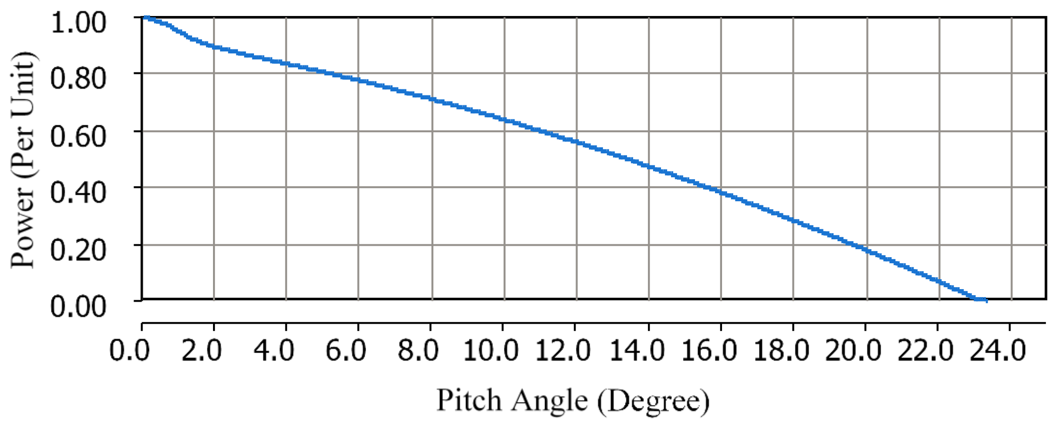

Fig 3-13: Pitch angle against turbine power

Fig 3.13 shows that maximum power can be obtained at passive pitch angle (set to zero), the power decreases as the pitch power rises in nonlinear manner, when the pitch angle is or over 24 degree, the power will be nearly reduced to zero.

3.4.4 Tower Effect

Wind shear and tower shadow effect have an important influence on the fluctuation of the output power of the wind turbine, so these two effects are considered during the investigation of wind turbine. Wind variation with respect to height is referred as wind shear. Each complete revolution comprises of three periodic power pulsations for a 3-blade wind turbine, which is referred as 3p frequency. A minimum wind speed will be reached by all the blades in a full cycle of a wind turbine, thus oscillation in the torque is observed, which as a result contributes to 3p frequency. The distribution of the wind changes because of the tower, thus affecting blade in alignment with the tower, this effect is known as the tower-shadow-effect. Many studies have been conducted on this effect [113-115]. The equivalent speed of tower shadow (V_{shadow}) and wind shear (V_{sheer}) are calculated below:

$$V_{shadow} = \frac{mV}{3\,r^2}\sum_{b=1}^{3}\left(\frac{a^2}{\sin^2\theta_b}\ln\left[\frac{r^2\sin^2\theta_b}{x^2}+1\right] - \frac{2a^2r^2}{r^2\sin^2\theta_b + x^2}\right) \tag{3.8}$$

$$m = 1 + \frac{\alpha(\alpha-1)r^2}{8H} \tag{3.9}$$

$$V_{sheer} = V \left(\frac{\alpha(\alpha-1)}{8} \left[\frac{r}{H}\right]^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{60} \left[\frac{r}{H}\right]^3 cos\, 3\, \theta \right) \qquad (3.10)$$

Fig 3.14 shows the influence of tower shadow and wind shear on wind speed. Since the large wind turbines have rotor speed between 15-20 r.p.m, here the rotor speed is set to be at 18 r.p.m. Tower shadow effect and wind shear effect on wind turbine torque when it operates at rated speed is depicted in Fig 3.14.

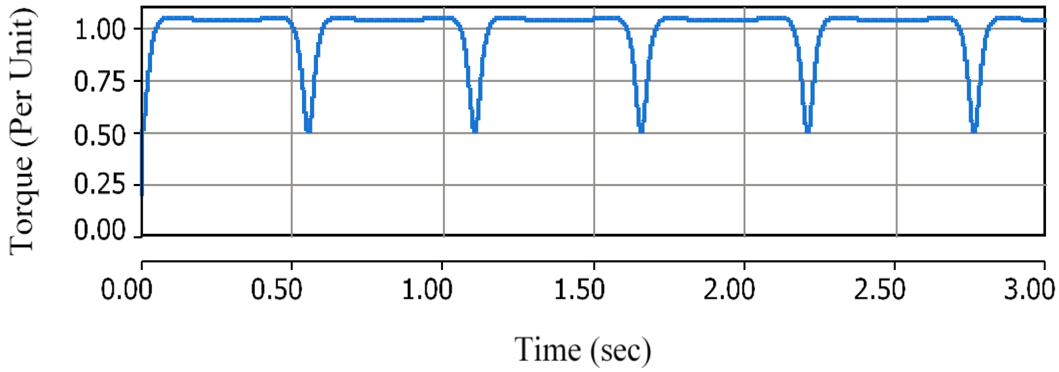

Fig 3-14: wind turbine torque with tower effect

The resultant influence of tower shadow and wind shear as shows that the torque of wind turbine is pulsating even in constant speed. It is determined that maximum torque is seen when a blade is pointing directly upwards for both wind shear and tower shadow effects. The maxmum torque drop occurs when a blade alaigned with the tower and this happens a three time per a complete rotor revelation. The modelled torque oscillations depend mostly on r, a, and x, as these are related to tower shadow. The proportionality constant between wind speed variations and torque oscillations is determined, allowing direct aerodynamic torque calculation from an equivalent wind speed. This model is a useful representation of the aero dynamic torque of a wind turbine for use in real-time wind turbine simulators and other dynamic-model-simulation-based applications. The torque variation caused by tower shadow may appear in the output power which may leads to further impact on power quality, even though lots of literatures ignored the effect of tower on variable speed wind turbine, in this work the tower effect is modelled for accurate results.

3.5 Summary

This chapter presented a brief description of the most used wind turbine types and their components, also the mechanical system was described in detail. Modelling of the mechanical system is first step of the wind turbine modelling process. There are two tasks taken into account when developing a mechanical model, firstly to simplifies the complex aerodynamical/mechanical behaviour, and then to assure a appropriate turbine representation, essential to accurately study the power system . The mechanical part of the wind turbine includes models for the rotor effective wind, the aerodynamic rotor, the blade pitching mechanism, tower shadow effect and the drive train. Moreover, pitch angle control, is discribed. The mechanical model is valid for both types of VSWTs, DFIG and the PMSG. The mechanical system is controlled by blade pitching. This is realized by a speed controller, which provides the reference pitch angle. There are a coordination between the mechanical and the electrical system. At partial load, the pitch angle is kept passive, while the control of the electrical system assures variable speed operation. Above rated wind speed the pitch angle is increased to limit the absorbed aerodynamic power. Due to the slower response time of the pitch mechanism the speed controller permits dynamic variations of the speed in order to avoid mechanical stresses during wind gusts.

Chapter 4 Direct-driven Permanent Magnet Synchronous Generator Wind Turbine

In the most recent models of wind turbines full scale power converter has been installed in the wind turbines. The power flows through a controlled power converter while the wind turbines stay isolated from the utility grid. This power converter has two parts, one which controls the generator power as the generator part, and the other one which control the DC link and exchange power with grid as the grid converter. The section 3.2.4 identified that induction or synchronous generators can be used with full power converter in wind turbine application, the assembling of synchronous generators can be done as conventional (separately excited with round or salient pole) or permanent magnet type. A gearbox is needed for the induction and conventional synchronous generators because of their construction in order to meet the grid demand by increasing the generator rotor speed. In PMSG construction, gearbox can be omitted by mounting greater amount of poles so it can be assembled with multi pole. Higher efficiency, reliability, less possible drive-train oscillations are obtained from PMSG.

Direct-driven PMSG have been discussed in this part of the study, as relatively slow rotor speed (15-20 r.p.m) is observed with large wind turbine. PMSG should be built with greater number of poles to provide the required frequency. The permanent magnet is able to provide the required excitation, therefore a greater number of PM material are installed on the rotor to achieve the multi-pole prototype, also as a result the diameter of the generator gets bigger and heavier. A picture of MW class PMSG designed for wind turbine is shown in Fig 4.1.

Flux-path direction categorizes the PM machines, therefore three types are mentioned as follows: Radial-flux (RFPM), Axial-flux (AFPM) and Transverse-flux (TFPM) permanent-magnet machines [116]. The radial-flux has been chosen here for the study as it is quite simple, has easy installation, better to be cooled and is the most sought after wind power application. RFPM is considered to be a non-salient rotor type as permeability of PM is approximately equal to the air, therefore the direct and quadrature reactance are nearly similar [117]. A damper design in the rotor is usually not included in PMSG as it is designed for low speed operation.

Fig 4-1: Direct-driven PMSG wind turbine [118]

4.1 PMSG Model

4.1.1 Steady state model

In the armature winding of PMSG, the permanent magnet material supplies the excitation which induce the voltage (E) (electromotive force EMF). In Fig. 3.17, the electrical model of PMSG is illustrated as one phase equivalent circuit.

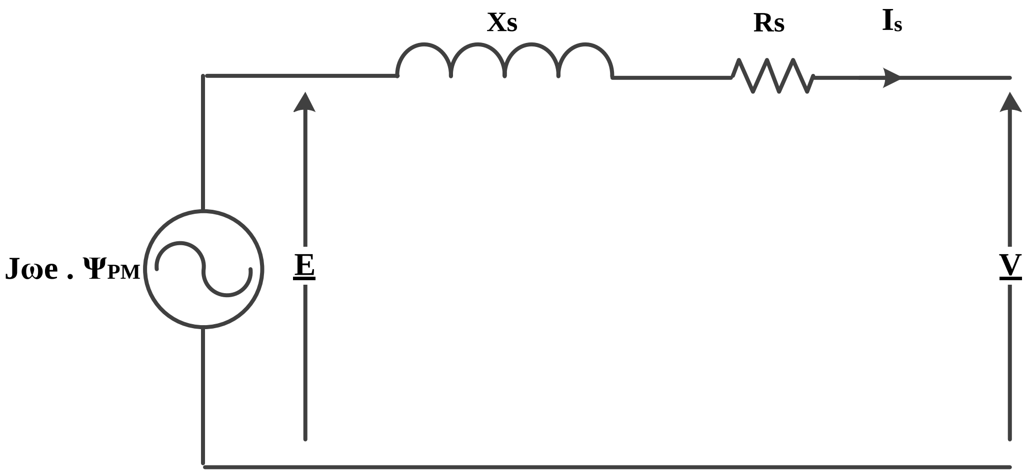

Fig 4-2: PMSG steady state equivalent circuit

Both the induced voltage and frequency are governed by the rotor speed ($\omega_e = P. \omega_{gen}$), as depicted in Fig 3.17. When no-load condition exists, E = V, and a phase delay between E = V is observed when the voltage drops and in the loaded generator the current flow through X_s and R_S.

4.1.2 Dynamic model

For power system analysis, PMSG is simplified by the following assumption [119, 120]:

- Symmetrically distributed stator windings are assumed.
- Sinusoidal distribution stator windings are observed.
- Damping windings are not accounted for.
- Constant resistors are assumed.

Based on these assumptions, the vector control then can be applied to PMSG, the induced electromagnet force E in the stator winding can be represented by the following equation:

$$\underline{E} = \omega_e \Psi_{PM} \tag{4.1}$$

The PMSG is model in d-q rotating reference frame (rotor-oriented dq-reference frame RRF), where the d-axis is aligned with the rotor flux so that it lags the q-axis by 90 degree. PMSG equivalent steady state circuit is converted to d-q and depicted in Fig 4.3.

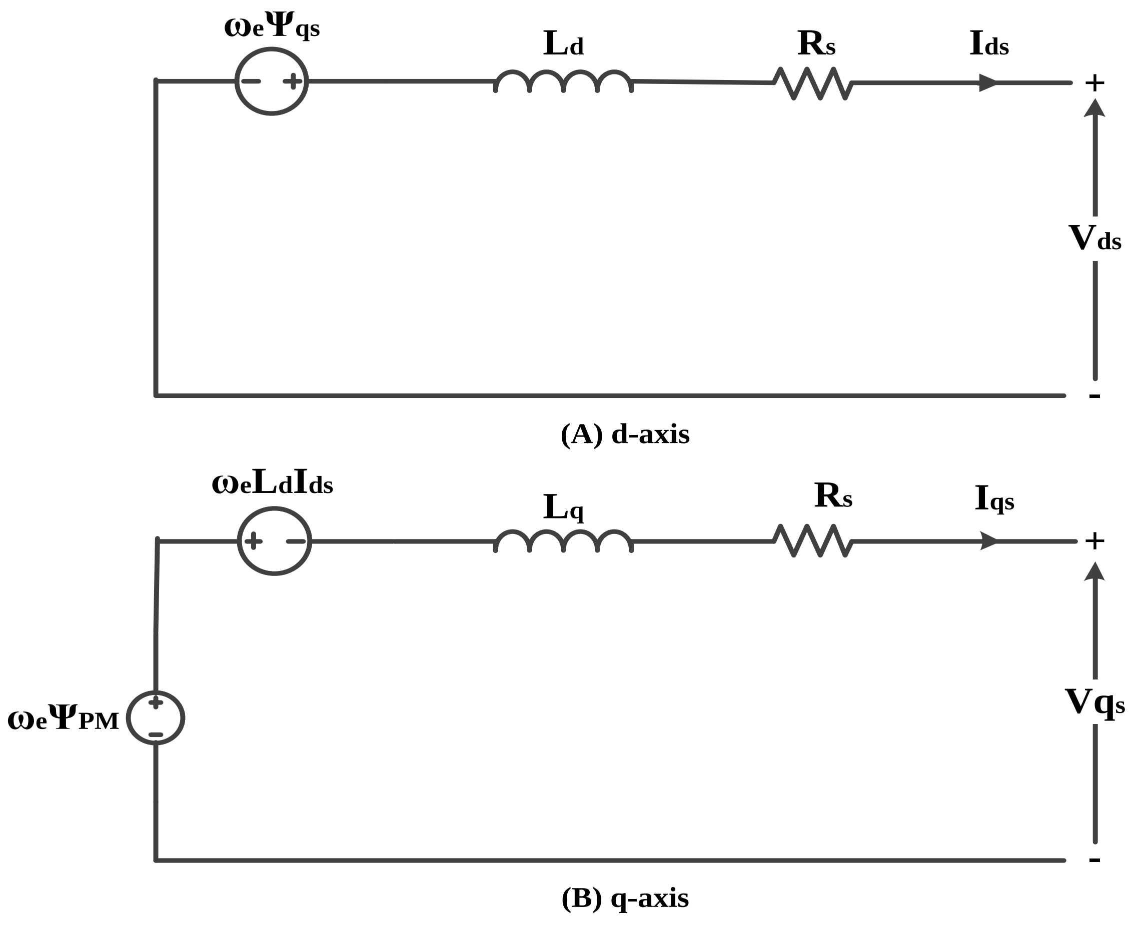

Fig 4-3: PMSG d-q equivalent circuit

The generator voltage equations in the d-q reference frame are given below: [121, 122]:

$$V_{ds} = R_s i_{ds} + \frac{\Psi_{ds}}{dt} - \omega_e \Psi_{qs}$$

(4.2)

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_e \Psi_{ds}$$

(4.3)

Equations 4.4 and 4.5 determine the d-q flux linkage.

$$\Psi_{ds} = L_{ds} i_{ds} + \Psi_{PM} \quad (4.4)$$

$$\Psi_{qs} = L_{qs} i_{qs} \quad (4.5)$$

Equations 4.6 and 4.7 when substituted in equations 4.2 and 4.3 gives the stator volt equations which will be as follows:

$$V_{ds} = R_s i_{ds} + \frac{di_d}{dt} L_d - \omega_e L_{qs} i_{qs}$$

(4.6)

$$V_{qs} = R_s i_{qs} + \frac{di_q}{dt} L_q + \omega_e L_{ds} i_{ds} + \omega_e \Psi_{PM}$$

(4.7)

In synchronous frame the electromagnet torque of PMSG is expressed by equation (4.8) [123,124]:

$$T_{gen} = 1.5\, P \,.\, (\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \quad (4.8)$$

Now by expressing the flux linkage by their components in equations (4.4) and (4.5) the electromagnet torque is given as:

$$T_{gen} = 1.5\, P \,.\, (\{L_{ds} - L_{qs}\} i_{ds} i_{qs} + \Psi_{PM} i_{qs}) \quad (4.9)$$

As the permeability of the magnet material and air are quite similar, surface-mounted PMSG is then considered to has non-saliency charchtersitc as conventional round-rotor synchronous generator, and thus $L_d = L_q = L_s$ [120, 123]. The electromagnet torque of PMSG can now be simplified as:

$$T_e = 1.5\, P \;\; \Psi_{PM} i_{qs} \tag{4.10}$$

With the assumption that the system is balanced and there is no zero-sequence current, the active and reactive power equation in synchronous reference frame then can be given as following:

$$P = 1.5\,(V_{ds} \; i_{ds} + \; V_{qs} i_{qs}) \tag{4.11}$$

$$Q = 1.5\,(V_{qs} \; i_{ds} - \; V_{ds} i_{qs}) \tag{4.12}$$

where P and $Q$are active and reactive power respectively.

PMSG full power converter is completely isolated from grid connection and the reactive power in equation (4.12) is exchanged just between the PMSG and the generator-side converter as mentioned earlier, this reactive power exchanged with grid is only utilized from grid-side converter. There is an absence of gearbox in the PMSG because of high pole-number construction, thus low speed design is observed in its rotor which doesn’t required to be damped. Additionally, no field winding has been observed in PMSG because of the excitation caused by the permanent magnet materials, therefore during load change, no contribution of PMSG is observed to damp the transient currents. As the damper and field winding in PMSG is not present, therefore transient and sub transient reactance cannot be defined for the PMSG as in wound rotor synchronous generator. The following assumption can be applied to PMSG:

$$X_d \; = \; X`_d = X``_d \tag{4.12}$$

$$X_q \; = \; X`_q = X``_q \tag{4.13}$$

Nevertheless, according to [124] the damper winding is less significant for multi-pole PMSG since it has slow rotor speed with slow dynamic. However, it the damping system is required, and then can be utilized by the converter control.

4.2 Power Converter for PMSG

Several converter topologies can be employed to deliver the output power of the generator to utility grid. The converters applied for wind turbine over the recent years are listed below [5]:

- Back-to back converter
- Multilevel converter
- Tandem converter
- Matrix converter
- Resonant converter

Back-to-back converter is considered to be the best possible topology for wind turbine application with respect to other converter types. Therefore, regardless of other possibilities, this study is based on the back-to-back converter.

In variable-speed wind turbine, the converter comprises of two parts, generator and grid sides. In PMSG wind turbine the generator converter has two topologies, IGBT voltage source converter (for back-to-back converter) which is discussed in detail, and then there is the diode rectifier equipped with boost converter. The diode rectifier contains passive 6-diode-bridge rectifier which is simple, low in cost and have less losses [125, 126]. Fig 4.4 illustrates the structure of this converter.

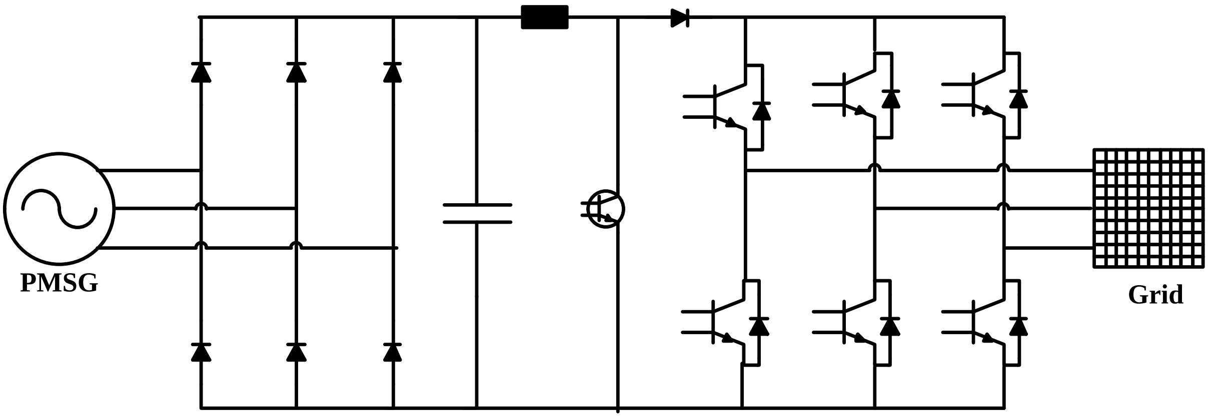

Fig 4-4: PMSG with diode rectifier topology

As seen in Fig 4.4, the generator's voltage is converted to DC voltage by 6 bridge diode rectifiers and then converted again to AC voltage by controlled inverter where it coupled to the network. The DC voltage is provided by the uncontrollable rectifier. The field excitation of PMSG is uncontrollable and has a fixed value which designed to be optimum for rated operation only. Therefore, the DC voltage is a function of the generator speed, thus, it increases as the generator's speed increases and vice versa, this means in low speed operation the DC voltage will be low. Correspondingly, because the generator reactive power cannot be controlled (because of diode rectifier uncontrollability), Hence, the current and voltage at stator terminals will continuously be in-phase, once the torque is applied, the stator current and load angle rises, as a result, the DC voltage drops [127]. As a sequence, the boost converter is important in order to preserve the voltage within its nominal value if the generator terminal voltage drops during varying operation.

In order to get the best possible model, a fully controlled active converter is applied to direct-driven PMSG, the reactive power then has the possibility to be changed by the converter, all the while improving the system efficiency. This fully controlled model is high in cost and extra care is required in terms of overload and high voltage conditions. Back-to-back converter as already told is the most popular fully-controlled converter, which comprises of 6 bridge insulated-gate bipolar transistor (IGBT) and PWM controlled voltage source converter. In Fig 4.5, an overview of the back-to-back converter is given.

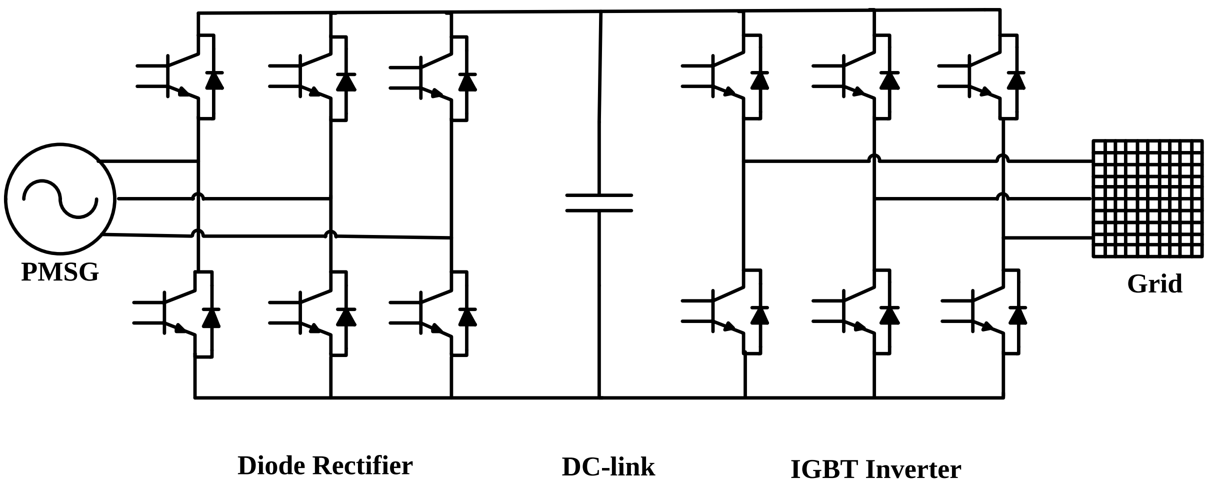

Fig 4-5: PMSG with back-to-back converter

Now the generator side converter (rectifier) is controlled by switching devices, which introduce a ripple to the DC voltage, in order to reduce and smooth this voltage ripple to accepted manner, a DC-link (capacitor) is required in back-to-back converter. Selecting of capacitor size must satisfy: voltage ripples, life expectancy and the control response [127]. Taking into account these characteristics, the capacitor size of back-to-back is calculated based on the subsequent equations [128, 129].

$$C = \frac{S_n}{V_{DC} \times \Delta V_{DC} \times 2 \times \omega_n} \tag{4.14}$$

$$V_{DC} = \frac{V_{AC} \times 2 \times \sqrt{2}}{\sqrt{3} \times m} \tag{4.15}$$

Similar to PMSG with diode rectifier topology, the grid side converter (inverter) supplies the utility grid with fixed frequency AC voltage by converting the DC voltage. As the generator terminals and the grid are fully decoupled, the inverter only can provide or absorb the reactive power independently from the generator. During normal conditions the wind turbine is operated with unity power factor, however, in grid fault conditions or if the voltage drops, the reactive power is supplied by PMSG wind turbine to compensate the voltage drop or for voltage stability contribution. Since the reactive power is produced just by the inverter, thus it is limited to the inverter rating as well as the active power operated by the inverter. The equation of reactive power limitation of PMSG wind turbine is given by equation (4.16)

$$Q_{max} = \sqrt{{S_n}^2 - \mathrm{P}^2} \tag{4.16}$$

4.3 PMSG Control

To utilize optimal power extracted from kinetic energy various control methods were applied to variable speed wind turbine, thus it was established that field-oriented controller (FOC) which considered the conventional control, direct power control (DPC) and direct torque control (DTC) are the most popular. Other advanced controllers were introduced too, namely fuzzy-logic and gain scheduled adaptive controller, and issues like generator parameter uncertainty and nonlinearity are addressed using these controllers. As power quality is the basic part of this study, here the conventional control which FOC is chosen for study as it is the simplest among all the other methods [130]. Fig 4.6 depicts PMSG model embedded with control concept. In the modular structure the grey blocks depict mechanical energy, a red block depicts electrical energy and yellow blocks show control. Mechanical and electrical systems have already been discussed. Machine side controller and grid side controller are the two components of PMSG, which adopted vector control for control.

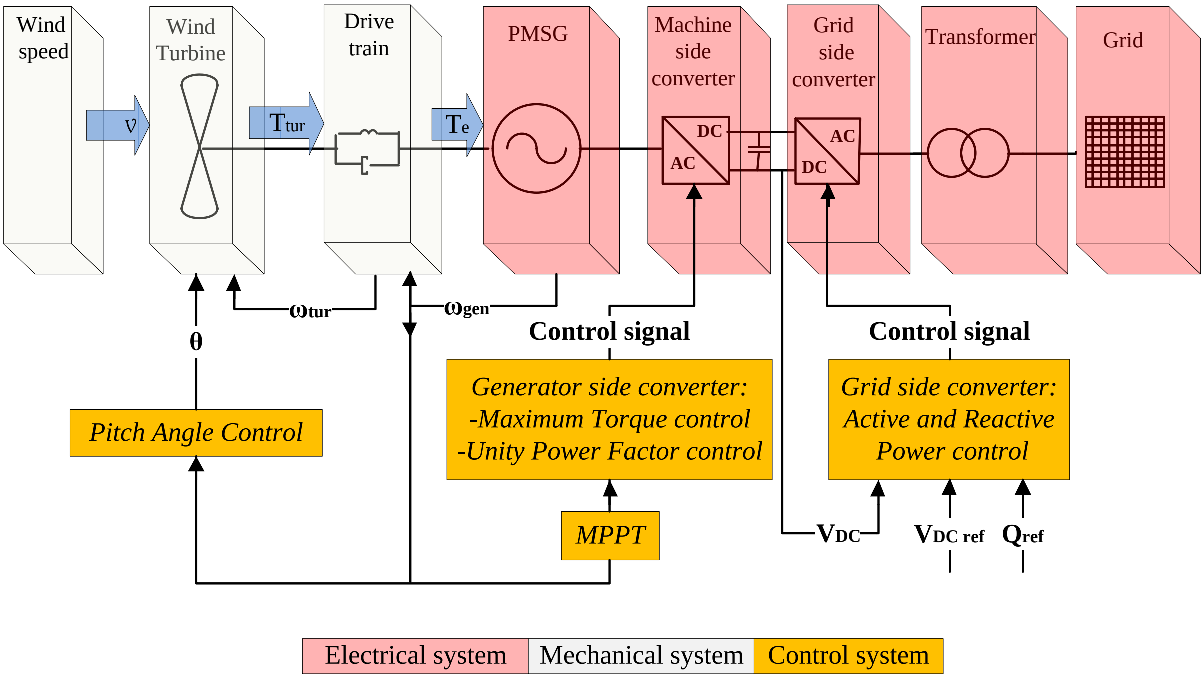

Fig 4-6: PMSG modelling scheme and control concept

4.3.1 Grid-side converter control

The grid-side control (inverter) is present inside the PMSG conception for contributing its role in the transmittance of wind turbine power and also acts as a controlling element in the power mechanism. Two sorts of archetypal control stratagems have been identified for the fulfilment of such accountabilities i.e. magnitude control and load angle. This thesis will provide great elucidation of the vector controller as vector control was the preliminary application to utilise motor applications in contemplation of providing greater efficiency. In grid side PMSG converter control, the active and reactive power are controlled independently, this is accomplished by reference frame orientation with stator voltage.

The grid side converter's vector control i_d demonstrated in the schematic phasor diagram, Fig 4.7.

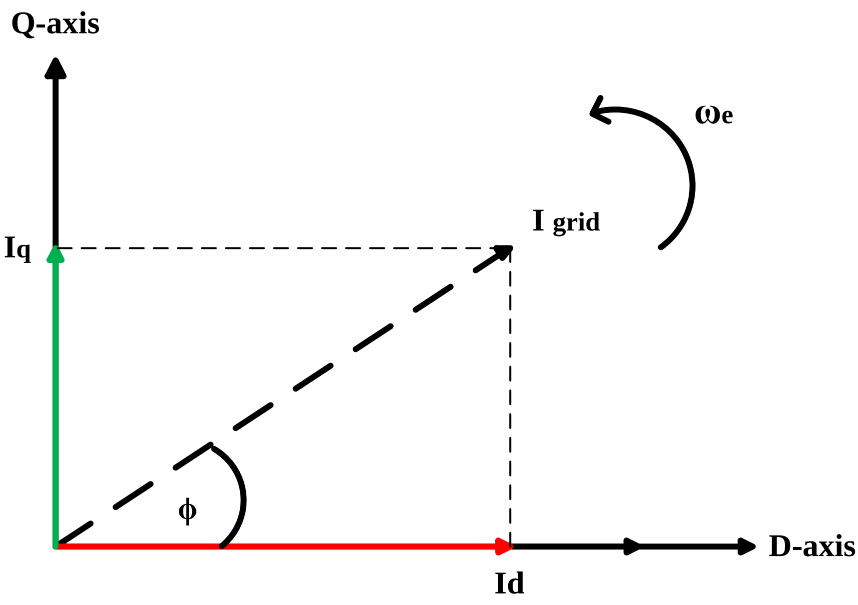

Fig 4-7: Phasor diagram of PMSG grid side converter

The grid voltage vector in Fig 4.7 is aligned to d-axis which makes the component of q-axis is zero. This however will simplify the equations (4.17) and (4.18) by applying zero to $V_{q,}$ the equation then will be as following [131]:

$$P = 1.5 \ V_{ds} \ i_{ds} \tag{4.17}$$

$$Q = -1.5 \ V_{ds} i_{qs} \tag{4.18}$$

Equations (4.17) and (4.18) shows both active and reactive power can be independently controlled, this is achieved by regulating currents components i_{ds} and i_{qs} since the V_{ds} is constant where it corresponding to grid voltage.

The active power is controlled through controlling the DC voltage by i_{ds} where i_{qs} control the reactive power directly. The block diagram for PMSG grid-side converter is given in Fig. 4.8.

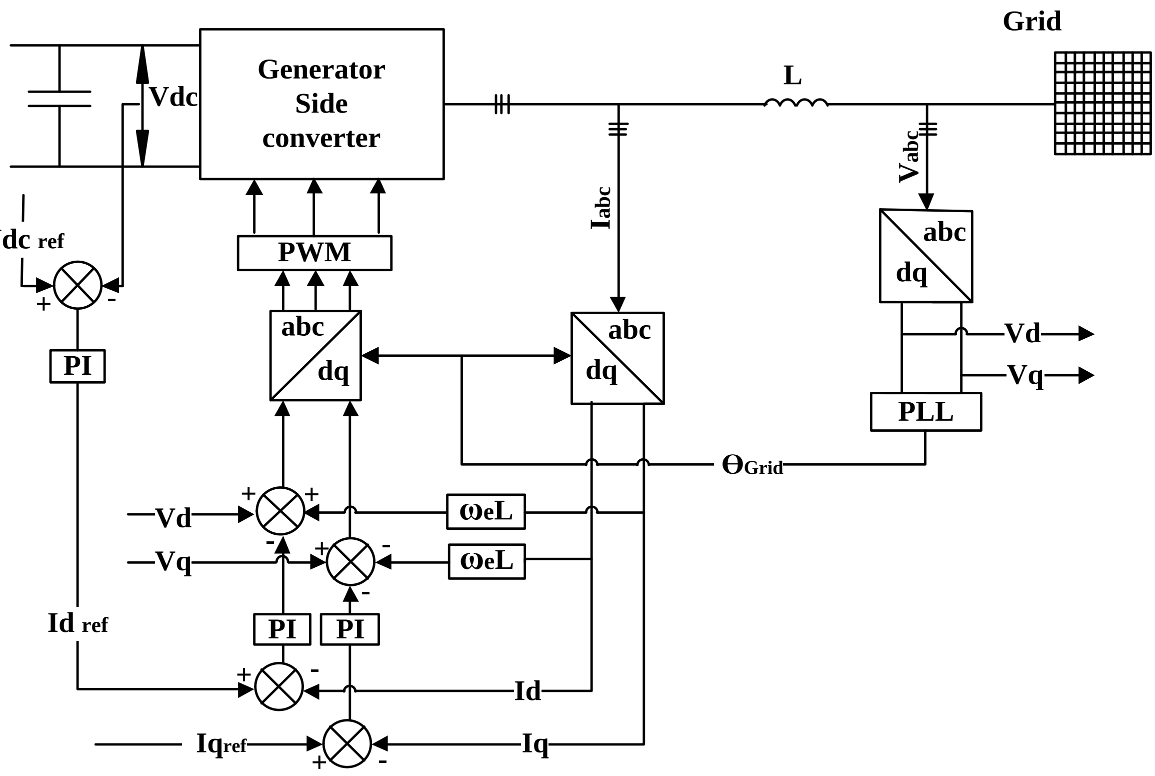

Fig 4-8: Vector control for PMSG grid side converter SVRF

The Parks transformation changes the acquired and immediate currents and voltages values into d-q elements; whereas, PLL (Phase Locked Loop Technique) utilises the electrical angle which comprises of two internal and one external loops in the controller and the external loop has the reference direct current element. In this case, the error proceedings arising from contrasting measurements of the DC voltage reference values and i_d component in the internal loop and this is achieved by PI controller. The demanded reactive power is found through the iq_{ref} component, where was put to zero to accomplish the unity power factor operation. There may be several grid codes necessitating the supply of reactive power in the wind turbine where grid is controlled in extremely significant conditions of voltage drop or fault. PI controller helps in figuring out the reference values of q-axis and d-axis voltages, contrasting the actual and reference values of iq and id in the two internal loops to realise a full dependent control for active and reactive power. In the meantime the so-called cross-coupling terms (ωeLid and ωeLiq) should be subtracted from their corresponding reference voltage [132]. the reference d-q voltage is attached with the voltage-feed-forward terms of V_d and V_q so that the system can work more rapidly and the d-q reference voltage resultant is restored back into its instantaneous three phases values in which the propagation of converter PMW signals takes place.

4.3.2 Machine-side converter control

The conventional vector control is used as well in controlling the generator side converter where either stator voltage or rotor flux reference frame can be implemented. The PMSG can be controlled by vector control in different methods. For example, the generator torque is controlled to be at its maximum value with minimum stator current. Alternatively, the full rating of the active power can be utilized by operating the generator in unity power factor. A brief description of control strategies for PMSG is given below.

4.3.2.1 Unity power factor control

In this strategy, both active and reactive power of PMSG can be directly controlled by the converter, the controller can be implemented in either SVRF or RRF [133]. The reactive power needs to be regulated to zero due to its autonomous control which is also its main objective and this further requires the functioning of generator at the unity power factor. MPPT scheme endows with the active power for acquiring maximum probable power from the turbine, but this event requires the reactive power to be controlled through I_d which tends to be a stator component as active power also regulates the current I_q [133]. According to the equation (4.16), the dimension of converter can be minimized for making it feasible only for active power with the unity power factor on the other hand, the produced torque is not optimised since the generator stator current is not entirely used for torque production in comparison to maximum torque control, another drawback is the loss in the copper is larger for the same toque, as consequence, the efficiency will be lower too.

4.3.2.2 Maximum-torque per ampere control

In this control strategy the main goal is to regulate the stator current only to produce the torque. By implying the vector control with field-oriented control, now the torque can be regulated directly by Iq since PMSG has the non-saliency characteristic (see equation 3.19). The task of controller now is to control the torque by regulating i_q whereas i_d is kept at zero to reduce stator current for given torque. Based on the equations (4.10), (4.11) and (4.12) active and reactive power as well as generator torque in RRF stated as following [119]:

$$T_{gen} = 1.5\, P \;\; \Psi_{PM} i_{qs} \tag{4.19}$$

$$P_{gen} = 1.5 \;\; V_{qs} i_{qs} \tag{4.20}$$

$$Q_{gen} = -1.5 \;\; V_{ds} i_{qs} \tag{4.21}$$

This control strategy has been chosen for this work, the schematic phasor diagram and generic control for PMSG convert are illustrated in Fig 4.9 and 4.10 respectively.

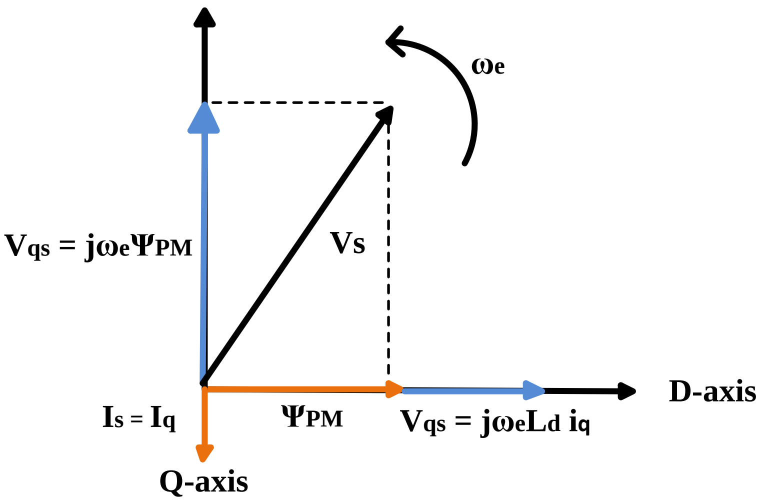

Fig 4-9: Phasor diagram for PMSG with maximum torque control

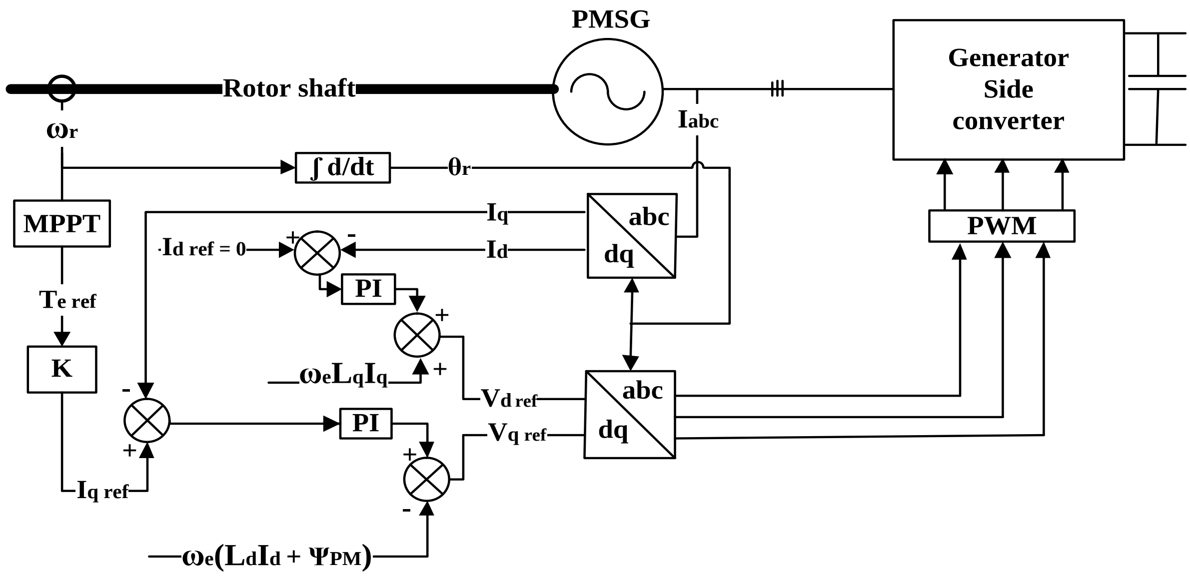

Fig 4-10: schematic vector control for PMSG with maximum torque control

Firstly, generator terminals currents were converted to d-q-axis currents in RRF by Park's transformation, these currents components then were regulated to their references. The Id reference is set to zero as mentioned early and I_q reference is gained by reforming equation (4.22):

$$i_{qs\,ref} = \frac{2}{3}\frac{T_{ref}}{P\,\Psi_{PM}} \tag{4.22}$$

PI controllers then used to generate signals for stator voltage in d-q reference frame, for better decoupling, cross-coupling terms are added. Moreover, the flux may induce voltage in the q-axis, thus it worth to subtract this voltage from q-axis. Finally, the d-q voltage reference then transformed to three phase signals by inverse Park's transformation.

4.3.3 Voltage control

Reactive power supply is necessary for grid codes i.e. fault ride-through. The grid side converter can simply take in the generator's operational point autonomously through reactive power supply as the beheld PMSG wind turbine configuration includes the full-scale frequency converter mechanism. This is the main differential point among various other turbine conceptions and the DFIG wind turbine as the other ones are attached with direct grid generator. However, the grid side converter rating restricts the reactive power supply amount.

The optimum value of reactive power can be gained from the inverter is given by the equation (4.16):

The below given figure illustrates a PMSG wind turbine IGBT converter implemented for fulfilling the apparent power need of 3.2 MVA. The turbine's voltage control capability can be improved by extending the size of the converter. Here the voltage controller is included in the control of grid-side converter which resultantly helps in attaining voltage support, as shown in the Fig4.11. The converter current control-loop along with the internal reactive power control-loop possesses the voltage controller in its cascade. The converter either supplies or draws reactive power from the grid according to the request from the voltage controller; the voltage controller generates the demand for reactive power by comparing the reference and measured voltage at PCC.

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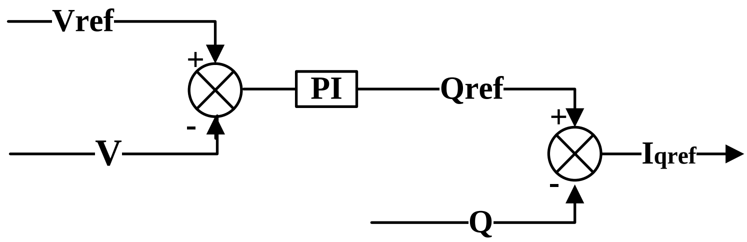

Fig 4-11: **Voltage controller of PMSG wind turbine [103]**

4.4 Summary

The present chapter focuses on modelling and control of a variable speed wind turbine with multipole permanent magnet synchronous generator and full-scale converter. Due to the self excitation and gearless assembly, PMSG require less regular maintenance and has a higher efficiency, this makes PMSG is attractive for wind turbine application specially offshore site.

A comprehensive dynamic simulation model is developed in the simulation tool PSCAD. The steady state behaviour and the differential equations used in the dynamic model are presented. Different converter topologies are discussed and it was pointed out that the IGBT converter is the most appropriate solution for PMSG wind turbine. The control of the PMSG wind turbine divided into two sections; the blade angle control controls the speed of the system while the power is directly controlled by the frequency converter. A vector control was adopted in this study, it is based on the idea that the DC voltage and reactive power supply to the power system is directly controlled by the grid side converter, while the machine torque is controlled by generator side converter. The converter control guarantees variable speed operation to gain optimal power production according to the MPP-tracking. Above rated wind speed the pitch angle control controls the generator speed and indirectly the power output to their rated values. A coordination between both power and speed controller is necessary.

Chapter 5 Doubly-fed Induction Generator Wind Turbine

DFIG Wind turbines, as described in chapter (3) equipped with a wound-rotor induction generator, which its rotor is coupled by full controlled converter (back-to-back voltage source converter) to the grid while the stator windings are connected straight to the utility grid. Fig 5.1 depicts the system of DFIG wind turbine.

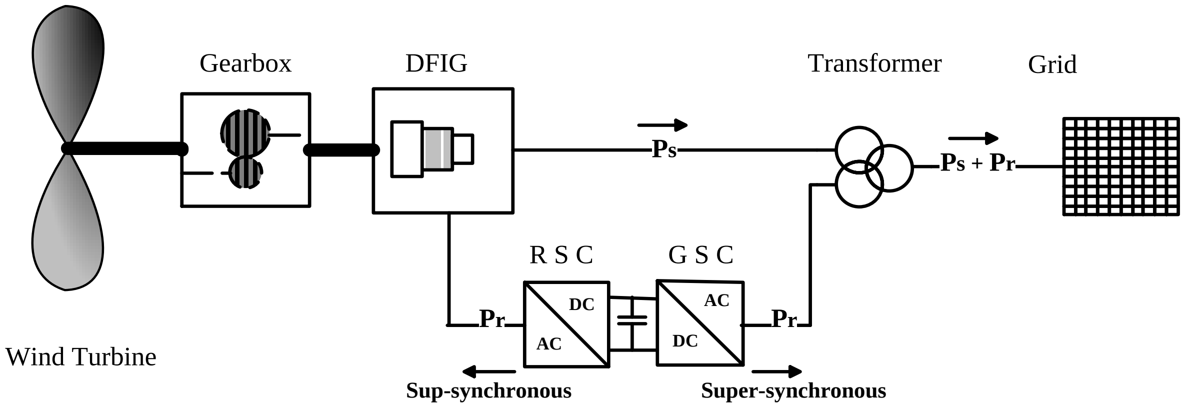

Fig 5-1: DFIG wind turbine system

The rotor terminals are fed by extra voltage from the machine-side converter which has a slip frequency. The variable speed operation is utilized by regulating the rotor voltage, which also achieve a decoupling active and reactive power controllability of DFIG. The DFIG has two mode operations, super-synchronous and sub-synchronous operation, the operation mode depends on the magnitude and phase of the rotor voltage. The power flows between the rotor terminal and the converter is depending on operation mode. During sub-synchronous speed (below rated speed), the converter supplies the power to the rotor windings, however, in super-synchronous operation the rotor feeds power to the converter and then to the grid. Thus, the rotor power (P_r) flows in two-way path, hence the converter must contain active semiconductors to enable bi-directional power flow.

5.1 **DFIG Model**

5.1.1 Steady state model

The schematic equivalent circuit of DFIG in steady state is depicted in Fig5.2, for simplicity all rotor quantities were referred to the stator [134].

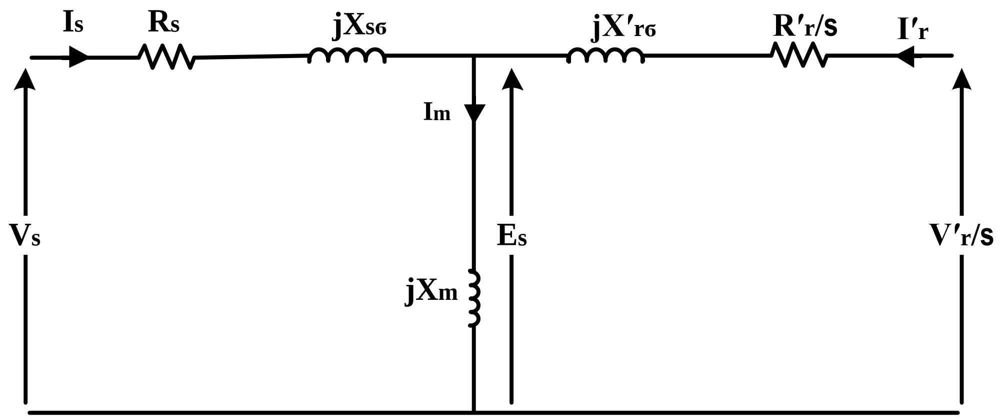

Fig 5-2: DFIG steady state equivalent circuit

The voltage of DFIG terminals based on equivalent circuit provided in the following equations:

$$V_s = R_s \cdot I_s + jX_{s\sigma} \cdot I_s + jX_m \cdot I_m \quad (5.1)$$

$$\frac{Vr}{s} = \frac{R'r}{s} \cdot I'r + jXs\sigma \cdot I'r + jXm \cdot Im \quad (5.2)$$

If the losses in DFIG are neglected, the power of stator and the rotor can then be expressed as following:

$$P_m = P_s + P_r \quad (5.3)$$

$$P_r = sP_s \quad (5.4)$$

where: P_s, P_r and P_m are: stator, rotor and mechanical power consequently.

5.1.2 Dynamic model

DFIG is utilised with a vector control in this thesis in order to attain dependable speed operation. Therefore, there is a dire need of conversion of sturdy equivalent circuit into d-p equivalent circuit which further helps in the implementation of the vector control. For this purpose, two steps are performed in its conversion. In the preliminary stage, stationary two-stages are attained by means of implementing Clarke transformation of alpha-beta frame from variables-3 phases (a,b,c). In the subsequent stage, rotating variables d-q frame of Park Transformation are converted from the stationary two phases.

These are the presumptions considered for simplified evaluation:

- Steadiness of the air gap disinclination.
- Symmetric winding of the stator and the DFIF rotor.
- Ignorance of saturation.
- Ignorance of skin impacts of the stator and the rotor.
- Negligence of the iron core losses.
- A sinusoidal allocation covering the area of the DFIG in rotor and stator windings.

The DFIG circuit's equivalency is illustrated within d-q axis of the arbitrary reference frame in Fig5.3:

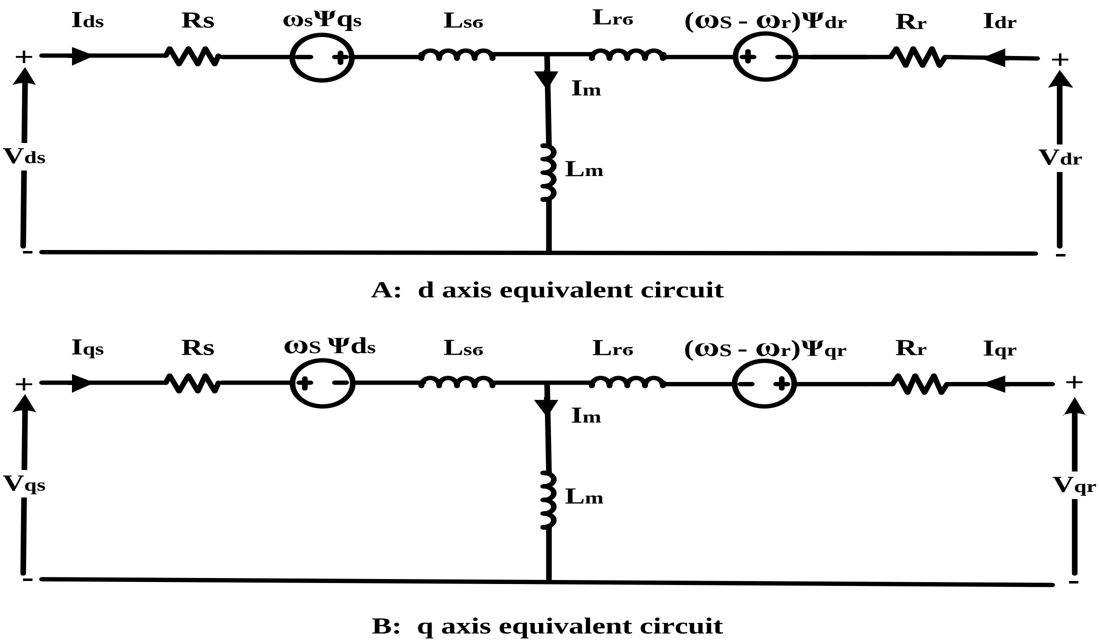

Fig 5-3: DFIG steady-state equivalent circuit

The d-q equivalent circuits in Fig.5.3 yield the dynamic voltage equations as following [135]:

$$V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_s \Psi_{qs} \quad (5.5)$$

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \quad (5.6)$$

$$V_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - (\omega_s - \omega_r)\Psi_{qr} \quad (5.7)$$

$$V_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + (\omega_s - \omega_r)\Psi_{dr} \quad (5.8)$$

The flux linkages are given by the following equations.

$$\Psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5.9)$$

$$\Psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad (5.10)$$

$$\Psi_{dr} = L_r I_{dr} + L_m I_{ds} \quad (5.11)$$

$$\Psi_{qr} = L_r I_{qr} + L_m I_{qs} \quad (5.12)$$

where: L_r, L_s and L_m represent: rotor, stator and mutual inductances and L_s and L_r can be defined as;

$$L_s = L_m + L_s\sigma \text{ , } L_r = L_m + L_{r\sigma} \quad (5.13)$$

$L_s\sigma$ and $L_{r\sigma}$ correspond to the stator and rotor leakage inductance.

Active and reactive power exchanged by DFIG from stator-side or rotor-side are given by the subsequent equations:

$$P_s = [V_{ds} i_{ds} + V_{qs} i_{qs}] \quad (5.14)$$

$$Q_s = [V_{qs} i_{ds} - V_{ds} i_{qs}] \tag{5.15}$$

$$P_r = [V_{dr} i_{dr} + V_{qr} i_{qr}] \tag{5.16}$$

$$Q_r = [V_{qr} i_{dr} - V_{dr} i_{qr}] \tag{5.17}$$

5.2 Power Converter for DFIG

The power converter (as explained in section 3.2.3) couples the DFIG rotor winding to the grid, it is essential that the converter uses active elements such IGBT or GOTO to allow the power flows in two directions. Different converters can be applied to DFIG to achieve wide speed operation like low-frequency converter, forced-commutated thyristor cyclo converter, or line-commutated converter [136]. Furthermore, generally DFIG employs voltage sourced converters with PWM technique because they produce a sinusoidal AC output voltage which is controlled in magnitude and frequency. Back to back converter has been chosen for DFIG wind turbine model in this work since it is widely used. The structure of DFIG back-to-back converter is shown in Fig 5.4, it is similar to the PMSG converter where it is separated into two sides, the rotor and grid side. Each converter consists of three-phase two-level IGBT-based inverters and a DC-link capacitor connects the two converters.

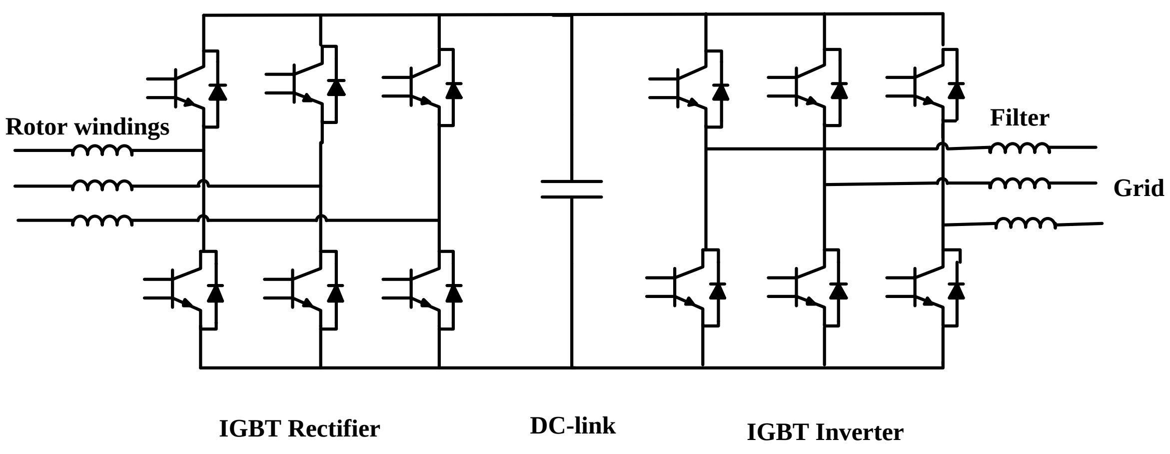

Fig 5-4: DFIG with back-to-back converter

Each AC phase is connected to two-level bridge which has positive and negative terminal connected to DC-link, thus; the inverter voltage of each phase can be only positive or negative value and as the bridge contains two levels only, a triple occurs in the output voltage. For this purpose, a filter should be added to the system to interface the inverter to the grid. Nevertheless, the DFIG rotor may connect directly to the rotor side converter (RSC) since the inductances rotor windings naturally act as filters [136]. Unlike PMSG, the stator windings are directly linked to the network while the converter is employed to couple the rotor to the grid. The main objective of the converter is to enable wide range of speed operation, this is achieved by operating the generator in both supper and sub synchronous speed where the converter duty is to handle slip power in both directions depending on the generator speed operation. If DFIG operate in speed lower than synchronous speed, the power supplied by the stator is balanced by the returning portion of the power through the rotor by the converter. Besides, during super-synchronous speed, the converter deliver power from both stator and rotor terminals to the grid.

5.3 DFIG Control

The performance of DFIG and its control strategies were extensively explained in [136]. The rotor-side converter assures wide range of generator operation and controls the generator's power (active and reactive) independently. The main task of control strategy is to capture optimum energy by wind turbine system under different wind speed conditions. The normal control falls into two parts i.e. the converter control that performs the coupling of the converter and the pitch angle control that manages the turbine blades, which were explained in section: 3.4.3. The modelling of DFIG control is illustrated in Fig5.5. the DFIG control model in Fig 5.5 is quite resumble to PMSG control model in Fig 4.6 in which generator-side converter controls the the generator active and reactive power whereas the gris side converter control the DC link and transfer the power to the grid, however, in DFIG, the reactive power is mainly produced by the machine itself so it is controlled via the generator-side converter whereas in PMSG the reactive power is produced only from the inverter since the the machine is completely isolated and then it is regulated by the grid-side converter. Moreover DFIG can produce reactive power from grid-side converter but it is limited since its size is small, thus the reactive power in DFIG is controlled by both converter sides.

An appropriate coordination is essential between the two controllers. The pitch angle control is slower in comparison to electrical control because it is operated by mechanical system means. The activation of pitch angle control occurs if the wind speed is more than its prescribed rate; whereas, there is an active participation of converter control in all sort of functional modes and it guarantees optimum function at lesser wind speeds. Furthermore, the converter control falls into two control blocks i.e. the grid-side and rotor-side converter control. The rotor side converter control regulates the rotor voltage whereas the grid side converter control regulates DC-link voltage to be in constant value and controls the converter

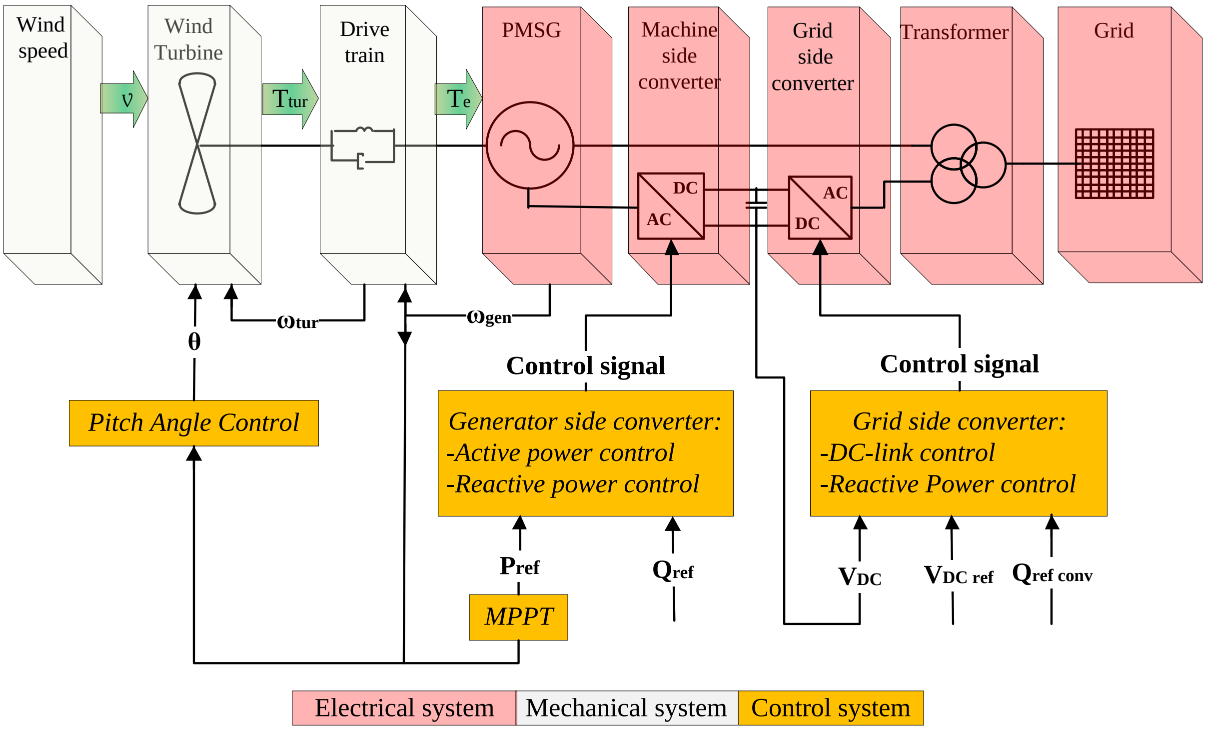

Fig 5-5: DFIG modelling scheme and control concept

reactive power. Different control strategies were applied to DFIG for example; vector control, direct power control and direct torque control. In this study, the reason behind selecting the vector control is that it is most commonly utilized everywhere.

5.3.1 DFIG reference frames selection

Usually there are three reference frame applied to DFIG to achieve the control which are:

- **Stator voltage oriented reference frame**

This reference frame normally applied to control the grid side converter and known also as Grid side converter voltage oriented reference frame. The d-axis is in alignment to the space vector of grid voltage that is associated to the stator winding and grid-side converter; hence, only the constituent d is a part of stator voltage. Consequently, through the below given equations, it is easy to attain both active and reactive power.

$$P = 1.5[V_{d-g}\, i_{d-g} + V_{q-g}\, i_{q-g}] \; = 1.5V_{d-g}\, i_{d-g} \tag{5.18}$$

$$Q = 1.5[V_{d-g}\, i_{d-g} - V_{q-g}\, i_{q-g}] = 1.5V_{d-g}\, i_{q-g} \tag{5.19}$$

where: the subscript (g) denotes to the grid, $V_{q-g} = 0$

The grid-side converter aim is to preserve the DC-link voltage at its nominal value whereas the reactive power is usually controlled to zero. The power flows in the DC bus is the same to that in AC side when the loss in the switching devices is neglected. By ignoring the loss in the switching devices, it can be outcome of from equations (5.18) and (5.19) that the DC voltage can be controlled by converter current d-component while the q-current controls the reactive power.

- **Stator flux oriented reference frame**

Under this reference frame, the space vector of the stator flux is in alignment with the -axis of the stator flux reference frame. The stator's amounts (voltage, current and flux) turns into steady state as the stator and stator frequency rotates together. For this purpose, the rotor-side converter is implemented in stator-flux oriented-reference frame. The stator resistance possesses a smallest value that can be neglected; therefore, through the integration of stator voltage, the stator flux is accomplished. The stator voltage was pause by the stator voltage at 90 degree that clearly depicts that they are perpendicular to each other. Hence, the stator voltage is illustrates the q-component in stator flux oriented reference frame. Therefore, it is simple to evaluate the active and reactive power via the below given:

$$P = 1.5\ [V_{ds} i_{ds} + V_{qs} i_{qs}] = \quad 1.5\ V_{qs} i_{qs} \tag{5.20}$$

$$Q = 1.5\ [V_{ds} i_{ds} - V_{qs} i_{qs}] = \ -1.5\ V_{qs} i_{qs} \tag{5.21}$$

where: $V_{ds} = 0$

The active power is operated by the rotor's voltage component, where it is in phase with the stator voltage through q-component; whereas, the reactive power is managed by the rotor voltage d-component. This reference frame is known as rotates with synchronous reference frame because it rotates with synchronous speed.

- **Rotor reference frame**

The rotor-reference frame d-axis is aligned to the rotor's mechanical axis of the DFIG. The rotor relatively rotates to the stator by the slip s. Consequently, the rotor reference-frame rotates with slip frequency $\omega_r = \omega_s - \omega_r = s\ \omega_s$. Therefore all the rotor quantities are then measured in the rotor reference-frame.

5.3.2 Grid-side converter control

There are two jobs that are performed using the grid-side converter in DFIF wind turbine i.e. to ensure that the DC-link is fixed regardless of the rotor power's direction and magnitude and to operate the reactive power of the converter in accordance with its reference, so as to attain unity power factor, usually the reactive power is initialized to zero; nevertheless, in order to contribute in the reliability of voltage and grid disturbance situations, the reactive power may be initialized to any value. The vector control controls the grid side converter on the basis of stator voltage oriented reference frame. Fig 5.6 illustrates the control strategy.

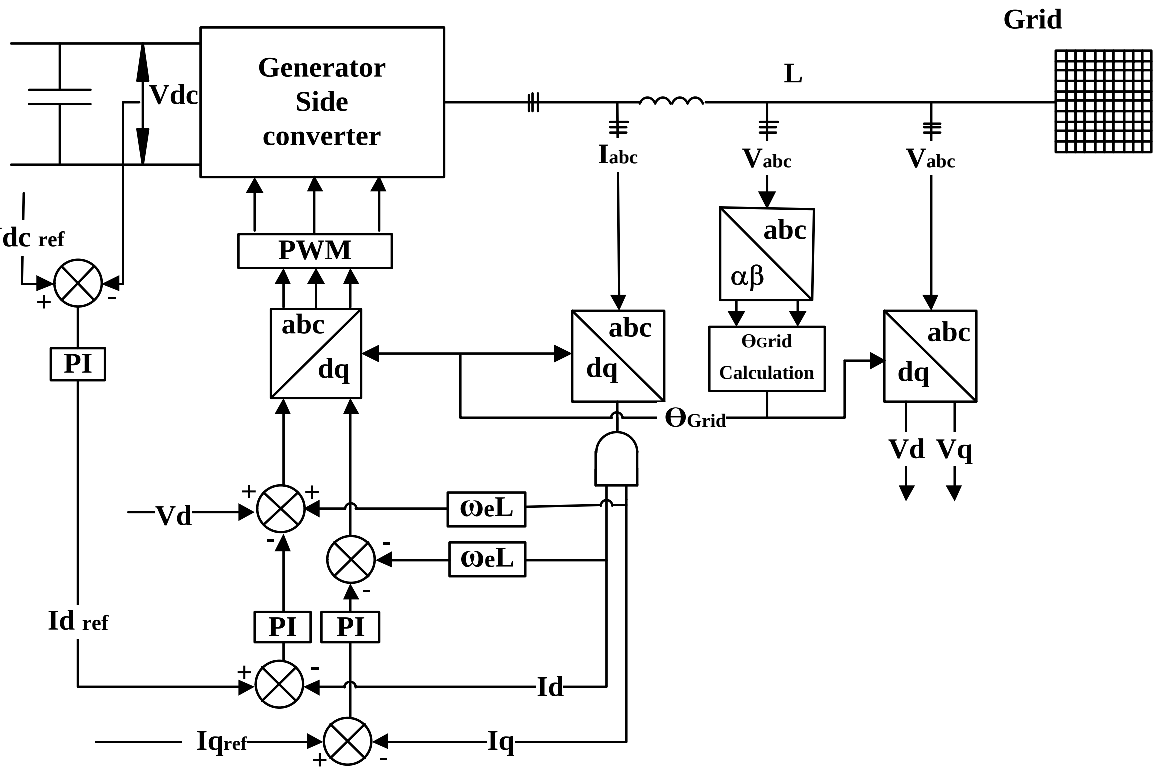

Fig 5-6: DFIG Vector control for grid-side converter in SVRF

Fig 5.6 shows that the DC-link voltage V_{DC} is controlled to predefined value $V_{dc\ ref}$ by slower outer control-loop, the resultant is the reference of d component of the converter current $I_{d\ ref}$. Another following faster loop is used to regulates the converter current I_d to $I_{d\ ref.}$

Meanwhile the converter current q-component controls the reactive power and in normal condition it is set to zero in order to achieve unity power factor operation. As the control of grid-side converter is recognized in a grid-side converter voltage oriented reference-frame where the reference of voltage vector is determined only by d-component, it becomes sufficient to control the q current (I_q) to zero, in order to accomplish the DFIG operation at unity power factor. Therefore, only just current control-loop is required, whereas the q-current is controlled to zero.

5.3.3 Rotor-side converter control

The rotor-side converter supplies voltage to the rotor winding with different magnitude. The converter controls independently the active power and reactive power through regulating the rotor voltage via its d- and q-components. In this task, we have implemented a vector control with flux oriented reference-frame (SFRF). Under this approach, there is an alignment amid the d-axis of the reference-frame and the stator-flux vector position, this results:

$$V_{ds} = 0 \ , \ V_{qs} = V = \Psi_{ds} \ . \omega s \tag{5.22}$$

The DFIG active and reactive power with vector control implemented in SFRT is given by [3.77] as below:

$$P_s = -1.5\, V_s \frac{L_m}{L_s} i_{qr} \tag{5.23}$$

$$Q_s = 1.5\ V_s\left(\frac{V_s}{\omega s L_s} - \frac{L_m}{L_s} i_{dr}\right) \tag{5.24}$$

The generic control for rotor-side converter is depicted in Fig5.7. The controller possesses two control loops with a motive to regulate the active and the reactive power. The cascaded structure is a part of both the control loop in which the reason behind the formulation of inner control loops is to accomplish faster responses and to manage the d-q current constituents to their references that the outer loops provide. For the active power loop (P_{ref}), the reference signal is provided through MPPT while for reactive power loop (Q_{ref}) the reference signal is allotted in accordance with the power system demand, it is mostly initialized to zero for unity power factor or it is provided via voltage control so as to favor the grid throughout the serious circumstances. To sum up this, in order to generate the d-q components for rotor voltage V_{dref} and V_{qref} , the outcome of the inner loops are utilized and afterwards they are inoculated to PWM-controlled frequency converter [137].

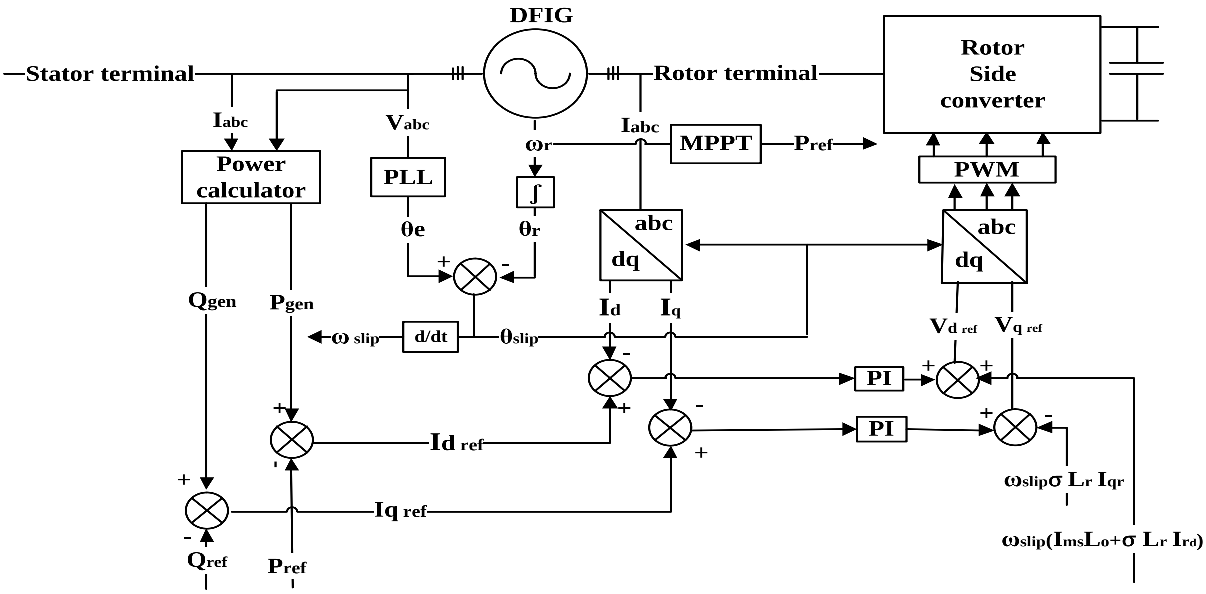

Fig 5-7: Vector control for DFIG rotor side converter in SVRF

The controller's parameters are determined according to the response of wind turbine to wind speed change and it beyond the scope of this research. As described before, the generator speed is a function of mechanical system which has a slow response time and is hence controlled by the slower acting pitch mechanism, whereas the converter control the electrical system which has a faster time response. Nonetheless, a coordination between both controllers is essential because both controls employ the generator' speed signal as their input. In pitch angle control, the speed signal is used to limit the rotor speed if it passes the rated speed, while in the converter's control the speed signal is employed to achieve the maximum power-point tracking (MPPT). MPPT obtains maximum aerodynamic power below wind speed by adjust the rotor speed so optimum tip speed ratio is obtained while the pitch angle control is deactivated in this operation and set to zero for optimal value.

5.3.4 Voltage control

With the intention to acquire grid support from the DFIG wind turbine, it is significant to implement a coordinated voltage control of DFIG to achieve better-quality procedure in grid faults. It totally rely on a strategy in which both the converters which involves RSC and GSC in a coordinated manner. The plan is to utilize the RSC as a default source of reactive power; whereas, in case the protection system is triggered and causes the blockage of RSC, GSC is utilized in the form of supplementary reactive power source.

5.3.4.1 Voltage control of rotor-side converter

With the motive to use finest DFIG control for support of grid if faults are triggered, RSC control is prolonged via voltage control block. Through the adjustment of the reactive power supply, the voltage at the point of common coupling (PCC) is regulated by this controller. The inductive or capacitive reactive power can be provided by the generator deliberately. For instance, we can use this if the reactive power is imbalanced in the system whenever the inductive load or motorizing unit is involved to the grid. The grid voltage is controlled by the voltage through providing or absorbing reactive power when the grid faults occur on condition that the crowbar is not triggered.

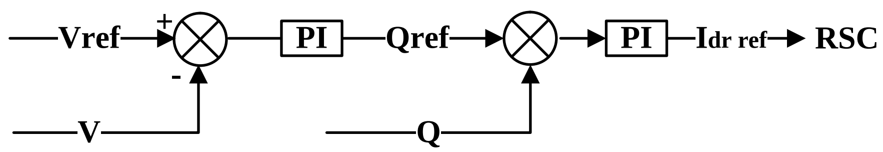

Fig 5-8: Voltage control for DFIG rotor side [103]

Voltage control for DFIG rotor side is depicted in Fig 5.6. As the reactive power encapsulated into the grid via the stator circuit is controlled by the RSC controller, this converter supplies the larger reactive power demand as compared to the GSC. Therefore, the chief motive of this strategy is to meet and manage the reactive power demand through RSC. The GSC is temporarily accountable for this job whenever the crowbar blocks the rotor side converter. Hence, it is extremely significant to ensure a coordinated voltage control amid both converters.

5.3.4.2 Reactive power control for grid-side converter

Apart from the RSC, even during the grid faults, the grid side converter is in the working state if the crowbar blocks the RSC. Later, the GSC is similar to STATCOM and provides additional services to reactive power supply.

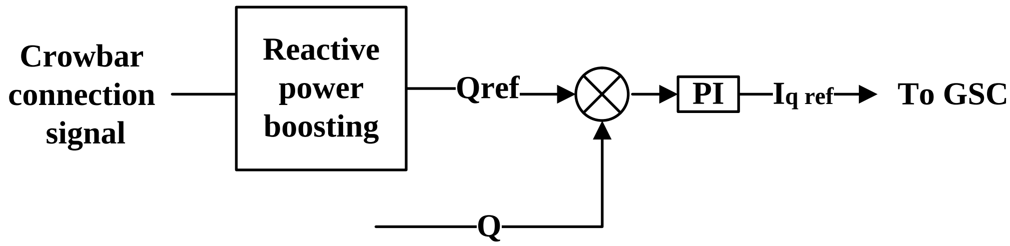

Fig 5-9: Vector control for DFIG grid side [103]

As illustrated in Fig5.9, the execution of reactive power boosting is depicted that offers a reference reactive power signals to the control of GSC. With the intention to attain the contribution of highest reactive power to voltage reestablishment from the converter, the reactive power reference for the GSC is usually set to its limits which are (+/-1 p.u.).

5.4 Summary

Chapter 5 focuses on the modelling and the control of variable speed wind turbine with doubly-fed induction generator. DFIG is the wide used WT concept nowadays sice it is simple, rigid and demands relatively small size power converter. In a first stage, a comprehensive model for steady state and dynamic of DFIG is given. Then a control strategy of the DFIG system is developed and implemented. The control is realized by vector control technique using d-q reference frames. Similarly to PMSG WT in previous chapter, DFIG control of the is realised with the aid of two coordinated controllers: a speed controller and a power controller. The power converter directly controls the DFIG active and reactive power, while the generator speed is regulated by the pitch angle. The converter control is additionally divided into rotor side converter control and grid side converter control. The rotor side converter controls the generator’s active and reactive power, while the grid side converter regulates the DC-link to constant voltage and exchange power with grid, moreover grid side converter contribures to the reactive power supply during voltage disturbances.

Chapter 6 Power Quality of Wind Turbines

6.1 Introduction

One of the rare inventions is electric power. Customers should have right to avail this facility without any interruption, however it is impossible to store it in a massive and immense quantity. Consequently, companies generate the electric power as per consumption. Moreover, generation plants of electricity are usually found outside the residence area. Owing to all these factors, it becomes difficult to regulate the quality of electrical power. The poor electric power cannot be eliminated and no procedure exists in this regard. As a result, precautionary measures need to be defined through which a smallest level of power quality could be guaranteed besides ensuring the right behaviour of the equipment that is fed from the power distribution system. If the voltage is continuous and has pure sinusoidal wave with a constant frequency and amplitude, this would be referred to as the perfect power quality. The key flaws that could compromise power quality are low-frequency conducted disturbances. These can be divided in the given below groups**:** voltage dips and short supply interruptions, harmonics and inter-harmonics, power frequency variations, flicker or voltage fluctuations and voltage unbalance [25]. The previous years have witnessed a rapid increase in the installation of wind power and other power generation units. In fact, a risky source of energy is believed to be the wind energy with respect to the power quality. In addition, when the grid involves wind turbines, power quality becomes a multifarious issue which greatly relies on the interaction between the wind turbines and the grid [29, 48, 114]. As far as power quality is concerned, the main influence on the grid due to wind turbines' integration is connected with fluctuations and voltage changes, harmonic content, flicker and power peaks. The technical features and the wind turbine's meteorological conditions are likely to determine the presence of these disturbances. These can be categorized as**:** turbulences or tower shadow; continuously variation in the output power because of tower effect, performance of electrical components for instance, mechanical performance of the rotor**,** transformers and generators and aerodynamics.

Before deployment, the engineers should estimate how the wind turbine will affect the power quality. What they actually need is the understanding with the electrical features of the wind turbine. Otherwise, an incongruous design of the grid connection would be observed as a result. The wind turbines' electrical characteristics are specific with regards to manufacturer and not specific to site. Thus, if engineers could obtain the real parameters for a certain wind turbine, they can subsequently calculate the likely this wind turbine impact on voltage quality when it installed at a specific site, probably as a multiple wind turbines.

Based on international guidelines, power quality emitted by wind turbines must be measured according to the relevant standards. For defining the power quality aspects of wind turbines, the standards' procedures were not available till the time the IEC (International Electro Technical Commission) was developed / established. In 1996, this commission started performing its operations to enable power quality for wind turbine [5]. Accordingly, at the end of 2001, the commission published first edition of this guideline, i.e., IEC 61400-21 (IEC, 2001) and afterwards, they published another extended second edition in 2008. Nowadays, the majority of big wind turbine manufacturers give the data of power quality characteristic accordingly. Now, literature contains a number of procedures for wind turbine power quality and the given below are the guiding principles containing requirements and rules for the power quality measurement of wind turbines:

- MEASNET guideline: "Power Quality Measurement Procedure of Wind Turbines" (MEASNET, 2000) [138].
- International Electrotechnical Commission (IEC) guideline IEC 61400-21: "Wind Turbine Generator Systems, Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines" (IEC, 2001, 2008) [139, 140].
- British standard (BS EN 61400-21:2008) Wind turbines. "Measurement and evaluation of power quality attributes of grid connected wind turbines" [141].
- The German guideline (FGW): "Technical guidelines for wind turbines, part 3: determination of the electrical characteristics" (2002) [142].

6.2 Power Quality Characteristics of Wind Turbines based on IEC61400-21

The power quality is considerably disturbed by the injection of wind turbines' power. The IEC 61400-21 standard contains and describes how to measure and assess the main parameters related to the power quality issues of a wind turbine. Measuring the wind turbine is conducted to be as non-site-specific as much as possible, thus the measured power quality characteristics of wind turbine at a test site are assumed to be valid at other sites. The proper formation of the test conditions is required for the validity of measurement procedure. In this regard, the MV-network is directly coupled to the wind turbine while the wind turbine terminals are used for the measurement of electrical characteristics. The rated data of the wind turbine is mandatory to be specified including rated apparent power S_n, wind turbine active rated power P_n, the rated current I_n and phase-to-phase voltage U_n Furthermore, the report test must clearly state the specific design of the addressed wind turbine as well as, the wind turbine's location and its terminals. The required power quality attributes of a wind turbine can be compromised by the seven parameters as per standard: harmonics and inter-harmonics; flicker or voltage fluctuations; active power; Response to voltage drops; grid protection; reconnection time and reactive power. In the given below subsections, those procedures and parameters would be described, which are stated for their measurement, highlighting the important issues through which the assessment of harmonic and flicker could be affected.

6.2.1 Flicker

Flicker is referred to as the instability of visual sensation made by change in the intensity of a light unit and this change is observed due to variations in the supply voltage. Moreover, this is also because of the individual nature of the sensitivity of annoyance regarding the understanding of every person to light variation. The major sources of these unrests in the electrical power system are the loads fluctuation in the power system, e.g. large machines, electric boilers, welding machines or arc furnaces [12]. As far as the power generation is concerned, the ideal voltage signal can be affected due to the wind turbines integration to the grid. The fluctuations in voltage are the most prominent among the disturbances caused by the wind turbines [18]. The fluctuating power is produced because of the fast change in wind speed, which can result in voltage fluctuations at the PCC (Point of Common Coupling), which sequentially generate flicker. The experts are likely to evaluate the flicker in terms of two quantities; short-term flicker (P_{st}) and long-term (P_{lt}) flicker severity. In addition, the flicker severity assessed over a short period (usually 10 min) is known as the P_{st} in which its critical value of irritability is set in P_{st} = 1. Whereas, the flicker severity assessed through longer period of time (two hours) is referred to as the P_{lt} and it is acquired by utilizing consecutive P_{st} values. Fig.4.1 presented the magnitude of maximum acceptable voltage change in relevance to voltage changes per min [143].

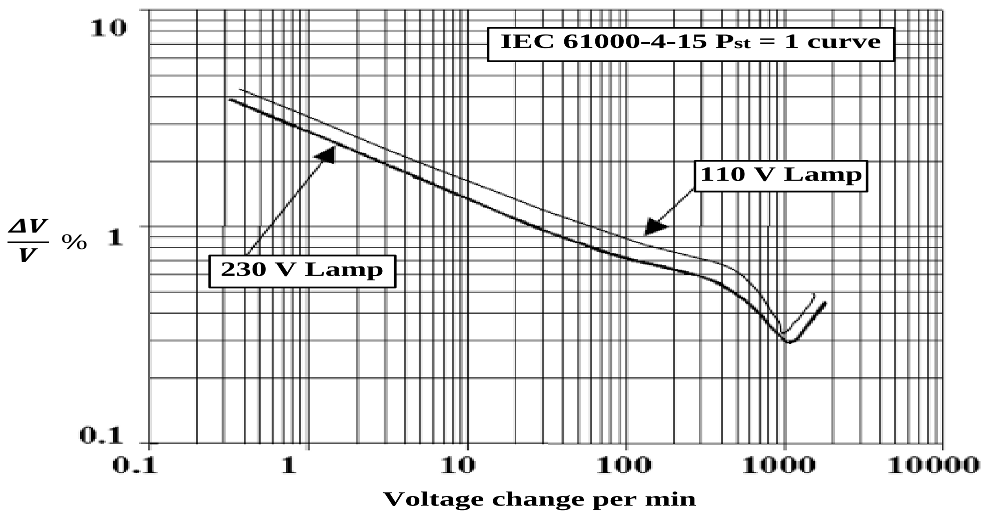

Fig 6-1: IEC curve for P_{st} =1 for different voltage change [143]

For different voltage change per min, the P_{st} =1 of two different common bulbs are shown by Fig 6.1 and it is clear that there can be an unusual change in P_{st} values with the change in voltage magnitude. When the voltage change per minute is nearly equal to 1000 change per min, then the critical value of flicker is occurred.

It is very difficult to accurately measure the flicker and for this purpose, IEC 61000-4-15 standard developed a device called flickermeter to calculate the functional specifications of flicker [143]. The block diagram of a flickermeter model is shown in Fig 6.2.

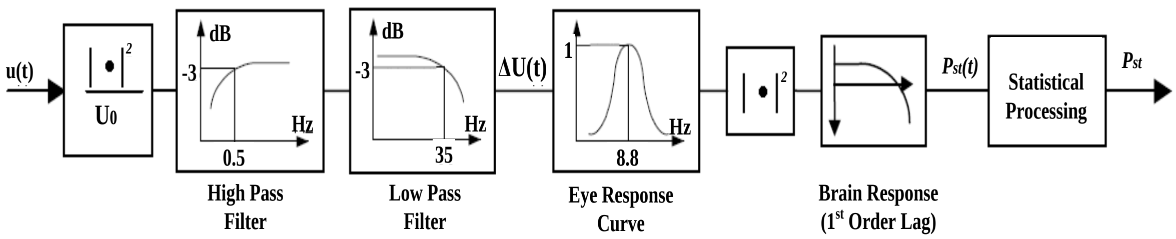

Fig 6-2: Block diagram of the IEC flickermeter [144]

The Fig.4.2 comprehensively describes the flickermeter structure and its function. The relationship between the human anxiety and voltage variation indicating a long-term, P_{lt}, and a short-term, P_{st}, indicator are represented by this flickermeter.

A test is specified by the IEC for the voltage fluctuations. The objective is to obtain the measurements apart from the attributes and network's condition where the wind turbine is coupled. Moreover, the representation of the flicker for two different situations is required by the standard. These two situations are switching operations and continuous operation. The test procedures for the two conditions are described by the following clauses.

6.2.1.1 Continuous Operation

The wind turbine typical operation, wherein either start-up or shut-down actions are not included is referred to as the continuous operation. A statistical calculation scheme and processing is established by the standard. Acquisition of the flicker coefficients is the main purpose of this scheme. Such coefficients are defined as a "normalised measure of the maximum flicker emission (99th percentile) during continuous operation from a wind turbine" [139]. The voltage measured during the continuous operation is used in estimation of these coefficients. A specific test procedure aiming to obtain the flicker coefficient is established by the specification. The system should process the phase-to-neutral voltage of wind turbine for no less than 15 registers of 10 min time-duration and same is continued for each 6, 7.5, 8.5 and 10 m/s of wind speed. Each network impedance and each time-series is defined in the standard with these values: 30◦, 50◦, 70◦ and 85◦. The wind turbine terminals are observed for taking the measurement and a grid model used for assessing the wind turbine's flicker is shown in Fig 6.3.

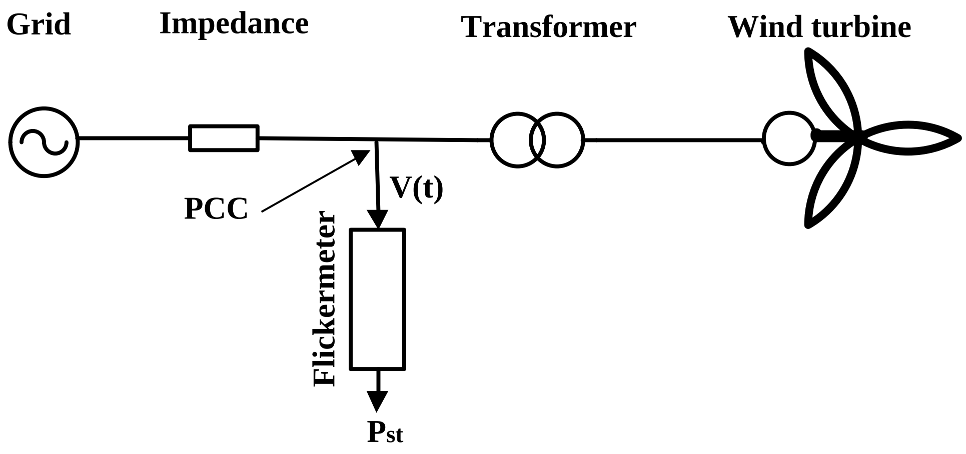

Fig 6-3: model for voltage Flicker measurement

Fig 6.3 represented a grid model for assessing the flicker emitted totally by the wind turbine, the voltage $V_{(t)}$ is measured at PCC and then set as input to the flickermeter which is compliant to IEC 61000-4-15 and then , P_{st} can be obtained. Based on the every calculated values of P_{st}, the flicker coefficient is determined by the aid of equation (6.1):

$$C(\Psi_k, V_a) = P_{st} \; \frac{S_k}{S_n} \tag{6.1}$$

The weighted accumulated distribution functions of the flicker are calculated by weighting procedure coefficients and it is carried out for every ψ_k, supposing four different mean wind speeds V_a = 6, 7.5, 8.5 and 10 m/s. Subsequently, the 99% percentile of $c(\psi_k, v_a)$ is reported for each accumulated distribution. The measurement of the reported flicker coefficients is specified by the assessment and the assessment also describes the procedure to predict the flicker level from a wind turbine (single or a group). The flicker emission (short and long-term) from the installed wind turbine must be compared to the flicker emission limits for the PCC where the wind turbine connected to, consequently, these flicker terms of single wind turbine must be obtained by equation (6.2) as follows:

$$P_{st} = P_{lt} = C(\Psi_k, V_a) \frac{S_n}{S_k} \tag{6.2}$$

The cumulative flicker emission can be estimated in case of connecting more wind turbines to the PCC, and this is shown in the form of given below equation (6.3) as:

$$P_{st.\Sigma} = P_{lt.\Sigma} = \frac{1}{S_k} \sqrt{\sum_{i=1}^{N_{WT}} \; [Ci(\Psi_k, V_a). S_{n,i}]^{2}} \tag{6.3}$$

The flicker emission limits given in equation (6.4) and equation (6.5) shall not be exceeded by the flicker level from a wind turbine.

$$P_{st} \le E_{Psti} \tag{6.4}$$

$$P_{lt} \le E_{Plti} \tag{6.5}$$

The standard IEC6100-3-7 provided in table 6.1 below describes the flicker emission limits:

Table 6-1
IEC 61000-3-7 FLICKER EMISSION LIMIT [145]

	Planning level in MV	Planning level in HV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

6.2.1.2 Switching Operation

The IEC 61400-21 standard states another procedure and statistical evaluation scheme to evaluate the effect of wind turbine at start-up, shut-down and switching between generators. To check the wind turbine effect during starting up and shutting down, three different factors must be considered:

- The total number of switching actions carried out within a 10 min (N10m) and 2-hour period (N120m).
- The standardised data of the flicker emission because of a single switching process called the flicker step factor $k_{f\,(\psi k).}$
- The standardised measure of the change in voltage as a result of a switching action called the voltage change factor $k_{u(\psi k)}$.

To calculate the value of $ku_{(\psi k)}$ and $kf_{(\psi k)}$ for every switching operation, the specification has provided a way of taking measurements and calculating the end results of the operations. The phase-to-neutral voltage $V_{(t)}$ is processed for 15 records during a period T_p long enough to decay the transient caused by switching operation. P_{st} values and the voltage $V_{(t)}$ are calculated similarly to the continuous operation case. The equations (6.6) and (6.7) can be applied to obtain $k_{f\,(\psi k)}$ and $k_{u(\psi k)}$ respectively, eventually, they are concluded in average of the 15 calculated values [139, 140].

$$k_f(\Psi_k) = \frac{1}{130}\ \frac{S_k}{S_n}\ P_{st}\ T_p{}^{0.31} \tag{6.6}$$

$$k_u(\Psi_k) = \sqrt{3}\ \frac{U_{max} - U_{min}}{U_n}\ \ \frac{S_k}{S_n} \tag{6.7}$$

By the employment of the observed voltage change factors and flicker step factors, the calculation method for switching operations explain the approximation of the flicker emission and variations in voltage throughout switching operations at a particular site.
The subsequent equation can be used to get the transient and lasting flicker parameters and a comparative analysis must be done against the determined flicker emission limits.

$$P_{st} = 18 \times N_{10_m}^{0.31} \times k_f(\Psi_k) \frac{S_n}{S_k} \quad (6.8)$$

$$P_{lt} = 8 \times N_{120_m}^{0.31} \times k_f(\Psi_k) \frac{S_n}{S_k} \quad (6.9)$$

Equation (6.10) and equation (6.11) can give us the sum of flicker emission when multiple wind turbines are attached to the PCC:

$$P_{st.total} = \frac{18}{S_k} \times [\sum_{i=1}^{N_{WT}} N_{10m,i} \times (k_{f,i}(\Psi_k) \times S_{n,i})^{3.2}]^{0.31} \quad (6.10)$$

$$P_{lt.total} = \frac{8}{S_k} \times [\sum_{i=1}^{N_{WT}} N_{120m,i} \times (k_{f,i}(\Psi_k) \times S_{n,i})^{3.2}]^{0.31} \quad (6.11)$$

Actions must be taken if an inclusive control system linked with the wind turbine installation limits the total number of switching operations.

$$d_{max} = 100 \times k_u(\Psi_k) \times \frac{S_n}{S_k} \quad (6.12)$$

The above equation can be employed to calculate the comparative change in voltage as a result of a switching operation of one wind turbine. The percentage of comparative change in voltage is represented by d [139, 140].

6.2.2 Harmonic Distortion

The utility network normally contains the voltage and current harmonics. Harmonic content is produced by rectifiers, inverters, non-linear and electronic loads etc. Equipment let-downs, hotness, protections failure and problems in communication systems are some of the impacts of the harmonics. For a wind turbine functioning under constant conditions and working with almost no reactive power, the standard explicitly details certain processes to measure the harmonics, interharmonics and any higher frequency components hence the reactive set-point control will be set to 0 if conceivable. The standard, however, does not consider short-duration harmonics produced during switching operations because the harmonics do not impact as much in such a small-time period [139, 140].

Tables need to be made to display the values of the individual and total harmonic current distortion in terms of % of I_n and the bin midpoints for wind turbine operation in the range of the active power bins 0, 10, 20, …, 100 % of P_n.
Sub-grouped values for frequencies equal to x50 of the fundamental grid frequency will represent the different harmonic current components and they shall be used to compute the entire harmonic current distortion.
According to the standard IEC 61000-4-7:2002, [146] the interharmonic current components shall be specified as sub-grouped values for frequencies up to 2 kHz while the standard IEC 61000-4-7 must be referred to for the higher frequency current components for frequencies ranging from 2kHz to 9 kHz.
Measurements affected by grid background noise must not be considered. For every 10% power bin, 9 ten-minute time-series of instantaneous current measurements must be observed. IEC61000-4-7 will be used for the calculation and grouping of the spectral components, the method of which will be selected suggesting that measurements are done on a variable source. According to IEC 61000-4-7, the precision class I will be used.
The report of the test will display the size of the window. For 60 Hz systems, 12-cycle window while the 10-cycle one for 50Hz is suggested.
Harmonic currents < 0.1 % of I_n will not be considered. The time series will not be measured using some exceptional weighting function but the all measured currents with rectangular weighting will use DFT (Discrete Fourier Transform). The active power shall be evaluated over the same time window as the harmonics.
Clause 5.6 of IEC 61000-4-7 explains how the harmonic current components for frequencies reaching x50 the fundamental grid must be sub-grouped.
The below equation can be used to calculate the total harmonic current distortion (THC).

$$THC = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_n} \times 100 \tag{6.13}$$

IEC61000-4-7 enlists how inter-harmonic current components <2 kHz shall be sub-grouped and explains how higher frequency components (2 to 9 kHz) must be calculated. Bands of 200 Hz shall represent the grouping of the output of raw DFT.

For every ten-min time-series, the frequency band (namely each sub-grouped harmonic, inter-harmonic and higher frequency current component) shall be calculated individually. Then, the top most 10-min means of every frequency band in every 10 % power bin must be stated.

The voltage harmonics during the test shall be reported. Measurement of voltage harmonics shall be achieved at the terminals of wind turbine and according to IEC 61000-4-7. 10-min average values of the complete harmonic distortion of voltage must be reported as a minimum. To evade undesirable harmonic voltages at the PCC, the harmonic currents shall be restricted.

IEC 61000-3-6 can be used to obtain the applicable limits for harmonics emission. The table below 6.2 displays limitation of current harmonics emission by the reference standard.

Table 6-2
IEC61000-3-6 Current harmonic limit [146]

Harmonic Order	IEC 61000-3-6 Current
3	-
5	5
7	7
9	-
11	3

Summation of harmonic current distortion from loads can be done by the IEC61000-3-6 standard. The equation 6.14 below helps calculate the harmonic current at the PCC because of a wind turbine installation with multiple wind turbines.

$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N_{WT}} \left(\frac{I_{h,i}}{ni}\right)^{\beta}} \tag{6.14}$$

β is to be chosen according to table 6.3, it is an exponent with a numerical value.

Table 6-3
Specification of exponents according to IEC61000-3-6 [146]

Harmonic order	β
h < 5	1.0
5 ≤ h ≤ 10	1.4
h > 10	2.0

If the wind turbines are equal and their converters' line commutated, the harmonics are likely to be in phase and β = 1 shall be used for all harmonic orders.

Higher frequency components and current interharmonics can also be evaluated using expression 6.14. As current interharmonics and higher frequency components are assumed to be uncorrelated, it is recommended to use β=2 in equation 25 for summation of these harmonics calculations.

6.2.3 Response to Voltage Dip

In wind energy generation systems, the quality of power system's service is controlled and assessed by employing the methods and process details stated in IEC 61400-21 standard. Regardless of the any problems that might occur in the network, the reliability of the system is maintained even when great inclusions of energy regenerating systems are carried out. Voltage drop presence is considered a specified issue for wind turbines behaviour in power system. These drops are random in nature and can be classified on the basis of their intensity and time. Past experiences have revealed that wind power generation is greatly affected as a result of these voltage drops and their recovery. The standard comprises of certain tests that determine whether the system is able to survive these voltage drops and to what extent exactly. This test is valid for when the turbine is not connected to the grid and consequently it is not requested to modify the voltage wave. Concerning the rated active power P_n: between 10% - 30% and P_n > 90%, the wind turbine works at two different circumstances observed in the test. The magnitude and duration of 6 rectangular voltage drops are given in Table 6.4.

Table 6-4
Specification of the test of voltage drops

Case	Magnitude of voltage phase to phase	Magnitude of positive sequence voltage	Duration (sec)
Symmetrical three-phase voltage drop	0.90 ± 0.05	0.90 ± 0.05	0.5 ± 0.02
Symmetrical three-phase voltage drop	0.50 ± 0.05	0.50 ± 0.05	0.5 ± 0.02
Symmetrical three-phase voltage drop	0.20 ± 0.05	0.20 ± 0.05	0.2 ± 0.02
Two-phase voltage drop	0.90 ± 0.05	0.95 ± 0.05	0.5 ± 0.02
Two-phase voltage drop	0.50 ± 0.05	0.75 ± 0.05	0.5 ± 0.02
Two-phase voltage drop	0.20 ± 0.05	0.60 ± 0.05	0.2 ± 0.02

Before the voltage drops and until it has recovered, time-series of voltage, reactive and active power and current are measured at the terminals by the specific method using certain test signals. Fig 6.4 shows a system to test wind turbines for respond to voltage dip. It consists of an emulator to set a fault by linking three or two phases to each other through impedance, or links the 3 or 2 phases to the ground using impedance. A short-circuit generates the voltage drops.

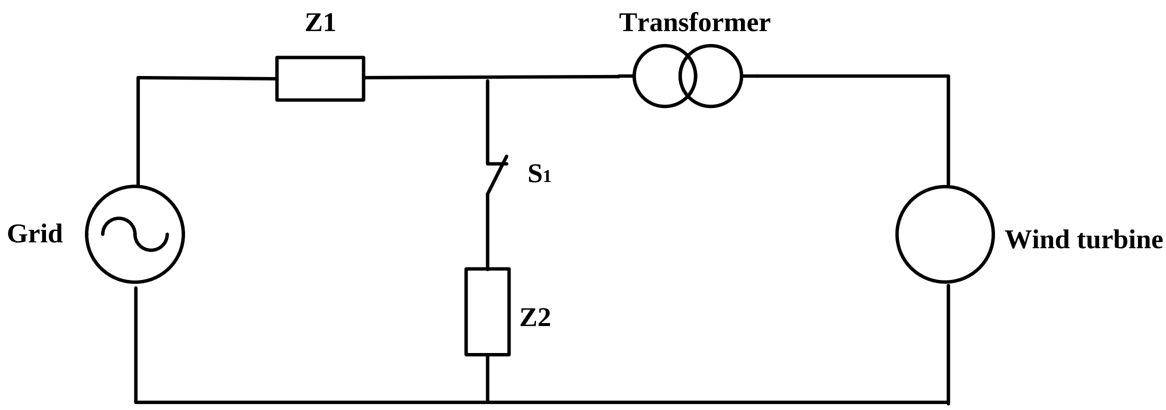

Fig 6-4: System with short circuit emulator for testing response voltage drops.

The voltage drop testing must not end up in an undesirable condition at the upstream grid and it must not disturb the wind turbine transient response considerably. The size of impedance determines both these factors. The effect of the fault on the main stream grid is limited using Z_1. Before and after the voltage drop, a by-pass link of Z_1 can be used. Another impedance Z_2 with a switch S_1 is used to drop the voltage. When the wind turbine is disconnected, the size of Z_2 shall be altered for attaining voltage intensities detailed in Table 4.4.

Equipment details must contain information about the values of the impedances Z_1 and Z_2.

A mechanical circuit breaker or power electronic device can be used as switch S_1 and it must regulate the time between disconnection and connection of Z_2, also for all three or two phases.

The voltage magnitudes specified in Table 6.1 may be affected by the wind turbine operation, but are defined for the wind turbine not connected to the setup outlined in Fig. 6.4 with the wind turbine is disconnected, the voltage drop shall be within the shape indicated in Fig 6.5. Closing time to opening time of the switch S_1 estimates the duration of voltage drop. To make up for the positive sequence voltage falling and escalating with a slope and the tolerance in working of the switch S_1, the time tolerance is included.

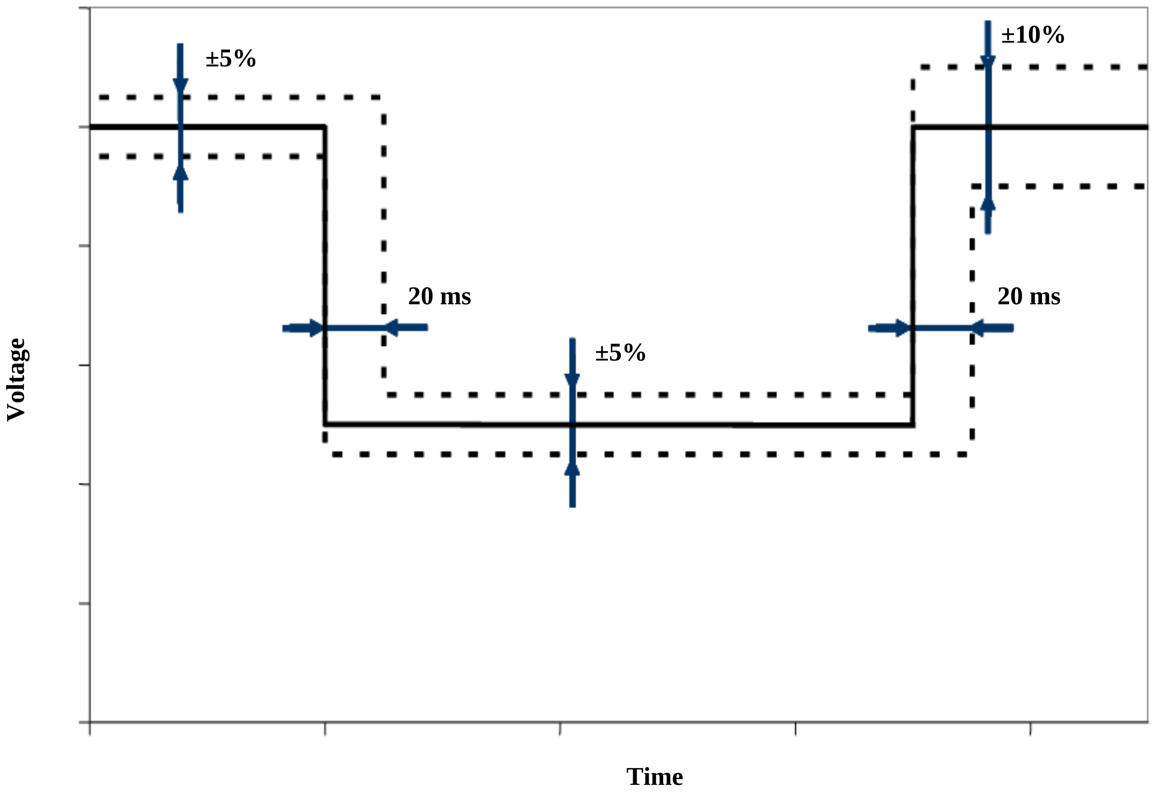

Fig 6-5: Tolerance of voltage drop [141]

To observe the response at rougher circumstances, perform the test at > 0.9 Pn and for response at the expected maximum operation (relying on conditions of the wind), carry it out between 0.1 P_n and 0.3 P_n [141].

6.2.4 Active and Reactive Power Control

The standard tests the wind speed to check the wind turbine capability to regulate the active and reactive powers. The tests might include both the wind turbine as well as its control system.

6.2.4.1 Active Power control

The three measurements regarding the active power are as follows [5, 139, 140]:

A- Maximum measured power

This shall be stated as a 0.2-sec average value (P_{02}), a 60-sec average value (P_{60}) and a 600-sec average value (P_{600}). Factors enlisted below must be kept in view while evaluations:

- Only take measurements through continuous operation.
- WT terminals must be used to measure the active power.
- For every 1 m/s bin of wind speed from cut-in to 15 m/s , at least 5 ten-min time-series of power are measured
- Measured the wind speed as 10-min mean values.
- Take $P_{0.2}$ as highest valid 0.2 sec average value.
- Take P_{60} as highest valid 60 sec average value.
- Take P_{600} as highest valid 600 sec average value.

B- Ramp Rate Limitation

The wind turbine capability to conduct in ramp rate-limitation control mode shall be specified by test results given in a graph. The graph shall show available and measured active power output during operation at 10% ramp rate value of rated power, test outcomes must be reported in terms of 0.2 sec average data.

The procedures below shall be applied when testing ramp rate limitation:

- Start the wind turbines from stand-still
- Set the rate of ramp to 10 % of nominal power per/min
- Once the wind turbine has connected to the grid for at least 10 min, then initiate the test.
- The availability of active power output shall be (as a minimum) 50 % of nominal power throughout the test.
- WT terminals must be used to measure active power.
- The test results shall be reported as 0.2 sec average data.

C- Set-point Control

The wind turbine ability to provide active power according to set-point control mode shall be conducted by test results given in a graph. Set point values changed from 100 % to 20 % of nominal power in 20 % steps with 2-min process every set-point value consistent with Fig 6.6 are showed in this graph.

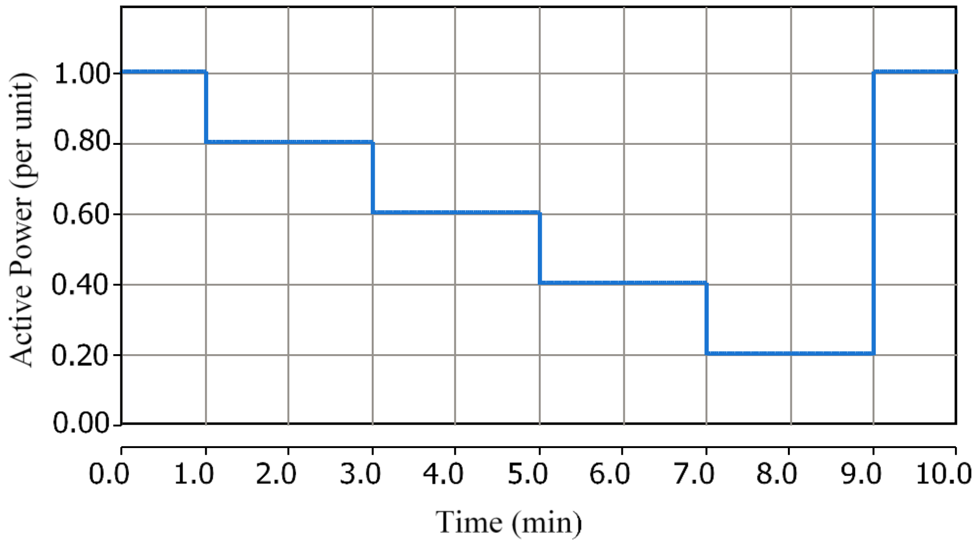

Fig 6-6: Adjustment of active power set-point [141]

The test results shall be reported as 0.2 sec average data.

NOTE the ability of a wind turbine to participate in an automatic frequency control scheme is closely linked to its ability to operate in active power set-point control mode. For example, the data acquisition system and supervisory control of a modern wind farm may regulate the active power set-point of the single wind turbines constantly to attain a particular frequency response. Therefore, participation in automatic frequency control can be done.

The following procedure shall be applied when the active power set point control is tested [140,141]:

- ❖ A test duration of 10 min is set to run the test.
- ❖ WT terminals must be used to measure active power.
- ❖ Throughout the test, maintain the availability of active power output during almost 90 % of nominal power.
- ❖ To guarantee robustness, deactivated ramp rate limitation for the period of the test.

- ❖ Set point values changed from 100 % down to 20 % of nominal power in 20 % steps with 2-minute operation every set-point value consistent with Fig 7.6.

The wind turbine's control system shall provide the active power availability, otherwise an estimated value is adopted which it is gained from combination between power curve and measured wind speed.

6.2.4.2 Reactive Power control

Two different assessments can be taken into account in order to test the reactive power capability of wind turbine. The control system, however, must be considered prior to undertaking of both assessments [139, 140].

Set-point Control

A table and graph can assist in describing the reactive power set-point control; the following procedures shall be take into account when testing reactive power:

- ❖ A mean value of 1 min can be utilized for the active and reactive capacity.
- ❖ The reactive capacity at reactive set point shall be depicted in the table, with value = 0 for operation at 0,10, 20, …100 % active power output.

The reactive power measurement shall be illustrated in the graph when reactive power reference is regulated according to Fig 6.7. The active power is set to 50 % of nominal power and it should be measured the in average values of 1 min.

One thing that must be taken into consideration is that the wind turbine capability to conduct in reactive power set-point control-mode is directly associated with its capacity to take part in the automatic voltage control scheme. The later can be achieved, for example, from the supervisory-control-and-data collection system of a contemporary wind farm which

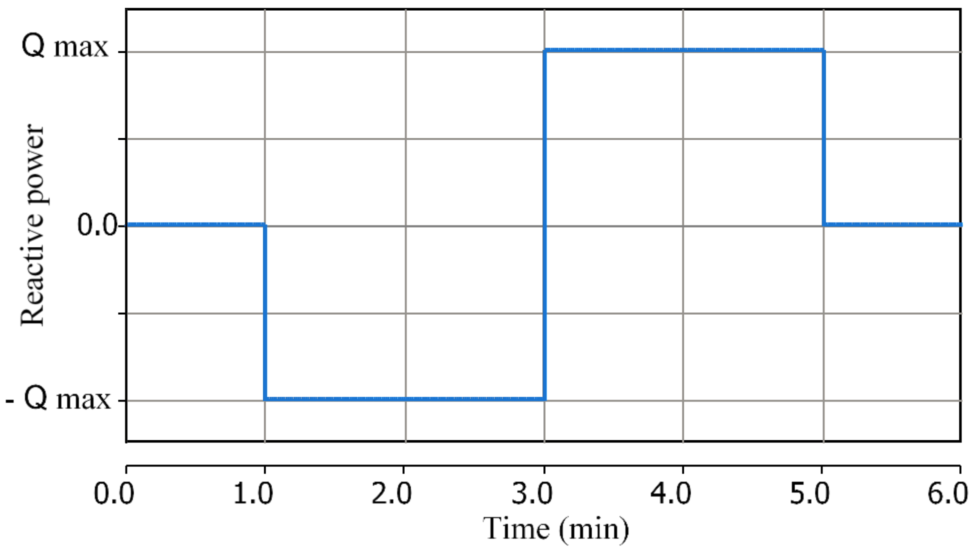

Fig 6-7: Adjustment of reactive power set-point [141]

consistently updates the reactive power set-point of the individual wind turbines for the achievement of a desired voltage response.

The following steps must be undertaken for the determination at a set point of reactive power = 0:

- ❖ It is important that the sample be only measured during the continuous operation.
- ❖ WT terminals should be utilized to determine the reactive power.
- ❖ The sample being measured should be timed so that not than less 30 one-min time-series of active and reactive power data is collected every 10% power bin.
- ❖ The sampled data shall be transferred to 1-min average data by using block averaging every 1-min time period.
- ❖ Utilizing the method of bins, the one-min average data is to be sorted in order for the reactive power to be collected in a table for 0,10, ...90, 100 % of rated power where the numbers are midpoints of the active power bins.

The following method should be undertaken for the assessment during the step change of the reactive power:

- ❖ It is important that the sample be only measured during the continuous operation.
- ❖ WT terminals should be utilized to determine the active and reactive power.
- ❖ The sample of reactive power will be 0.2sec mean of the data

- ❖ The active power output will be about half of the rated power.
- ❖ The reactive power’s set-point shall be varied as illustrated in Fig 6.7.
- ❖ Along with the reactive power’s set-point value, the measured reactive power shall be illustrated in a graph as 0.2s.

Reactive Power Capability

Taking into consideration the maximum inductive and capacitive reactive power from wind turbines, the characteristics of the WT shall be illustrated in a table as one-min mean data as function of the one-minute mean output power for a range of 0, 10, 20,…. 90,100 % of the nominal power. Moreover, the wind turbine shall be set to the operation mode of the maximum inductive reactive power for allowing the determination of maximum capacitive reactive power in the complete range of the power.

The procedure given below must be applied for every two setting modes:

- ❖ It is important that the sample be only measured during the continuous operation.
- ❖ WT terminals should be utilized to measure the reactive and active power.
- ❖ At least 30 1min in time-series of reactive and active power must collected at each10 % power bin while taking the measurements.
- ❖ The block averaging for each 1 min period should be used on the sample data, so that 1 min average data is transferred.
- ❖ The 1 min average data shall be sorted according to the method of bins so that the reactive power can be specified as average bin values in a table for 0, 10, ...90, 100 % of rated power. Here 0, 10, ...90, 100 % are the midpoints of active power bins [141].

6.2.5 Grid Protection and Reconnection Time

6.2.5.1 1- Grid Protection

Tests are carried out to assess the functionality of the wind turbine grid protection system. The disconnection levels and disconnection times obtained from these tests will help to determine the actual disconnection levels and disconnection times of the WT for over- and under-voltage and over- and under-frequency. Any given voltage or frequency that causes the wind turbine to disconnect is known as disconnection level. The time duration from start of the under-/over- voltage or frequency and until the wind turbine has completely disconnected is known as disconnection time. A separate three-phase voltage source, having variable voltage and frequency and fed into the control of the WT is used to perform this operation. The set-point protection levels and disconnection times of the WT controller shall also be specified. The generator of the wind turbine is powered off while performing these measurements concerning the grid protection to avoid any safety hazards [140].

- The procedure given below shall be applied to determine the protection levels:

❖ Under-voltage protection level, (U_{under}): The voltage of the separate 3 phase voltage supply shall be gradually decreased from 100% of nominal voltage in all three phases at nominal frequency, 1% of nominal voltage is decreased in each step which consists of 20sec until the WT disconnects completely.

❖ Over-voltage protection level, (U_{over}): The voltage of the separate 3 phase voltage supply shall be gradually increased from 100% of nominal voltage in all three phases at nominal frequency, 1% of nominal voltage is increased in each step which consists of 20sec until the WT disconnects completely.

❖ Under-frequency protection level, (f_{under}): The frequency of the separate 3 phase voltage supply shall be decreased from 100 % of nominal frequency at nominal voltage where 0.1Hz is decreased every 20sec until the WT disconnects completely.

❖ Over-frequency protection level, (f_{over}): The frequency of the separate 3 phase voltage supply shall be increased from 100% of nominal frequency at nominal voltage where 0.1Hz is increased every 20sec until the WT disconnects completely.

- Procedure given below will be employed to determine the disconnection time:

❖ The disconnection time of the wind turbine is determined either from the data sheet of the wind turbine or by a measurement of the disconnection time independently.

❖ The time duration from the beginning of the voltage drop until the wind turbine has disconnected can be defined as the disconnection time.

❖ Under-voltage: A step in which voltage is shifted from nominal voltage to U_{under} –5% of nominal voltage and is then fed to the circuit breaker of the WT by the separate voltage supply.

❖ Over-voltage: A step in which voltage is shifted from nominal voltage to U_{over} + 5% of nominal voltage shall be given to the circuit breaker of the WT by the separate voltage supply.

❖ Over-frequency: A frequency step from nominal frequency to f over +1Hz shall be given to the circuit breaker of the WT by the separate voltage supply.

- ❖ Under-frequency: A frequency step from nominal frequency to f under –1Hz shall be given to the circuit breaker of the WT by the separate voltage supply [141].

6.2.5.2 Reconnection Time

After the disconnection of wind turbine because of a grid failure, the reconnection time must be specified by test results given in a table. The table have columns that represent the reconnection time after the grid failure for 10-sec, 1-min and 10-min. The reconnection time is defined to be the time that wind turbine takes to start providing the active power from the instant that the grid is available on the terminals of wind turbine. The procedure given below should be applied [140]:

- ❖ During the reconnection time the average wind speed shall be greater than 10 m/sec.
- ❖ The circuit breaker in the grid should be opened rendering the wind turbine unavailable. This breaker will typically be the MV breaker coupling the wind turbine to utility grid. The breaker shall be opened while the wind turbine is still in operation. When the breaker is closed, grid is made available again to the wind turbine.
- ❖ The failure time is clarified as the time period between opening and closing the breaker. The breaker is operated manually in majority of grids, a tolerance of ±1 sec should be applied to grid failure time.
- ❖ The measurement of active power is performed at the WT terminals.
- ❖ The measurement of voltage is performed at the WT terminals.
- ❖ The reports of the test results are based on 0.2sec average data of the power and voltage.

The reconnection time is determined from the time when the voltage returns to its normal level (between 0,9 and 1,1pu) to the time when wind turbine starts producing power again on the basis of voltage and power measured in these tests ($P > 0$).

6.3 **4.3.1 Fault Ride-Through (FRT)**

Transmission system operators (TSO) in several nations are establishing grid connection needs for the wind generators to make sure that electric system is stable and has sufficient amount of access to wind power, which are also called grid codes. They fulfil various technical needs. The rules are formed on the basis of the size of MW and as per the country setup. General needs consist of the following: wind farm modelling, active power control¸

voltage control, ranges and quality, fault ride-through ability, frequency control and ranges, tap-changing transformers along with authentication [147]. This particular research includes the needs for fault ride-through (FRT) ability of the wind turbines. This capability of the wind turbine allows it to stay linked to a grid throughout a voltage dip. Inside many grid codes nationwide; use of a voltage profile is made in order to define the ability that wind turbines are supposed to bear while being linked to a grid. In addition to this, wind turbines have another task to sustain the grid voltage as a result of defined needs [67].

6.3.1 Fault Ride-Through (FRT) Capability

The capacity of the wind turbine system to stay steady and linked to the network in case of any issue which can happen on the network is defined as the fault ride-through ability of generators which is also known as low-voltage-ride-through ability [147]. Due to errors in the transmission systems huge temporary voltage defects in a power system can be caused. It is believed that huge standard synchronous generators usually stumble simply when there is a long-term fault on the grid through which they are directly connected. Design of each power system is made in a way so that it can bear large unexpected loss of a particular value of generation capacity and it can function accordingly. If a generation unit is connected to healthy grid lost the connection and stability during and or after a grid fault, this generation will be lost. It is evidently seen that the frequency of the system is reduced at a very fast rate in case of huge loss of generation and the need of load shedding arises in order to make sure that the system remains stable [148]. Previously, wind turbines had quite less needs regarding their functioning during a grid fault; they used to cut off in the duration as per the voltage amplitude and fluctuations in the frequency. Presently, needs for FRT demands the wind turbines to stay connected along with this in few countries to support the grid and keep the power system stable. Needs of grid code for the FRT ability for the WTs vary from one grid code to other, to illustrate this point of view, an example of FRT in great Britain, German, and Danish grid codes are described in this study.

6.3.2 Requirements for FRT Capability in Great Britain (National) Grid Code

A general idea of the FRT needs inside the British national grid codes formed for the wind turbines is mentioned in the discussions below. In Fig 6.8 voltage profile for VRT is shown.

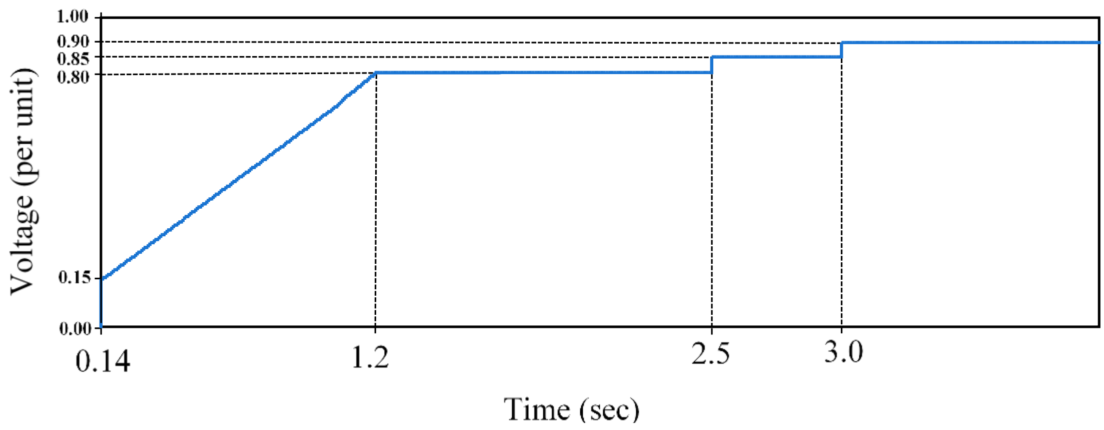

Fig 6-8: FRT Voltage Profile in National grid code [149]

As per the Fig 4.8 it is seen that the voltage has fallen to 0 (normally happens due to a fault) and stays for 140 m-sec after that it retains 80% of its value in 1.06 sec and it lasts for 1.3 sec, then rises up till 85% of its ration and stays for 0.5 sec, then one more rise of 5% happens.

In [149] FRT needs are described of the Grid Code of the Great Britain. The entire needs are not described through a voltage duration curve though the synopsis contains the following needs [150]:

1- Wind turbine system must not loose the connection or stability during fault (balanced or unbalanced) last for 140 m-sec on high-voltage power system (200kV or greater). Every generating unit is supposed to generate the greatest reactive current throughout the time of fault to the transmission system and should not going beyond the transient rating of the generating unit during the 0.5 seconds of resolving the fault, almost 90% of the intensity of the active power production of the nominal power should be brought back to straight away prior to the occurrence of the defect.

2- Wind turbine system must not loose the connection or stability during fault (balanced or unbalanced) more than 140 m-sec on high-voltage power system (200kV or greater) wherever at or exceeding the solid line illustrated in Fig 4.8.

3- Every generating unit should be given active power output not less than the amount of the restored balanced voltage on the transmission system throughout the time of voltage dip, and it should generate greatest reactive current and should not go beyond the transient rating boundaries of the Generating Unit.

Moreover, all Generating units should retain not less than 90% of the active power output which was produced just before the fault occurrence during one second after the voltage recovery at generators' terminals.

6.3.3 Requirements for FRT Capability in Danish (Energinet.dk) grid Code

Each and every wind turbine constructor is supposed to provide a simulation model of the wind-turbine system in suitable power system software (PSSE, Matlab, DIgSILENT, PSCAD) due to the requirement of the "Danish transmission system operator Energinet.dk" [151]. The transmission system operator should be provided with the test report on the basis of simulation model that is accountable for authenticating the dynamic performance of the wind turbine during grid faults. There are some conditions that should be kept in mind at the time of simulation of the grid fault. When the fault incident had not occurred, the wind turbine should be functioned at a wind speed that leads to rated power production and at nominal speed. Furthermore, in order to prevent short circuit, full compensation of the system is needed. It is preferable and adequate to simulate a three-phase fault since the worst-case scenario is illustrated by this short circuit. The grid is categorized through an R/X ratio of 0.1 and possess a short circuit power S_k of ten times the rated wind turbine power P_{wind}. A machine transformer is used to connect the wind turbine to the grid. With the purpose of short circuit simulation, the voltage source should be passed through a predefined voltage profile. Fig 6.9 depicts the voltage profile. The RMS values of the wind turbines characteristic amounts should be a part of the test report.

The voltage profile specifies the fault ride-through. This voltage profile simulates a voltage reduction of 25 % rated voltage lasting for 100 m-sec and then linearly increase till the voltage up to 75 % at 750 m-sec. The voltage is recuperates completely greater than 90% 10sec after the fault occurrence. The voltage profile specifies a lower margin where the wind turbines must stay connected at or above this margin. Disconnection will only occur in case a grid fault leads to a voltage drop lower than the prescribed voltage profile.

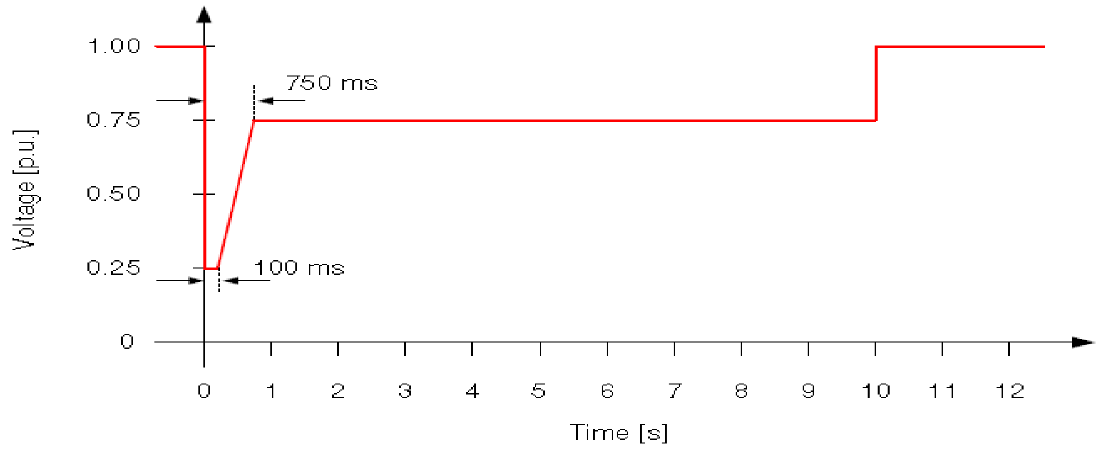

Fig 6-9: FRT Voltage Profile in Energinet grid code [151]

The production of active and reactive power from the wind turbine is specified by the Energinet.dk grid code throughout the grid fault. Besides, when the voltage dip is concerned, the active power at PCC should fulfil the requirement of the following equation:

$$P_{current} \geq 0.4 \; * P_{t=0} * \left(\frac{U_{current}}{U_{t=0}}\right)^2 \tag{6.16}$$

Furthermore, the contribution of wind turbine to reactive power production is achieved by remaining reactive current. In short, it is possible to accomplish reactive power supply on the basis of provided active power. Consequently, the wind turbine is accountable to generate or absorb highest reactive current of 1 p.u [151].

6.3.4 Requirements for FRT Capability in German (E.ON) Grid Code

The first power system operator was the "German transmission system operator E.ON Netz", who came up with grid codes specialised on wind turbines. Nowadays several other network operators worldwide establish grid codes. In accordance grid faults, the requirements of FRT and reactive power injection are nearly similar in the grid codes of E.ON Netz GmbH and the specification given by Energinet.dk. There is a slight difference between the voltage profile described by E.ON and the one depicted in Fig 6.10 outlining the limiting curve, above which there is a need of wind turbines to achieve FRT. The voltage profile falls into four fields or areas. The area above the dotted line is area 1 in which the generation unit is not allowed to disconnect. Area 2 is described by the solid line in which there is a need of FRT;

however, it is in favour of short term interruption of the generation unit as long as occurring instability exist. The voltage profile states voltage reduction of 0 % of the voltage and last for 150 m-sec following by linear rise in the voltage till 90 % at 1.5 sec after the fault occurrence. Therefore, the E.ON defined voltage drops are profounder and elongated in comparison to Ernginet.dk profile whereas it is somehow resemble to National grid code. Nevertheless, apart from this, the severity of the need of Energinet.dk to withstand a fault leads to a 75 % voltage level and last for 10sec is greater than the E. ON requirement in reference to overall voltage re-establishment. There is no need of any FRT for area 3 and 4 in Fig 6.10 [152].

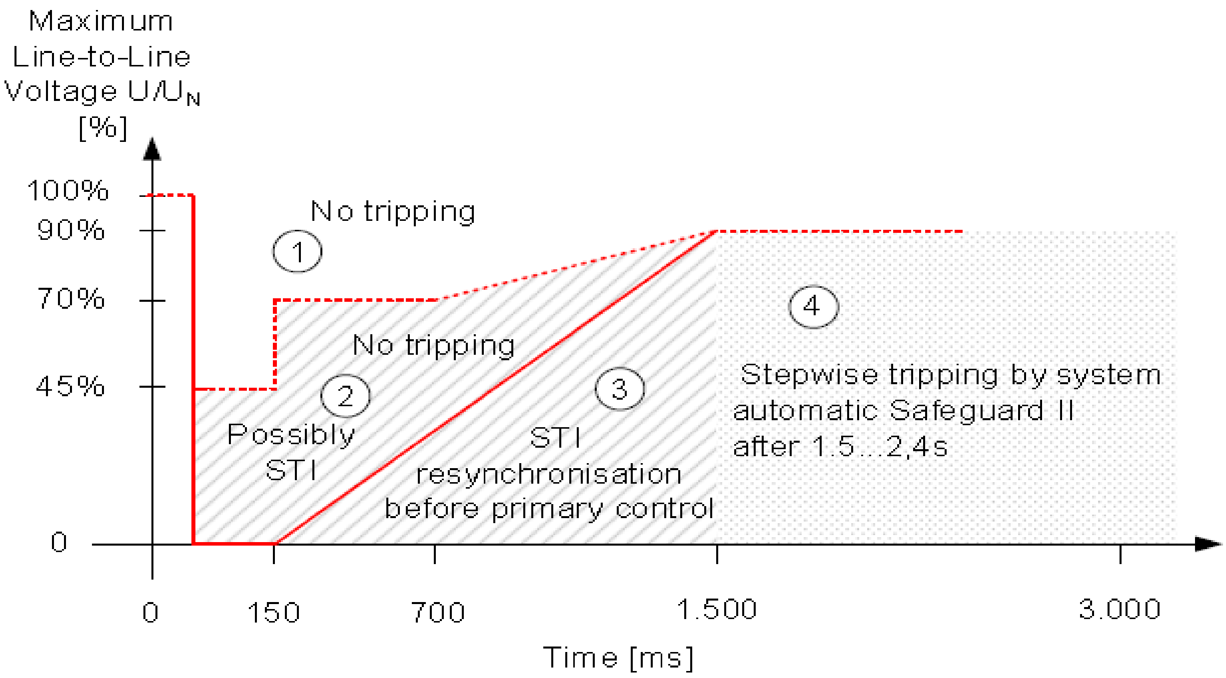

Fig 6-10: FRT Voltage Profile in E.ON grid code [153]

In opposition to Danish grid code, the supply of reactive power during voltage dip is needed by the E.ON Netz GmbH. The wind turbine reactive current must be provided independently of the voltage level which is as follows [152]:

$$(I_Q - I_{Q0}) \geq 2 * \frac{(U - U_0)}{U_n} * I_n \tag{6.17}$$

There highest reactive current of 1 p.u. is needed for voltage drops lower than 50 % of rated voltage. Besides, according to E.ON, the needed reactive current within 20m-sec rise time should be attained by the voltage control after the recognition of fault. Apart from the

Energinet.dk grid code, there is no specification of the active power production throughout the fault. Which clearly shows that the reactive power supply is line up and there is a need of highest reactive power for voltage drops lower than 50%. Hence, there is no remaining current for active power production.

6.4 Short-Circuit Current of Variable-Speed Wind Turbines

A short-circuit (SC) is defined as an unwanted function of an electricity network, resulting due to irregular connection that takes place due to fault among two or more positions at other voltage potentials in general functioning. It causes unacceptable overloading of equipment (transformers, transmission lines, cables, generators, etc) that can even lead to damage of some components. Examining, functioning, and design of the electrical power systems need many studies in order to analyse and estimate the performance, consistency and security of the system, for instance: stability, secure device synchronization, initiating the motor, dependability analysis along with short-circuits. Researches regarding short circuits are often conducted by the power system organizations and such researches give greatest SC current utilized for designing the electrical units which are (transformers, circuit breakers, and cables) and minimum SC current for appropriate relay setup and mechanism. In this manner, accurate design can be achieved and proper security of the power systems can be ensured and it permits secure and cost-effective functioning. Few unlikable effects of improper in dimensioning and securing the power system are the following:

- Disturbance in the power supply.
- Destruction of the electrical apparatus.
- Extra-high voltages.
- Heat and thermal stresses of the machine.
- Damage of security and consistency of the power supply;

Extensive wind power incorporates results in an increased impact on the power quality when the established capability of the wind power farms is increased. The raised capacity of wind power causes a larger short-circuit being given to the power system. The study on short-circuit current behaviour of the wind turbine is quite important as every type of wind turbine contains different effects on the power grids. Currently several researchers have conducted study on the impact of the short-circuit defects on wind farms and the short-circuit features of various wind turbines. In this research short-circuit features of PMSG as well as DFIG wind turbines will be focused.

6.4.1 Short Circuit Current from DFIG Wind Turbine

Use of DFIG wind turbine is made with a wound-rotor induction generator. This type of wind turbine has a variable speed operation where the shaft speed varies within a slip range of ±0.3 of rated speed. It is considered same as a normal induction generator apart from added rotor voltage (V_r), that displaying a voltage provided by the converter. In order to secure the power electronics converter from the effect caused by overvoltage and crash due to heat throughout the SC faults, a crowbar technique is utilised. For the purpose of limiting the DC voltage, another technique is also can be made by adding dynamic braking on the dc bus. The rotor terminals are necessarily short circuited because by appropriate crowbar resistance (R_{CB}), in the situations of faults. As there is a direct link between stator windings and grid, a temporary inrush current take place in the fault. As per [89], for a DFIG generator the constant transient time ($T'_{r.CB}$) is given as:

$$T'_{r.CB} = \frac{L'_r}{R_r + R_{CB}} \tag{6.18}$$

Along with this the, maximum SCC of a DFIG is given as:

$$i_{max} = \frac{\sqrt{2}V_S}{\sqrt{X_S'^2 + R_{CB}^2}} \left[e^{-\frac{\Delta T}{T'_S}} + (1-\sigma)\ e^{-\frac{\Delta T}{T'_{r.CB}}} \right] \tag{6.19}$$

In the conditions where $R_{CB} \gg R_r$, the $T_{r'.CB}$ is less and the time when the first peak is formed is given as $\Delta T \rightarrow 0$. In this situation, Ref [123] suggests a simplified equation for DFIG maximum SCC.

$$i_{max} = \frac{1.8V_S}{\sqrt{X_S'^2 + R_{CB}^2}} \tag{6.20}$$

As can be deduced from equation 6.20, a higher crowbar resistance may cause a less peak current; whereas a maximum crowbar resistance value ($R_{CB \cdot max}$) can be determined if most permissible rotor-voltage is known.

6.4.2 Short Circuit Currents from PMSG Wind Turbine

As mentioned before the PMSG wind turbine is completely integrated to the grid through a complete power converter and hence the current can be managed right away through the help of the inverter (GSC). The SCC caused by a three-phase fault is restricted to the nominal current or just a bit greater than it. It is quite usual to design PMSG power converters to have an overload ability of 10% over their rated. Keep in mind that in all kinds of fault situation, the generator remains linked to the converter and separated from the fault on the grid [90]. Therefore, even if there is defect in the grid, the generator output current is managed to remain in the current boundary (e.g., 1.1 p.u.). Though, it should be noticed that when there is a fault on the grid, the provided output power is smaller than the rated power. Though a balance can be made in the currents, because of decreased voltage or an unbalanced voltage; a decreased output power is provided. Consequently, the wind turbine should be controlled for the purpose of decreasing the aerodynamic power respectively (pitch control along with converter control). Any difference between the input power (generator to converter) and the output power (inverter to grid) will cause rise or drop the DC bus voltage.

6.5 Summary

The power quality is considerably affected by the integration of wind turbines. The present chapter gives a description and assessment of the main power quality characteristics caused by integrating wind turbines to the grid. Measurements' procedures, definition and assessment of these characteristics are stated in the IEC61400-21standard. This standard has become the reference normative for the certification of the grid-connected wind turbines in terms of power quality. Based on the standard, seven parameters are stated regarding the power quality of wind turbine which are: flicker; current harmonics; response to voltage drops; active power; reactive power; grid protection and reconnection time. A comprehensive experience and knowledge on power quality problems are required for the implementation of the measurement and assessment procedures. Furthermore, fault ride through and short circuit current also were described, the voltage profile and the requirements for fault-ride through of three grid codes was given which are: British, Danish and German grid codes.

Chapter 7 Simulation Results and Discussion

7.1 Case Study

A case study of distribution network dispersed with WTs is modelled and simulated to measure and assess the power quality produced by PMSG and DFIG variable speed WTs; both topologies are equipped with back to back converter. The control strategies for these WTs are described in previous chapters. Fig. 7.1 illustrates a radial diagram of the proposed power system.

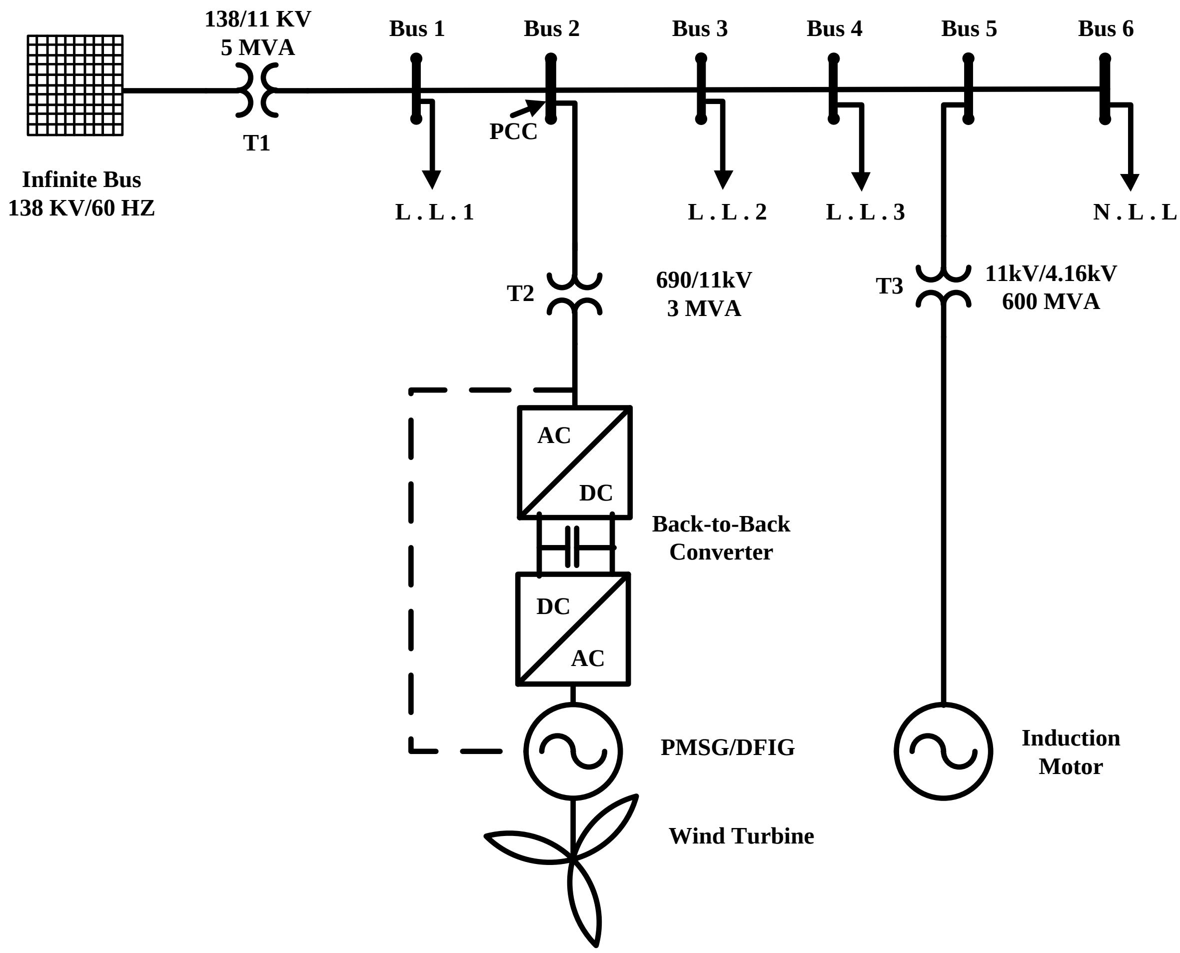

Fig 7-1: **Radial diagram of the case study [154]**

A medium 11 kV distribution feeder with two generation units i.e. the wind turbine and infinite bus is a part of the power system depicted in Fig 7.1. The feeder is associated with 5 loads, which involves three almost same linear loads with lagging power factor of 0.8, nonlinear DC motor load and motorized load. In total, there were 3 transformers that were installed to the feeder out of which, two had the motive to step-down the voltage at the main in-feed point and the motorised load connection point and one is a step-up transformer for integrating the WTs. The wind turbine was functioned at dissimilar speed and all weighs. Also, At PCC, faults were carried out. In the appendix the description of the system constraints is depicted.

7.2 System Performance under Variable Wind Speed

Wind turbine equipped with PMSG and DFIG are implemented in PSCAD package to evaluate their performance and dynamic behaviours under normal operation and different wind speed circumstances, first; steady wind speed profile (deterministic wind speed) with no turbulence intensity is applied to the system and then; a random speed is adopted.

7.2.1 PMSG performance at cut-in to cut-off wind speed

In this section, the PMSG WT is experienced under steady wind speed to address the ability of the system to track the change in aerodynamic power. In Fig 7.2 usual quantities of the PMSG wind turbine system are shown for steps in wind of 1 m/sec per 30sec, these quantities include generator speed, pitch angle, wind speed and active power. It is has been proved by Fig 7.2 that the pitch angle is passive at or below the rated wind speed which gives maximum aerodynamic power. In the meantime, the converter controller regulates the active power according to reference signal gained from maximum power-point tracking scheme (MPPT) so all available aerodynamic power can be gained and converted to electrical power. The increase in power does not occur instantaneously when the wind speed rises because the reference power is given by speed control which is determined by the generator rotor speed, the generators' rotor speed increases as the wind speed increase in a manner that optimum power obtained from wind, there are a time delay in rotor speed to reach its desirable speed because of high inertia of WTs.

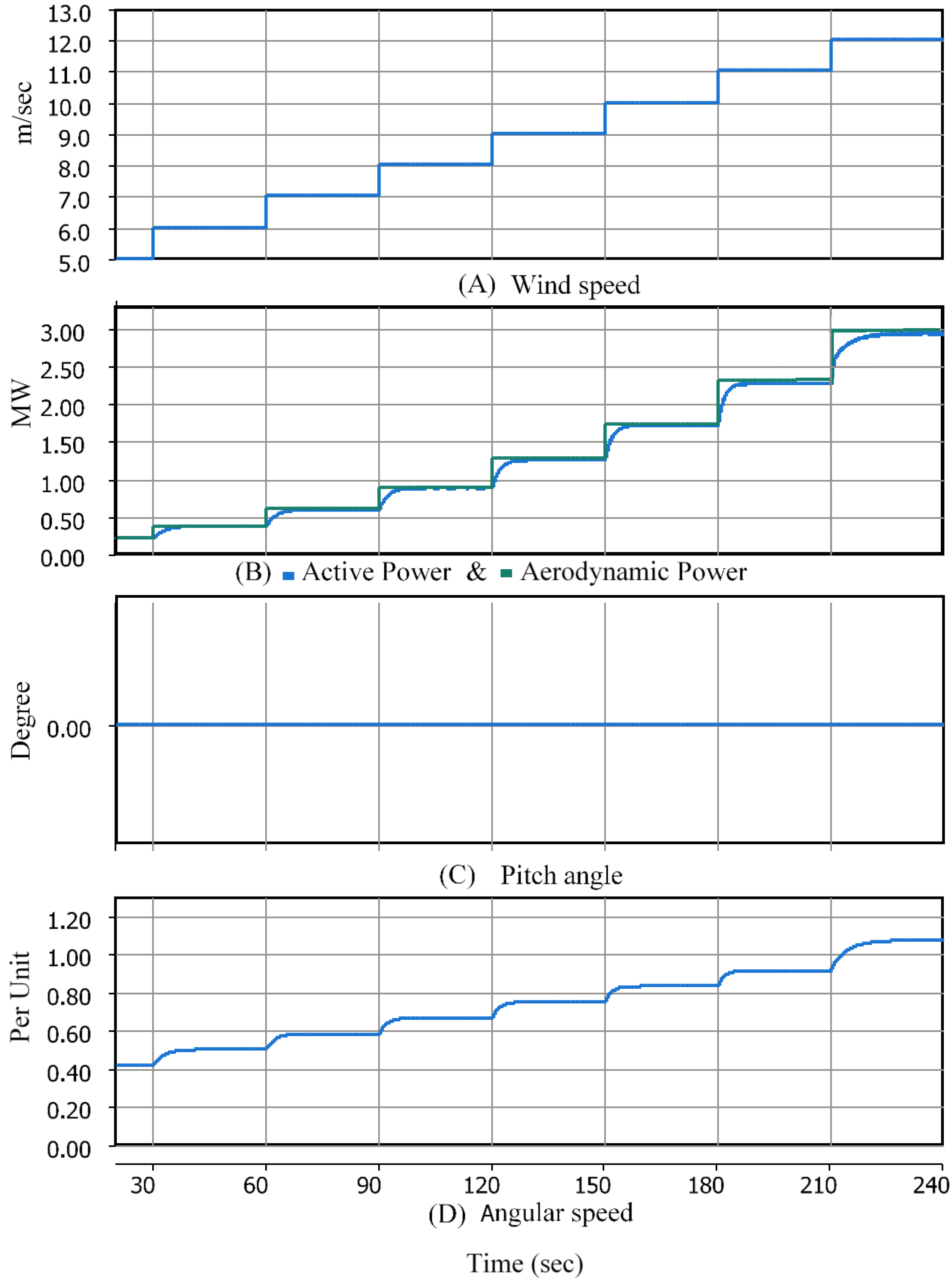

Fig 7-2: PMSG under varying wind speed from 5 m/sec to 12 m/sec.

7.2.2 PMSG performance at high wind speed

In condition where the wind speed is above rated value, the WT is required to keep its output power at rated power and not exceed this value in order to protect the generator, for this purpose the PMSG were examined under high wind speed (above rated) to demonstrate the performance of WTs in this condition, the simulation results where depicted in Fig 7.3, the WT were operating in rated speed when a sudden change in wind speed of 2 m/sec occurred and last for 30sec and then another steps in wind speed of 2 m/sec to each 30sec till the wind speed reach cut-off wind speed which is 20 m/sec.

Fig 7.3 presents the response of wind turbine parameters: active power, rotor speed and pitch angle for wind speeds above its rated. The generator speed and the pitch angle responded to wind speed changes. However, this response does not cause large overshoot and oscillation in the active power and rotor speed. The power controller limits the active power to its rated value which is 3 MW, however, a slight deviation of 0.5 % occurs because the mechanism of blade control reacts slowly in comparison to the power controller. Thus small dynamic deviations are allowed in the generator speed in order to absorb sudden rise in turbine power caused wind gust and store in turbine's inertia [103].

The simulation results approve that PMSG wind turbine has a good dynamic performance during varying wind speed operation.

7.2.3 PMSG performance at random wind speed

In reality, the natural wind speed is not purely stable and it has fluctuation and gusts depending on the ambient environment, for this purpose the WTs have to be tested under fluctuating wind speed to assess the performance of the blades and system controllers. The adopted wind profile in this simulation is chosen to be rated speed as a mean speed with turbulence intensity of 30% so the WTs operation overlapping between low speed and pitching operation. Fig 7.4 show the performance of PMSG when varying wind speed applied and how the active power, generators' speed and pitch angle respond to this fluctuation.

The result in Fig 7.4 shows that when the WTs rotor speed goes above their rated the pitch

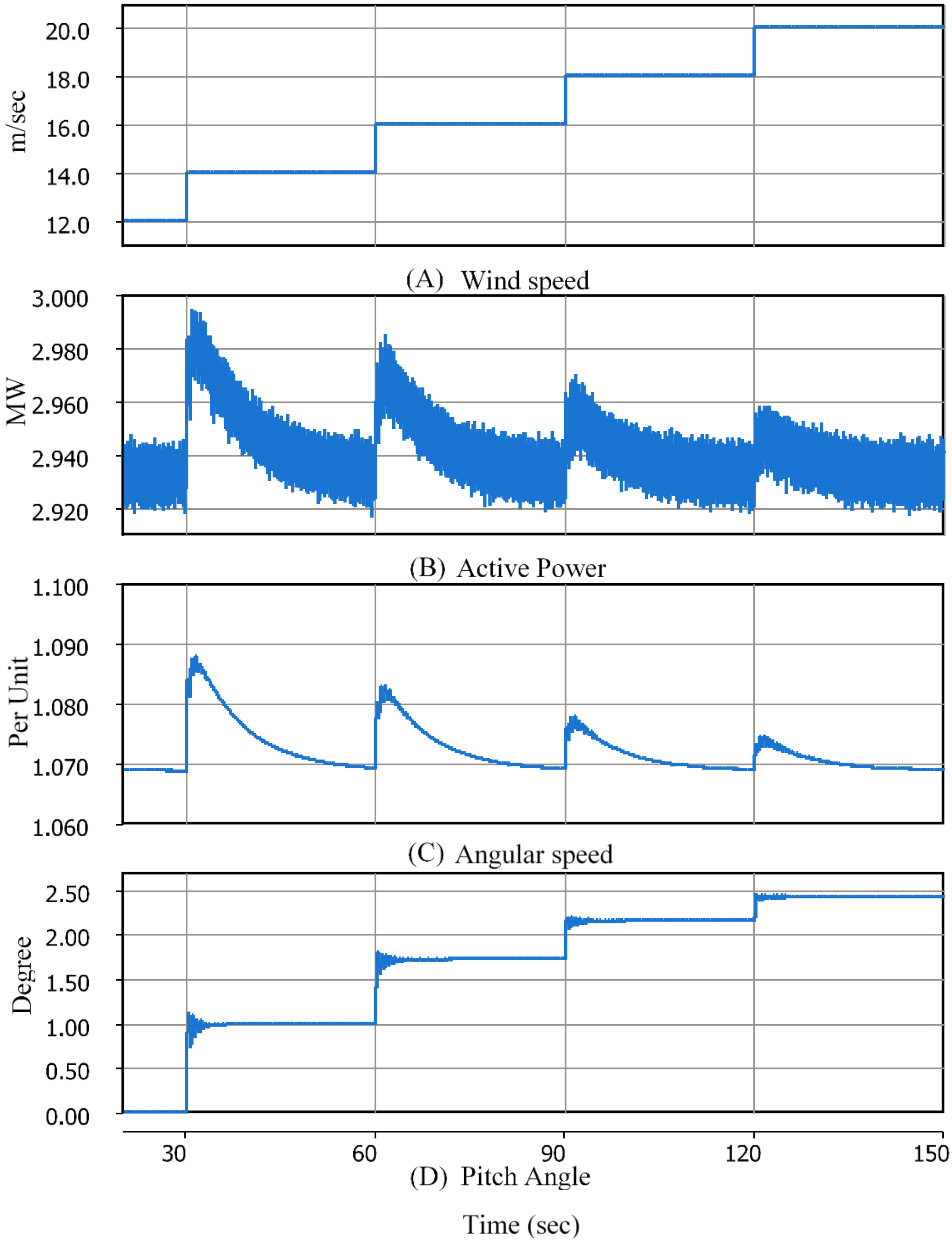

Fig 7-3: PMSG under high wind speed from 12 m/sec to 20 m/sec

angle increases to keep the speed within its reference, and like explained earlier, small overshoot is likely to occur in the active power and rotor speed. When the wind speed decrease below rated value, WTs active power and rotor speed decrease too and operate in maximum power-point tracking mode which the pitch mechanism became deactivated.

7.2.4 DFIG performance at cut-in to cut-off wind speed

Similarly to PMSG, the DFIG WT is also experienced under steady wind speed to address the capability of the system to track the change in aerodynamic power. The quantities of the DFIG turbine system are depicted in Fig 7.5 include the wind speed, pitch angle, generator speed, and the active power. A step change in wind speed of 1 m/sec every 30sec is applied to examine the system. The result in Fig 7.5 shows that the DFIG controls active power to reference signal supplied by the maximum power-point tracking (MPPT) ensuring that all accessible aerodynamic power can be extracted and then converted to electrical power. It can be promised that at partial load operation the wind turbine assures maximum energy capture. At or below rated wind speed (12 m/sec) the pitch angle is passive (zero). The aerodynamic increases with an increase in wind speed. However, this will not lead to similar instantaneous increase in active power as the reference power is provided by the speed control, which is determined by the generators' rotor speed; the rotor speed of the generators increases with an increase in wind speed, such that optimal power is provided by the wind. Due to the high inertia of WTs, there is a time delay in rotor speed to obtain the required speed.

7.2.5 DFIG performance at high wind

To assess the performance of DFIG wind turbine at wind speed above its rated value, another case study is conducted. There is a step variation in wind speed by 2 m/sec, from 12 m/sec to 20 m/sec, signifying the operation from rated speed up to shut down. Fig 7.6 illustrates the step response of blades angle, generator speed and active power for wind speeds over rated wind speed. Similar to the PMSG wind turbine, wind speed brings about a change in the pitch angle as well as the generator speed. In contrast to the power controller, the pitch method exhibits slower response. Therefore, there are dynamic changes in the generator's speed at every step in wind speed, because of which the rapid wind speed changes

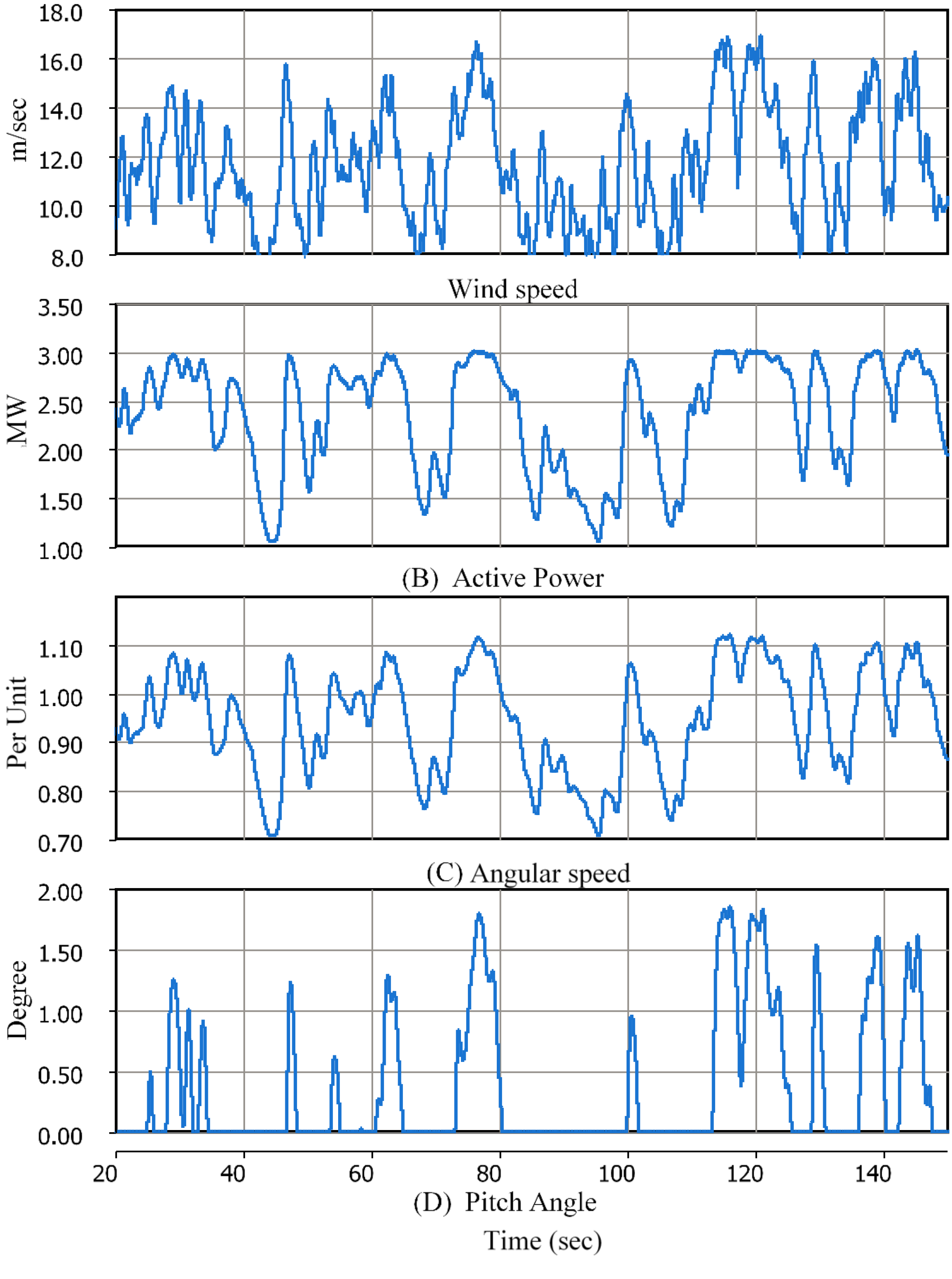

Fig 7-4: PMSG under random wind speed

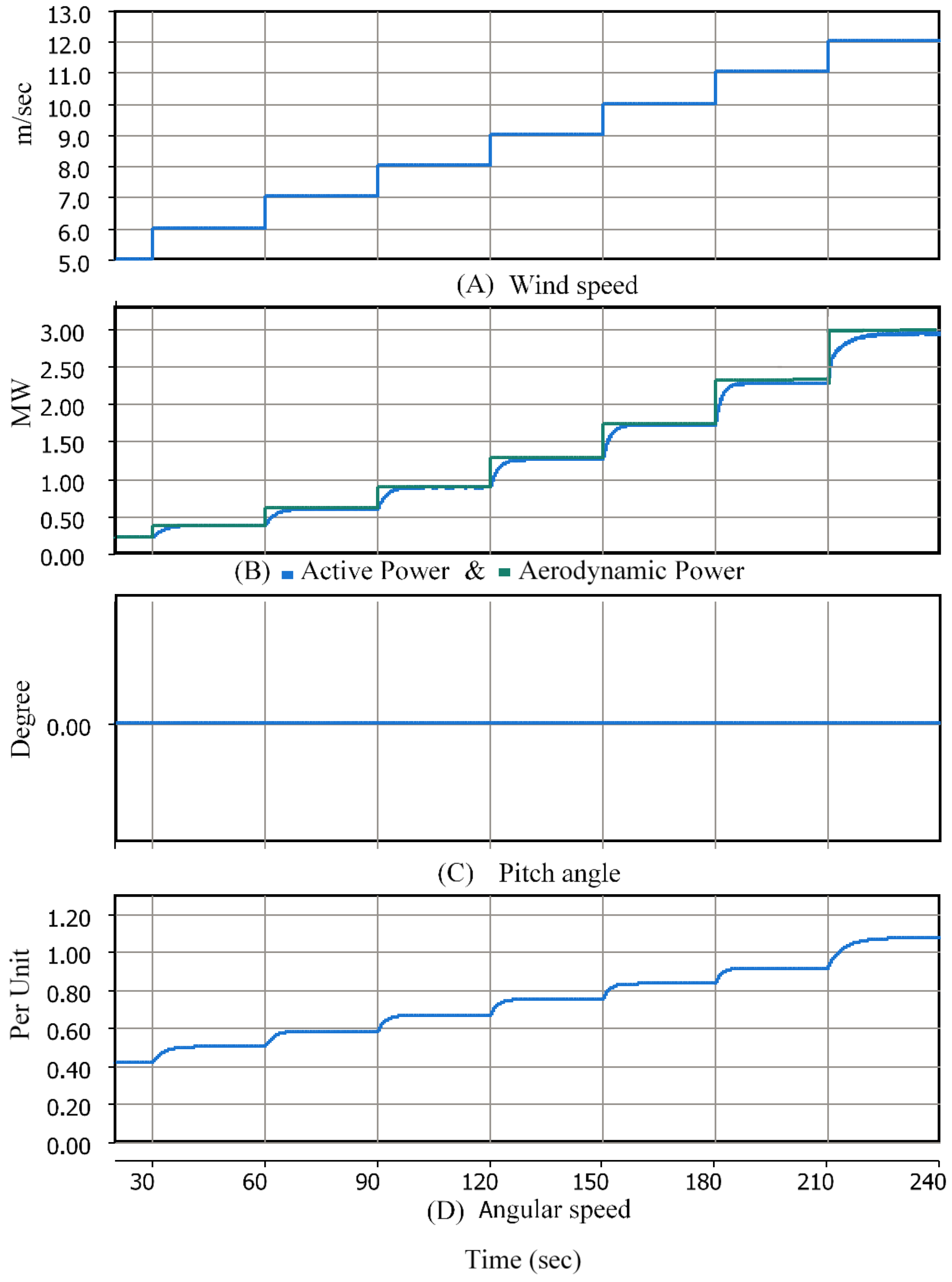

Fig 7-5: DFIG under varying wind speed from 5 m/sec to 12 m/sec

are taken in by the rotation energy stored in rotating masses. However, both active powers still present overshoot with 3% and generator speed with 2.5%. The reason for this overshoot is that the pitch angle mechanism woks slower compared to the active power. The two WTs are capable of functioning during high speed and can be maintained on their rated value of 3 MW.

7.2.6 DFIG performance at random wind speed

The natural wind speed is actually not entirely constant, and has fluctuations and gusts that arise because of the ambient weather condition. This is why DFIG WT has to be examined using fluctuating wind speed so that the performance of blades and system controllers can be examined. Just like the case PMSG case, a group of simulation is performed to the DFIG wind turbine, where there is stochastic mean wind speed of rated value (12 m/sec), and the turbulence intensity is 30%; hence, the WT function overlaps between low speed and pitching function, and the turbine works partially at rated and partially at partial load. Fig 7.7 presents simulation, in which wind speed, generator speed, pitch angle and active power generation of the system are plotted across a simulation time of 140sec. The performance of variable wind speed turbines with DFIG are depicted in the simulation findings of the varying wind circumstances. The results are identical to PMSG case, when the generator rotor speed goes over its rated value, there is an increase in pitch angle, leading to a decline in the aerodynamic power. This causes a decrease in the generator rotor speed, bringing it within its rated speed. There are chances of small overshoots taking place in the rotor speed and active power due to slower working of pitch angle method. When the wind speed becomes less than its rated value, there is a decrease in WTs active power and rotor speed as well, which now functions at maximum power-point tracking mode, while the pitch angle control gets deactivated and has a value of zero.

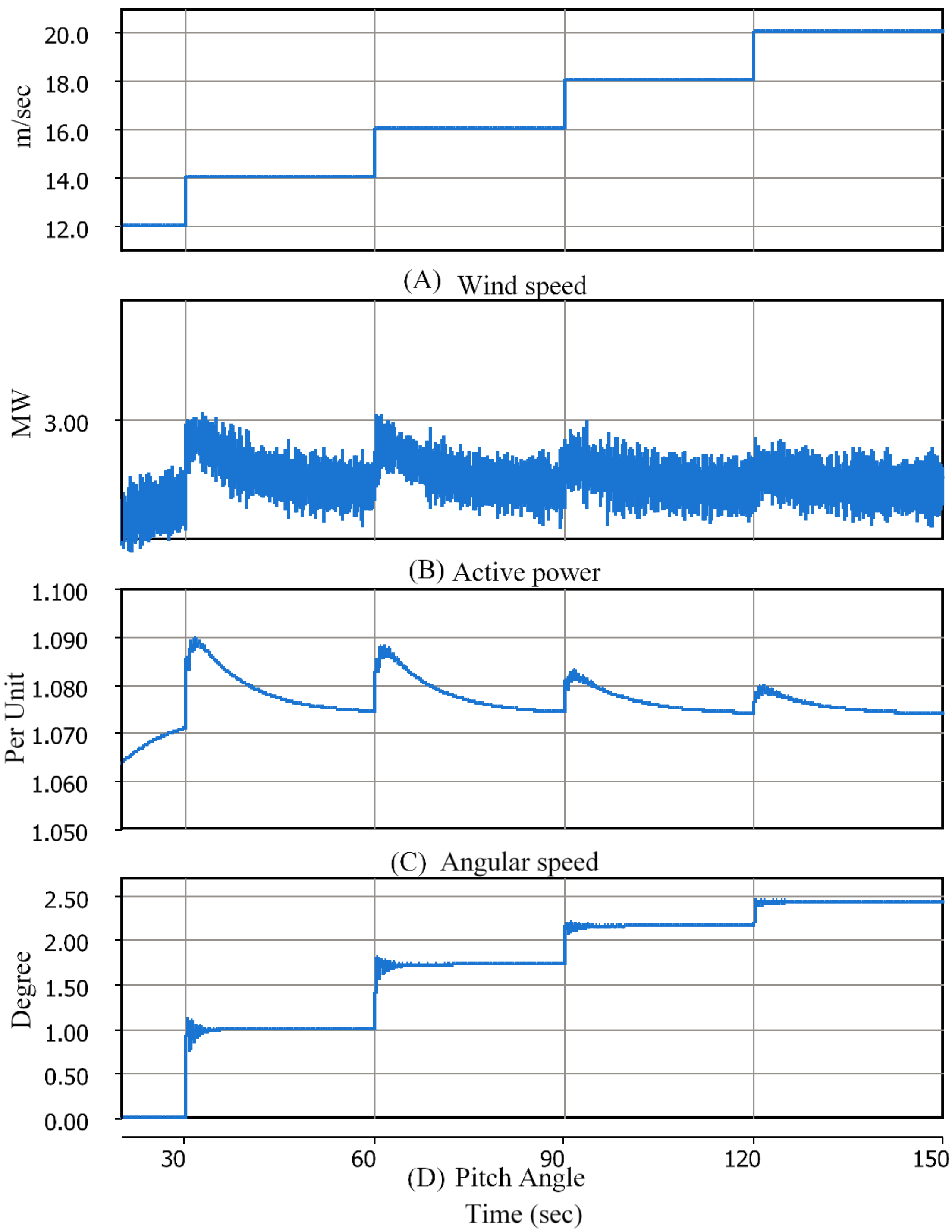

Fig 7-6: DFIG under high wind speed from 12 m/sec to 20 m/sec

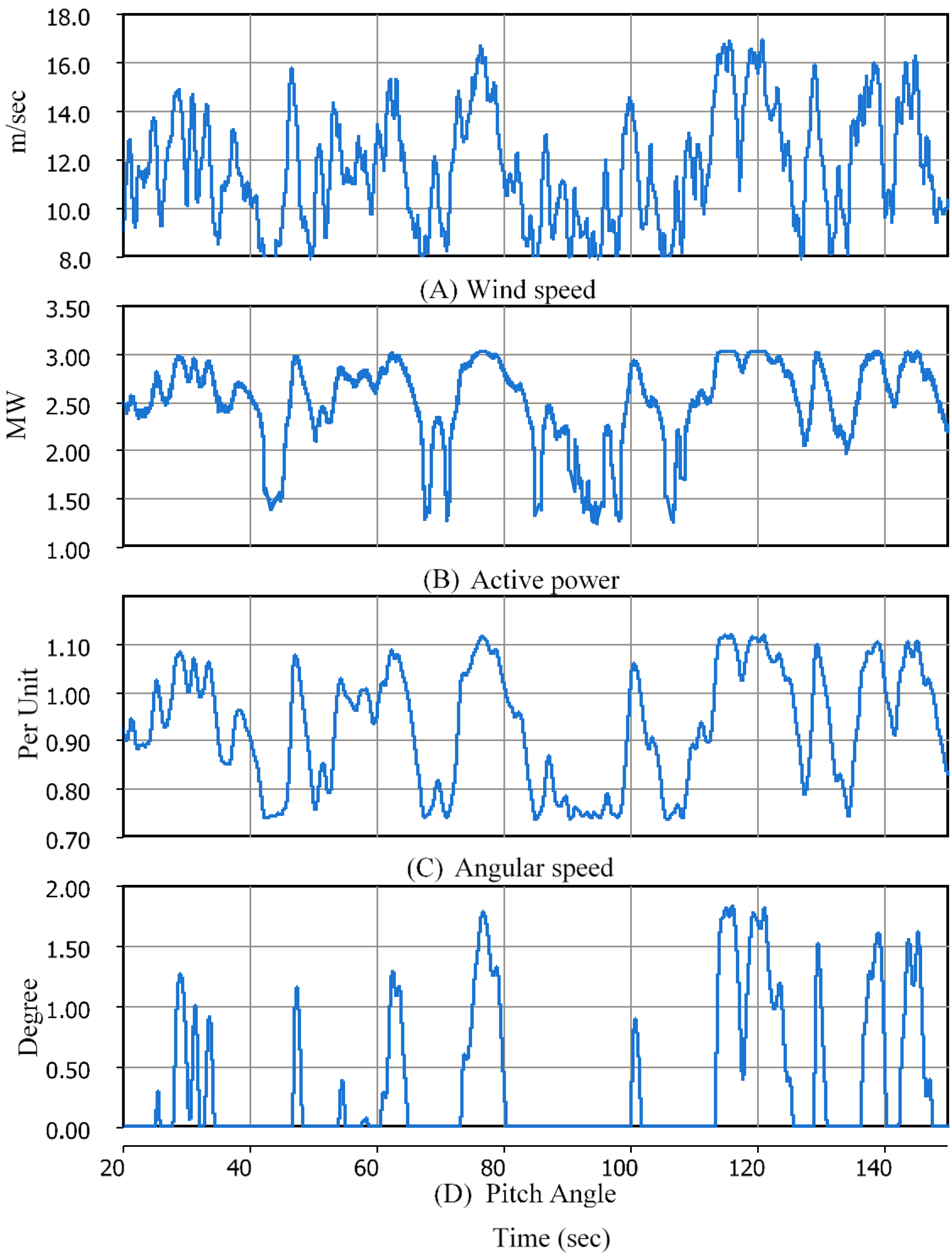

Fig 7-7: DFIG under random wind speed

7.2.7 Summary

In this section, a simulation of PMSG and DFIG variable speed wind turbines with varying wind speed circumstances was illustrated. The two WTs systems had back to back converts installed with vector control strategy, as explained in Chapter 4 and chapter 5. The PSCAD software was used to model the system as it allows thorough dynamic time domain simulation and includes extensive library tools pertaining to wind turbine. The purpose of this was to assess the way the variable speed WTS operated using varying operation modes and to determine the controller capacity of the WTs so as to regulate the WTs in varying range of standard operation. In the foremost simulation, testing of WTs took place with wind speed ranging from cut-in till rated speed. Both the WTs depicted similar performance in tracing the optimal power reference provided by the maximum power point scheme. Next, high wind speed was used in WTs, ranging from rated to cut-off. The WTs once again demonstrated the same performance, with the pitch method performing an important part in maintaining the active power and generators' speed almost constant. Lastly, random wind speed was used in the previous two simulations so that there is variation in wind speed between low and high speed. According to the findings, the WTs can adhere to reference power lower than the rated speed and keep the power at its rated speed when there is high speed wind.

7.3 Flicker Emission.

In this section, the emission of voltage flicker from variable speed WTs with PMSG and DFIG generators are conducted. Three different case studies are adopted to address all flicker issues, first both WTs are operated in the case study in section 7.1 in full range of wind speed operation starting from cut-in till cut-off wind speed, then, other case studies based to IEC61400-21 is considered where the flicker coefficient of single wind turbine has to be reported for different wind speed and grid impedance angle as explained in section 6.2.1, finely; the factors which effect flicker of WTs which are the turbulence intensity and mean wind are studied by a case study.

7.3.1 Flicker emission under the case study.

This section deals with the short-term flicker intensity of variable speed WTs while operating continuously. This study considers the case study given in section 7.1, in which WTs are included in the power system at PCC, situated in bus 2. The wind speed ranges from cut-in to cut-off, with step variation of 1 m/sec every 20sec. An example of integrated wind speed of mean speed of 10 m/sec, having a turbulence severity of 0.1 is illustrated in Fig 7.8, along with tower shadow effect and the ensuing aerodynamic power. Table 7.1 presents the features of PCC and wind profile for short-term flicker.

Table 7-1
PCC and wind profile parameter

Parameter	Value	Unit
Wind speed	5-12	m/sec
Turbulence intensity	0.1	-
Grid Impedance angle	54	Degree
Short-circuit capacity	31	-

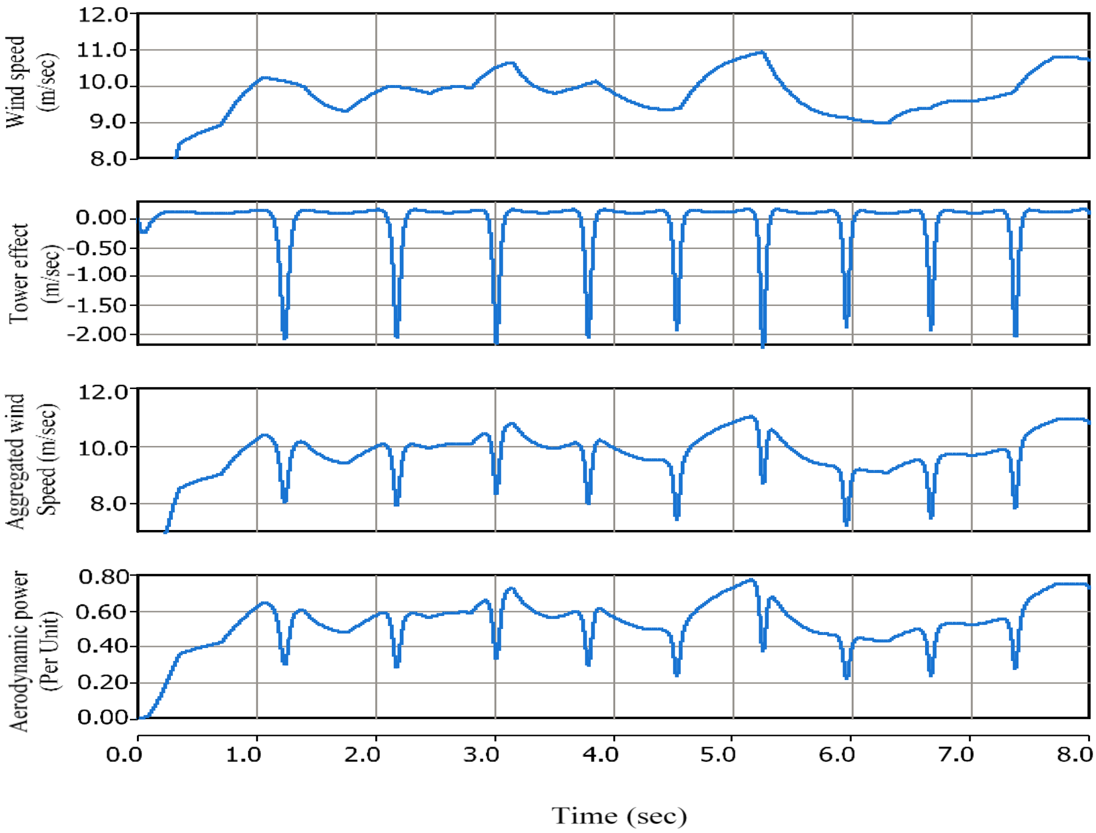

Fig 7-8: Wind speed and tower shadow effect of WTs for case study

The wind speed range of the wind turbine can be extensive so that the maximum power can be obtained from kinetic energy. The variation in wind speed is almost 2 m/sec in Fig 7.8, according to the turbulence intensity in natural wind speed. It is suggested by the spectrum of wind speed that the 3*p* frequency element that arises because of the turbulence and the tower shadow effect, is signified in the wind model. However, the larger frequency elements like 6*p*, 9*p*, 12*p* that are actually present are not considered in the model. The 3*p* frequency element is transferred to the output power. Due to the changes in the turbine power caused by turbulence intensity and tower shadow impact, the generator power at PCC will be affected, and voltage fluctuations and flicker will arise in the grid.

Fig 7.9 presents the simulation findings of short-term flicker from PMSG and DFIG for an extensive wind speed range, from cut-in to rated wind speed, having step change of 1 m/sec.

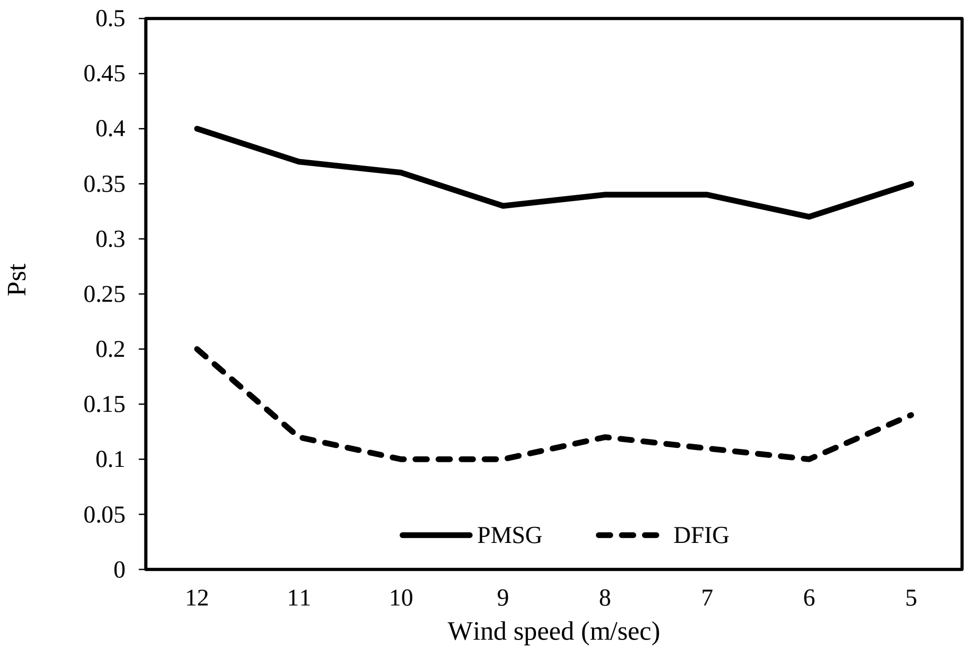

Fig 7-9: Wind speed and tower shadow effect of WTs for case study

On the basis of voltage fluctuations at the PCC and the flickermeter model, Fig 7.9 presents the results for short-term flicker severity (P_{st}) for the two WTs. The highest values in the base case is computed at rated wind speed of 0.4 and 0.2 for PMSG and DFIG respectively, representing the flicker level with respect to a single wind turbine linked to the grid. When wind speed is low, the flicker values are almost the same for every generator and rise sharply when the speed gets close to its rated value. This happens because the voltage changes are directly related to active and reactive power. The reactive power is maintained at zero, and the active power is directly related to wind speed cubic, hence, when there is high speed wind, there is a sharp increase in active power, which causes a significant increase in flicker. The tower shadow effect and wind changes lead to mechanical stress, which is not completely transmitted to out-power. Therefore, the regulator of variable speed WTs decreases the voltage fluctuations at PCC and cause less flicker in PMSG and DFIG in contrast to fixed speed wind turbines [11]. Furthermore, the capability to restrict the reactive power also causes a decrease in flicker by fixing Q at zero, hence decreasing the voltage fluctuation. On the other hand, it is shown in Fig. 7.9 that DFIG has lower flicker because there are two control paths in DFIG (rotor and grid side); the output active and the reactive power, which cause smooth functioning in output power and terminal voltage [17]. IEC6100-3-7 has suggested that in distribution networks, a flicker emission of P_{st} = 0.8 is deemed to be appropriate for wind turbine systems. The flicker level in the base cases is quite lower than the P_{st} constraints. Nevertheless, the flicker level may be considerably distinct for multiple wind turbines that are linked to a comparatively weak grid.

7.3.2 Flicker emission based on IEC61000-21

Due to switching functions like start-ups, and rapid changes in the output power at continuous operation, flicker is released by wind turbines. According to the standard IEC61000-21, the flicker in continuous and switching operation needs to be mentioned, as discussed in chapter 6. Both the WTs are simulated in this study to obtain results in conformance to IEC61000-21.

7.3.2.1 Continuous operation

Flicker emission because of continuous operation is examined by presuming that a flicker coefficient, $C(\Psi_k, V_a)$, is involved in each of the wind turbine. This coefficient is a normalised measure of the highest expected flicker emission while the wind turbine undergoes continuous operation. In accordance with the standard given in section 6.4, four distinct values of grid impedance angle and wind speed are taken into account. To determine the flicker emission of an individual wind turbine, flicker coefficient having the appropriate $C(\Psi_k, V_a)$ multiplied by S_n/S_k. On the other hand, the emission form a wind farm can be determined using the equation 6.3 given in section 4. Table 7.2 (PMSG) and Table 7.3 present the flicker coefficient of the suggested WTs.

Table 7-2
Flicker coefficient of PMSG

Annual Wind speed (m/s)	Grid impedance angle 30°	50°	70°	85°
6.0	4.6	3.4	3.4	1.7
7.5	4.0	4.0	3.2	1.8
8.5	3.4	3.6	2.6	2.6
10	4.8	4.0	3.0	2.2

Table 7-3
Table 5.3: Flicker coefficient of DFIG

Annual Wind speed (m/s)	Grid impedance angle 30°	50°	70°	85°
6.0	1.2	1.0	0.8	0.7
7.5	1.0	0.8	0.6	0.6
8.5	1.0	0.9	0.6	0.6
10	2.6	2.0	1.6	1.4

According to the simulation outcomes given in table 7.2 and 7.3, the flicker coefficient for PMSG and DFIG changes with the grid impedance angle and wind speed. Flicker coefficient in equation 6.1 relies on short-circuit ability that is constant in this study. There is an increase in grid impedance; for a given impedance, there is an increase in value of x and decrease in R. Both PMSG and DFIG variable speed WTs are capable of regulating reactive power that are normally fixed at zero value to make the WT work in unity power factor. Hence, the value of R simply ascertains the flicker emission as well as the flicker coefficient.

7.3.2.2 Switching operation

Flicker emission because of switching operations is determined by assuming that every wind turbine has a flicker step factor $k_f(\Psi_k)$ which is a "normalised measure of the flicker emission due to a single worst-case switching operation". A start-up is usually the worst-case switching operation, even though IEC 61400-21 also calls for the evaluation of switching operations between generators (for example, to achieve two speed operation) if needed for the wind turbine being examined. In switching operations, flicker step factor and voltage change factor are calculated while starting the WT at cut-in and rated speed. Fig 7.10–7.13 shows the flicker that is caused by linking the WTs in cut-in and rated speed. The variation in PCC voltage while switching operation is being carried out is a defining aspect of $k_u(\Psi_k)$ and can be seen in Fig 7.14–7.17 for the two wind turbines (PMSG and DFIG).

Significant variation is found in the simulation findings of the switching operation of PMSG and DFIG, either in $(k_f(\Psi_k))$ or $(k_u(\Psi_k))$. There is complete decoupling from the grid, which allows for the smooth connection of PMSG at cut-in as well as rated wind speed. The factor is a function of P_{st}. The flicker emission that is obtained when PMSG is functioning at rated speed and cut-in speed is illustrated in Fig 7.10 and 7.11 respectively. A current is released by the inverter, which brings about a sudden increase in the power sent to PCC, causing the PCC voltage to fluctuate. This causes a small increase in P_{st}, as shown in Fig 7.10, 7.11. This rapid increase falls down with time and reaches the normal flicker emission level of the WTs. This increase in P_{st} is determined by the current value that depends on the reference power. The inverter has the ability to restrict the current so that it goes over the rated value, and then it is restricted. However, when starting at rated speed, is greater due to the high power obtained from the wind turbine.

P_{st} that is a result of coupling DFIG to the grid when there is rated and cut-in speed is shown in Fig 7.12 and 7.13 respectively. When DFIG is integrated to the grid, the value of P_{st} is significantly larger as compared to when PMSG is used. It can be seen in Fig 7.12 that P_{st} = 2.3 at rated speed, and in Fig 7.13 that P_{st}=0.5 at cut-in speed. In addition, the overshoot decays over a longer time. This happens due to a direct connection that leads to a large inrush current when the generator is being connected. In addition, large reactive power is needed by DFIG so that the stator winding can be charged, which has an impact on voltage fluctuation at PCC.

Fig 7.14 and Fig 7.15 illustrate the fluctuation in PCC voltage when starting the PMSG at rated speed and at cut-in speed respectively. These figures demonstrate that small voltage fluctuations take place when connecting PMSG. This variation is 5% and 2% for rated speed and cut-in speed respectively.

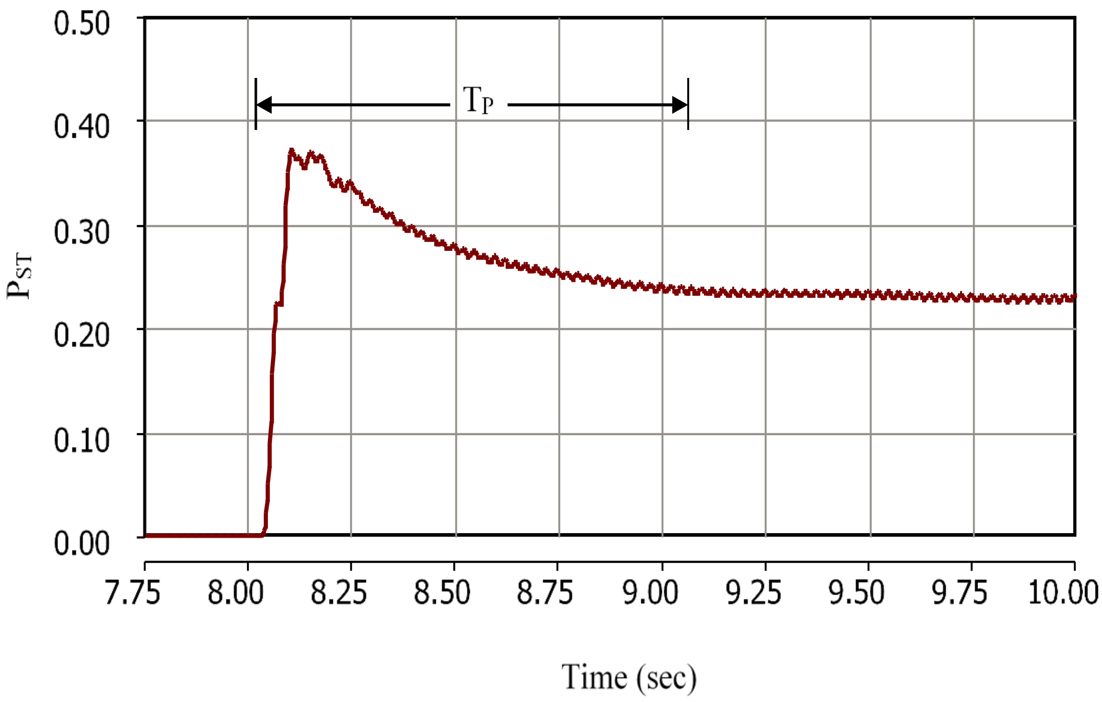

Fig 7-10: PMSG Flicker during starting up at rated speed

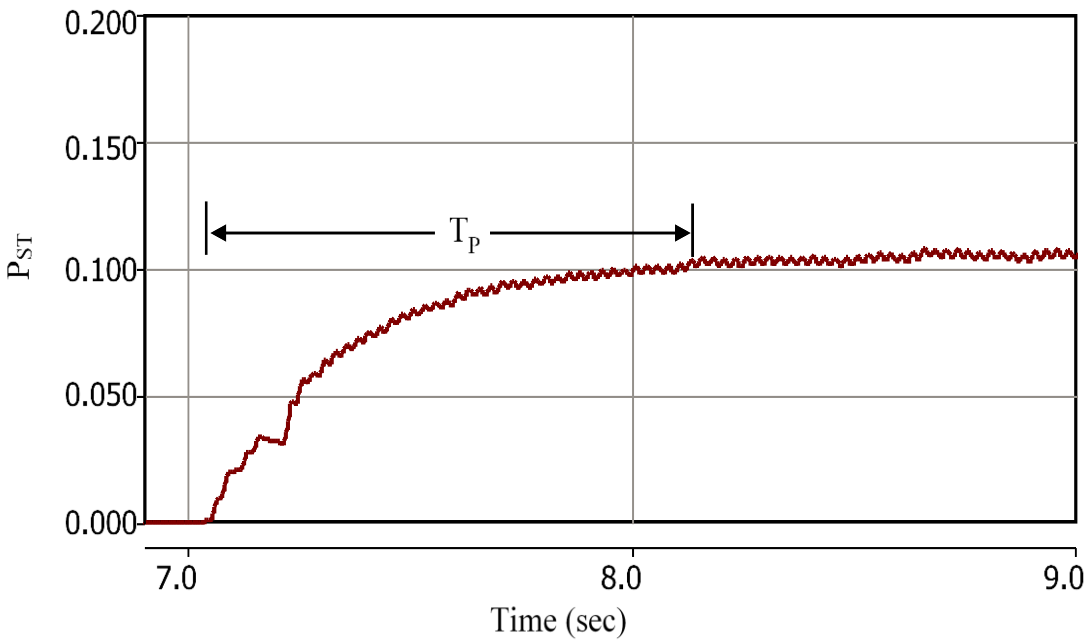

Fig 7-11: PMSG flicker during starting up at cut-in wind speed

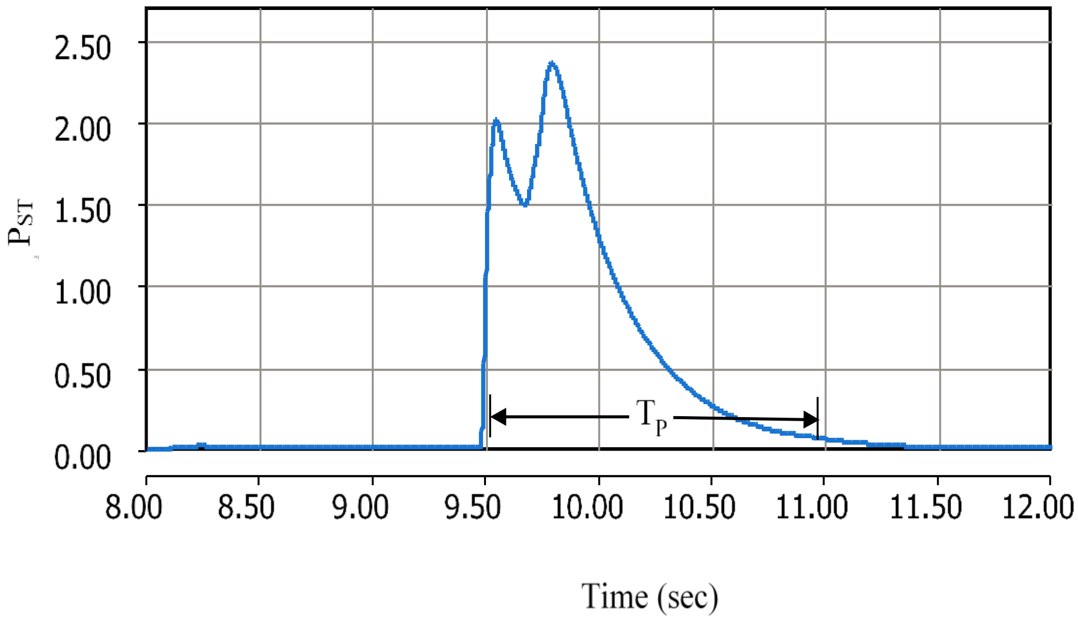

Fig 7-12: DFIG Flicker during starting up at rated speed

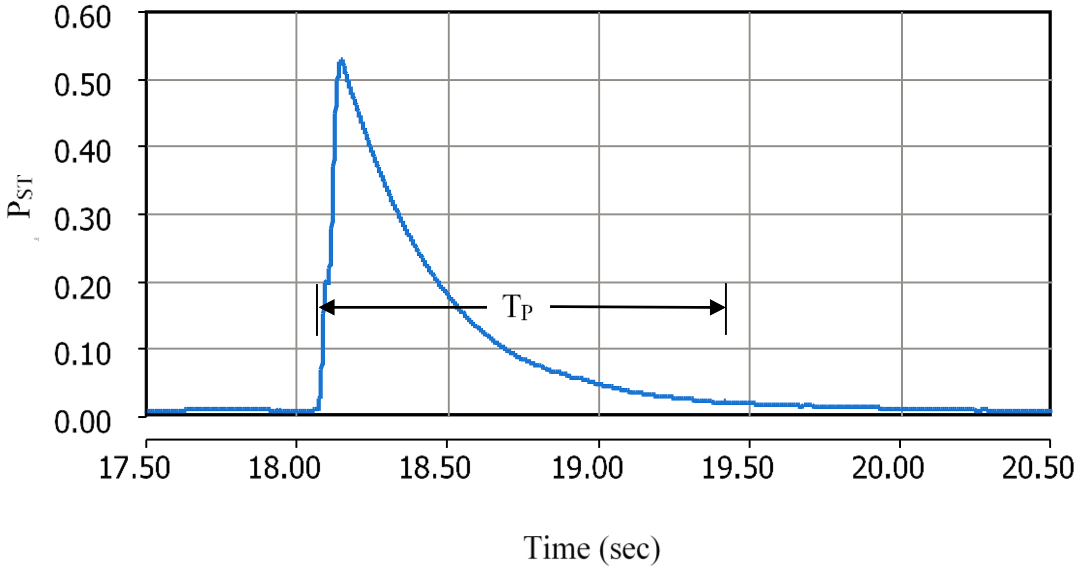

Fig 7-13: DFIG Flicker during starting up at cut-in wind speed

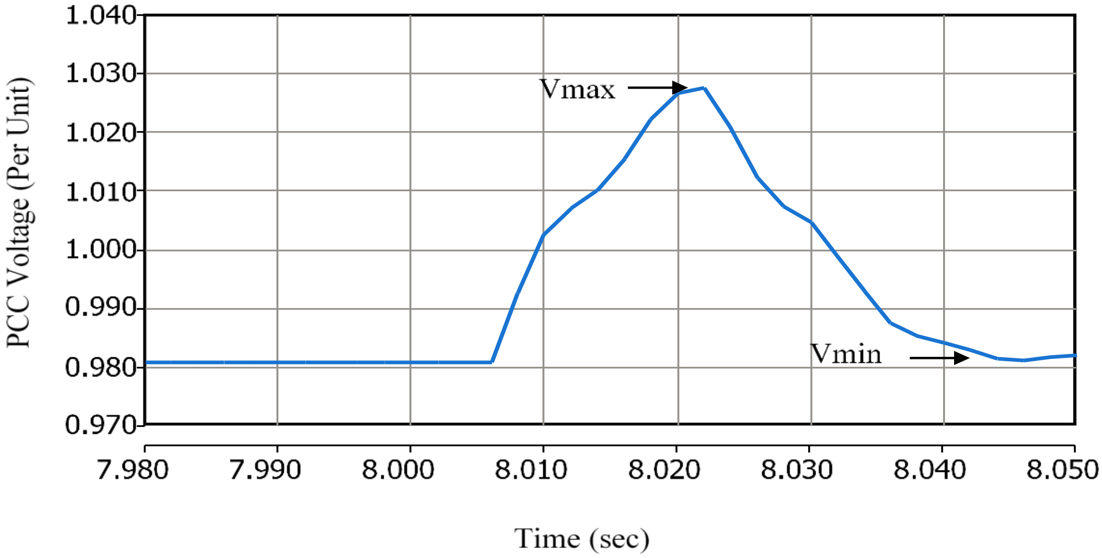

Fig 7-14: PCC voltage during starting up PMSG at rated wind speed

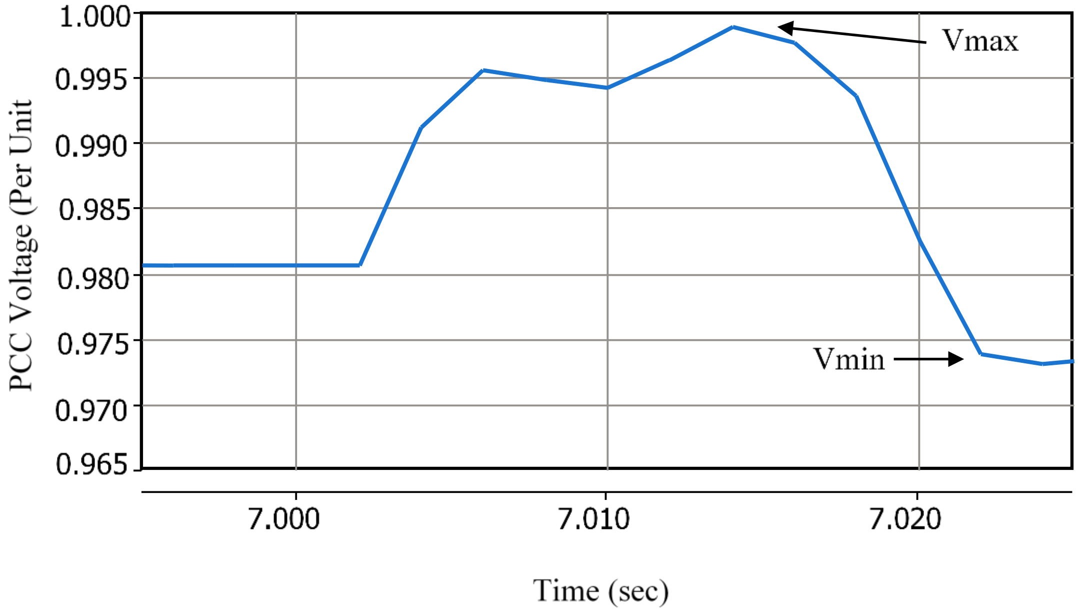

Fig 7-15: PCC voltage during starting up PMSG at cut-in wind speed

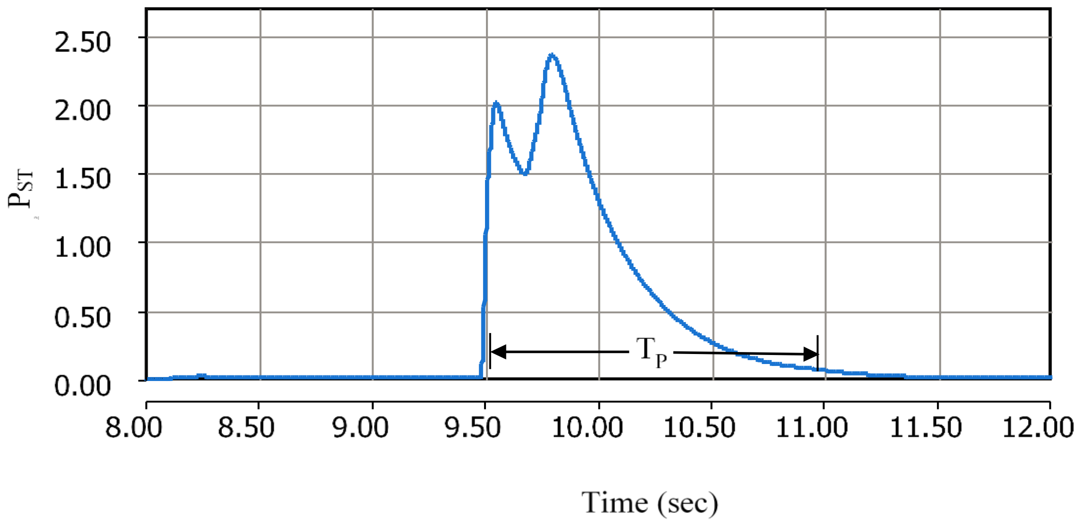

Fig 7-16: PCC voltage during starting up DFIG at rated wind speed

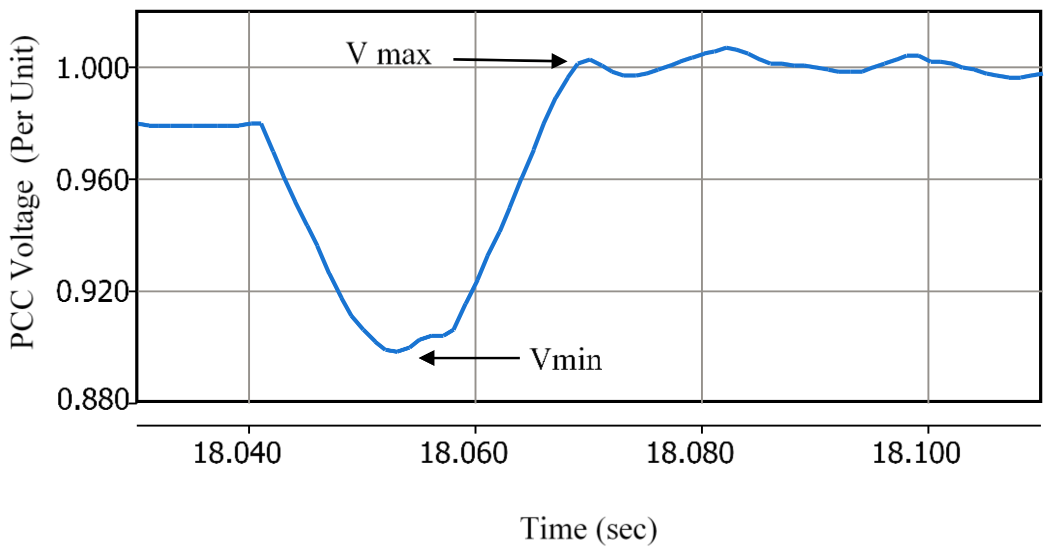

Fig 7-17: PCC voltage during starting up DFIG at cut-in wind speed

The voltage fluctuations that take place when connecting DFIG at rated and cut-in speed are shown in Fig 7.15 and Fig 7.16 respectively. The simulation outcomes depict that there is a significant impact on the PCC voltage when DFIG is connected, with the changes being 12% for rated speed and 6% for cut-in speed. The inrush current is five times more than the rated current, and it is not possible to regulate or restrict it, leading to the large disruption in voltage.

Table 7.4 presents the voltage change factor and flicker step factor for DFIG and PMSG wind turbines.

Table 7-4
Flicker step factor and Voltage change factor for PMSG and DFIG

	Rated speed		Cut-in speed	
	PMSG	DFIG	PMSG	DFIG
Flicker step factor	0.031	0.086	0.02	0.06
Voltage change factor	0.52	2.07	0.51	1.558

These results are computed from Fig 7.10 to 7.16, and using equations 6.6 and 6.7 in chapter 6. The results show that PMSG functions between during switching operation due to the complete isolation of the full-power converter.

7.4 Harmonic Distortion

As per IEC6100-21 standard presented in section 6.2.2, it is imperative to report WTs current harmonics (till the 50th order). In this study, the measurement was achieved at PCC using Fast Fourier Transformation (FFT) created in PSCAD library. Tables 7.5 and 7.6 present the existing harmonics simulation findings for PMSG and DFIG respectively, in which a complete operation of wind speed is used on WTs in step change of 1 m/sec. The slip of DFIG is included in the parameter in table 7.6 for subsequent analysis. Almost 50th harmonics should be presented by the standard; however, this result considers the following harmonics order: 3rd, 5th, 7th, 9th and 11th only as the rest of the harmonics are lower than 0.1% of the rated current so they are not needed to be stated according to IEC6100-21 standard [140, 141]. WTs harmonics may damage electrical devices, and so, IEC61000-3-6 standard is used to restrict its use, since IEC6100-21 does not establish any harmonics emission limit of WTs. Table 7.7 presents the IEC61000-3-6 standard.

Table 7-5
Percentage Current Harmonics of PMSG

Wind speed (m/sec)	Harmonics 3rd %	5th %	7th %	11th %	THD %
5	0.14	0.17	0.10	---	0.06
6	---	0.15	0.12	---	0.98
7	---	0.25	0.12	---	0.93
8	---	0.25	0.18	---	0.29
9	---	0.24	0.20	---	0.35
10	0.10	0.18	0.22	---	0.35
11	0.60	0.38	0.23	0.15	1.45
12	0.30	0.45	0.25	0.17	8.00

Table 7-6
Percentage Current Harmonics of DFIG

Wind speed	Slip %	Harmonics 3rd %	5th %	7th %	9th %	11th %	THD %
5	45	2.10	1.72	1.00	0.72	0.57	5.7
6	35	1.50	0.62	0.37	0.30	0.25	3.1
7	24	0.67	0.43	0.39	0.19	0.19	1.9
8	13	0.59	0.44	0.35	0.16	0.40	2.3
9	1.0	0.42	0.40	0.30	0.14	---	2.1
10	-8.0	0.57	0.45	0.56	0.22	0.15	3.3
11	-19	1.15	0.61	0.47	0.30	0.23	3.8
12	-30	2.30	2.00	1.25	0.75	0.75	14.5

Table 7-7
IEC61000-3-6 Current harmonic limit [146]

Harmonic order	IEC 61000-3-6
3	-
5	5
7	7
9	-
11	3

Both generator currents include harmonics as shown in Tables 7.6 and 7.7, and it can be seen that they have different variations in wind speed values. These tables examine the variation of the WTs in current harmonics and overall harmonics disturbance, as per the wind speed

This study presents the simulations of the DC/AC IGBT-PWM inverter that has L filter and AC/DC IGBT-PWM active rectifier for the PMSG and DFIG WTs. PCSAD Simulink was used to carry out the simulations. The overall harmonic distribution rates were presented using the FFT solution methods. It is vital to achieve a high power quality and dynamic performance for tasks in grid/load connected IGBT-PWM converters. The switching frequency and the grid filter (presented between the grid/load and the converter) determine the power quality of an IGBT-PWM converter. As shown in the case study, it is advantageous to use L-filter since sinusoidal load or line currents can be obtained even at low and moderate switching frequencies, such as 4 to 7 kHz. It is also verified that low cost can be obtained with the L-filter.

The low order frequencies, i.e. 3^{rd}, 5^{th}, 7^{th} and 11^{th} are the most dominant harmonics. The power electronic equipment is a fundamental tool in variable speed WTs structures, hence, harmonics are obtained in both currents and voltage because of semiconductor switching operation. Back-to-back converters are installed in PMSG and DFIG, having two similar IGBT 6 bridges. The AC-DC power converter functions as an active rectifier, having IGBT 6 pieces of semi-conductive circuit parts. The generator speed and stator current determines the control of trigger circuit. IGBT 6 pieces' semi-conductive circuit parts are also included in the DC-AC power converter.

Keeping in view the PMSG case, the current flows solely from the volt-source inverter (VSI). A ripple in the current is sent out by this inverter at the DC side, and a voltage harmonics at the PCC side. Equation 7.1 and 7.2 present the harmonics produced by DC and AC sides respectively [11,27,28]:

$$f_{DC} = \left|6k\right| f, \;\; k = 1,2,3, \ldots \tag{7.1}$$

$$f_{AC} = \left|6k \pm 1\right| \;\; k = 1,2,3, \ldots \tag{7.2}$$

When grid impedance is used to couple the PMSG to the grid, a harmonic in the current is produced after the distorted voltage of VSI is applied over grid impedance. It is important to have a filter to interface the VSI to utility so that the harmonics release is restricted. In this study, passive filter is selected, whereas the DC link makes the harmonics and the ripple effect of the DC current smooth so that no damage is caused to the generator. When the wind speed increases, the PMSG current harmonics given in table 7.5 also increase as the out-power is directly related to the wind speed. Hence, an increase in power causes the current to increase, which is why the harmonic level also increases (the harmonics value is assigned to rated current). It is ensured in tables 7.5 and 7.7 that the emission limits are adhered to by PMSG.

The current flows through rotor as well as grid side converter in DFIG, based on the generator operation mode (super-synchronous or sub-synchronous speed). The generator speed range operation is controlled by altering rotor voltage, which depends on slip [27]. The value of the rotor harmonics is related to the slip value, irrespective of its polarity, which is given in the simulation findings in table 7.6 where the current harmonics changes with the slip. However, when there is negative slip (related to supper-synchronous speed), there is greater output power and current which generate greater harmonics; however, they are still less than the standard limit. In contrast to DFIG, low harmonics current is emitted by PMSG.

7.5 Active and Reactive Power Control

7.5.1 Active power control

Set-point control is the sole active power factor that is taken into account in this study. With respect to variable wind speed WTs, the other factor, maximum measured power, does not have to be taken into account as $P_{600} = P_{60} = P_{20}$ [5]. On the basis of the standard presented in chapter 6, a reference set-point is used on WTs. Fig 7.18 presents the ability of PMSG and DFIG to track this active power reference.

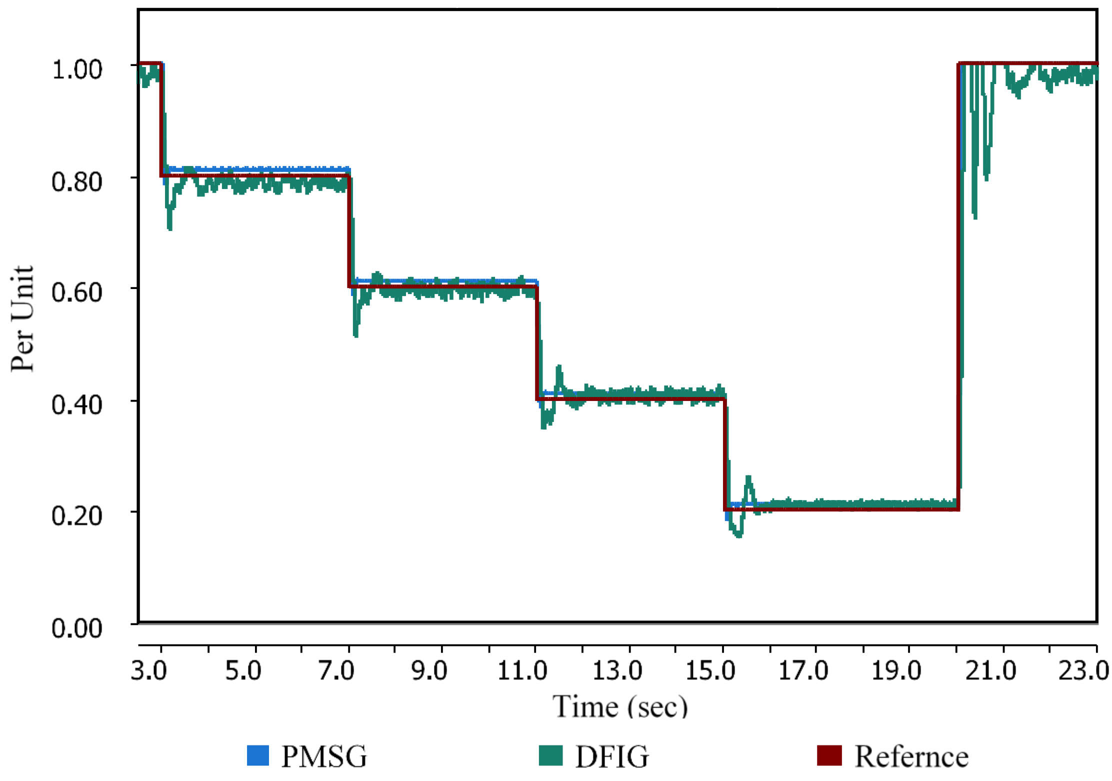

Fig 7-18: Measurement of active power set-point control for PMSG and DFIG

The simulation outcomes given in Fig 7.18 ensure that the active power of both the WTs respond quickly to the variation in their reference and fulfil the standard requirements accurately. In contrast to DFIG, PMSG depicts somewhat faster performance as the power can be regulated immediately by the inverter. With respect to DFIG, there is a small transient overshoot because of the power stored in the stator.

7.5.2 Reactive power control

7.5.2.1 Reactive power control according to IEC

The reactive power of PMSG and DFIG test are given in Fig 7.19, consistent with IEC 61000-21. Here, WT functions at 50% of rated active power and the control reference is changed from zero to largest inductive reactive power that continues for 5 seconds. It is then converted into maximum capacitive reactive power for 5sec or more, after which it is once again set at zero.

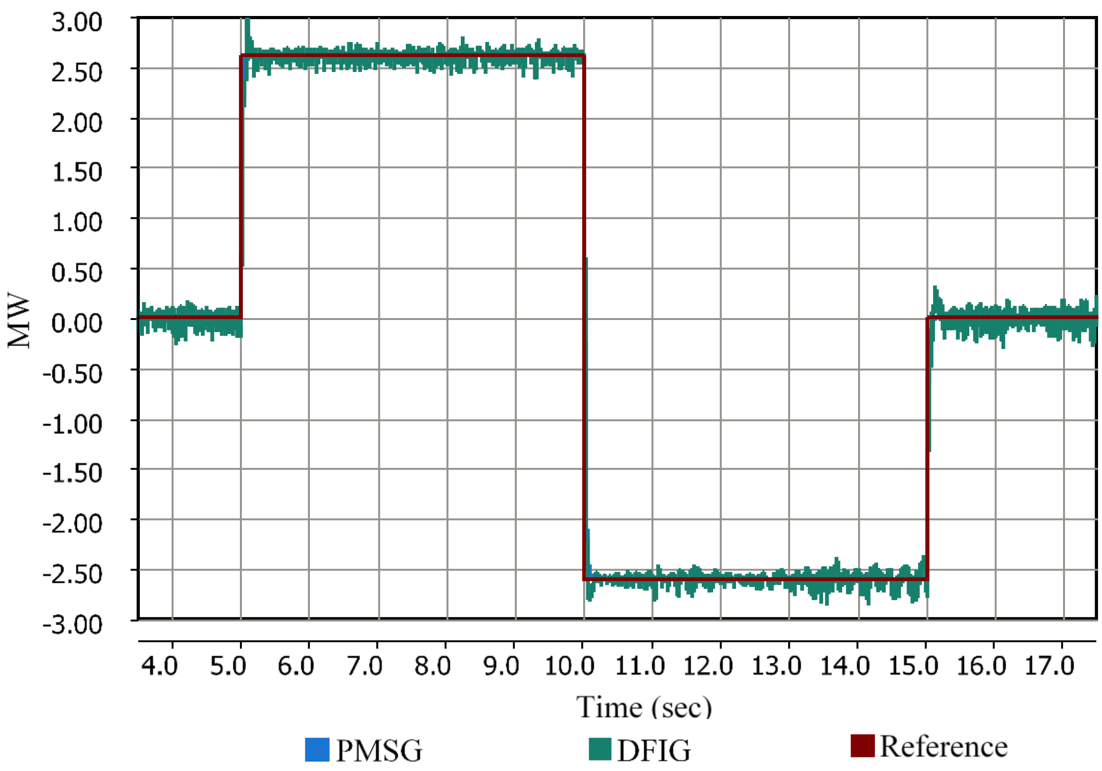

Fig 7-19: Measurement of reactive power set-point control for PMSG and DFIG

Fig 7.19 shows that WTs can rapidly track the precise reactive power reference given by IEC 614000-21. It takes very little time to change the WTs from inductive to capacitive mode (less than 0.1sec). Because of this, the variable speed WTs can support voltage consistency during disturbance and can also help in reducing flicker. The response of PMSG is somewhat faster than DFIG as it generates reactive power solely from the inverter that functions like STATCOM [15]. If there is any fault, maximum reactive power can be provided by PMSG, while DFIG regulator is restricted by the crowbar and can only help in maintaining reactive power provided by the converter [11].

7.5.2.2 Voltage control

The WTs capacity to compensate for the decrease in voltage is determined in this simulation. This is possible by providing reactive power that can be attained by maintaining PCC voltage using voltage control. This control is additional to the prevailing control in chapters 4 and 5. In case of any fault, the grid can be supported by voltage control, as has been elaborated subsequently.

Fig 7.20 illustrates the function of the voltage controller by connecting a 1.5 MVAr inductive load to draw reactive power at PCC of the wind turbine system, at t = 4sec.

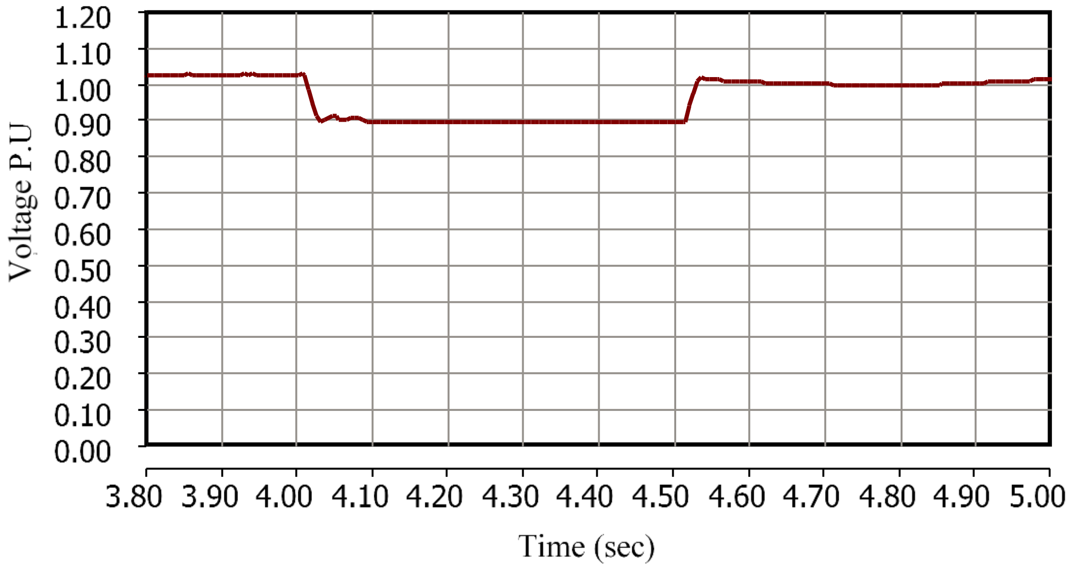

Fig 7-20: PMSG Voltage control capability

The simulation case compared the wind turbine connection to inductive load with and without voltage controller. Due to the coupling of the inductive load (at time of 4sec), there is an imbalance in the reactive power, and hence, the voltage falls to almost 90% level. Once the voltage controller is disabled, the grid does not receive any more reactive power, and when the inductive load is connected, the voltage remains at the lower level. The voltage control gets activated after the inductive load has been coupled for 0.5sec (at time of 4.5sec). Activating the voltage controller causes the converter to provide reactive power right after the inductive load is connected. The active power can still be regulated to its reference value. As the converter rating is 3.2 MVA, the reactive power can be compensated by the converter without decreasing active power.

An example of the voltage signal when there is common coupling of the DFIG following the connection of inductive load to the grid is demonstrated in Fig 7.21.

There is a decrease in voltage to less than 1 p.u. because of the reactive power requirement of the inductive load. When the voltage control (from rotor side converter) is deactivated, the voltage stays at a low level. Nonetheless, using the voltage controller causes the voltage level to be re-established rapidly.

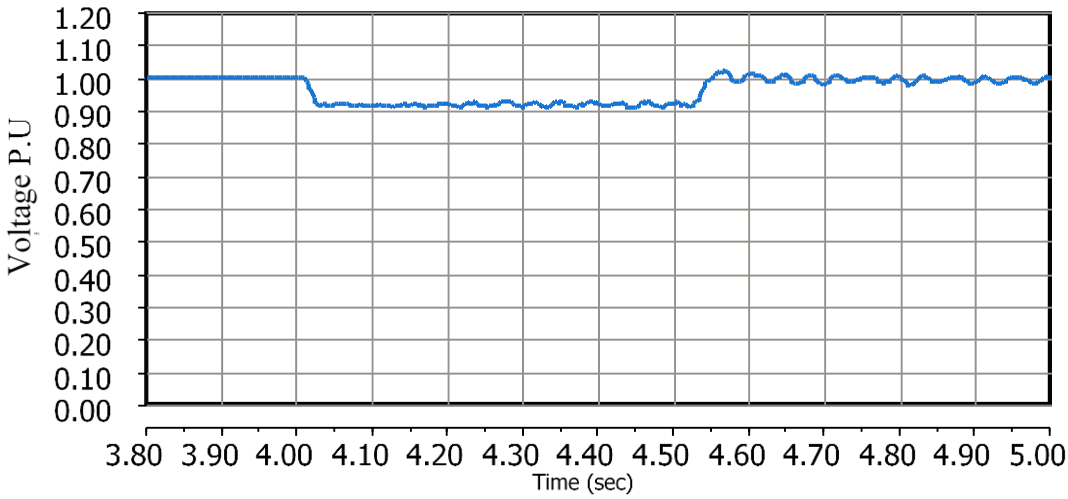

Fig 7-21: DFIG Voltage control capability

7.5.2.3 Slow voltage variation

Section 7.1 presents a case study which has inductive, resistive and mortised loads. There is a decrease in voltage at PCC (bus 2) and at other buses. In this study, the application of voltage control to WTs is tested. Fig 7.22 presents the findings of these tests.

PMSG and DFIG with voltage control during standard operation are illustrated in Fig 7.22. Voltage control is essentially used to improve the voltage when it decreases by coupling the inductive load so that the WTs can fulfil the reactive power requirement. Somewhat better performance was exhibited by PMSG as compared to DFIG as it has a larger capacity. PMSG and DFIG have varying abilities to provide reactive power. PMSG only supplies reactive power from the inverter. Hence, it relies on the converter size and the operating active power. Normally, the converter size is rated more than the rating of WT and is considered to be 3.2 MVA. The largest reactive power production of DFIG is obtained using equation 4.16. The generator creates the reactive power ability of DFIG and is restricted to the machine's parameter that can be explained the P-Q relationship. On the whole, PMSG and DFIG exhibit almost the same capacity while performing standard operation.

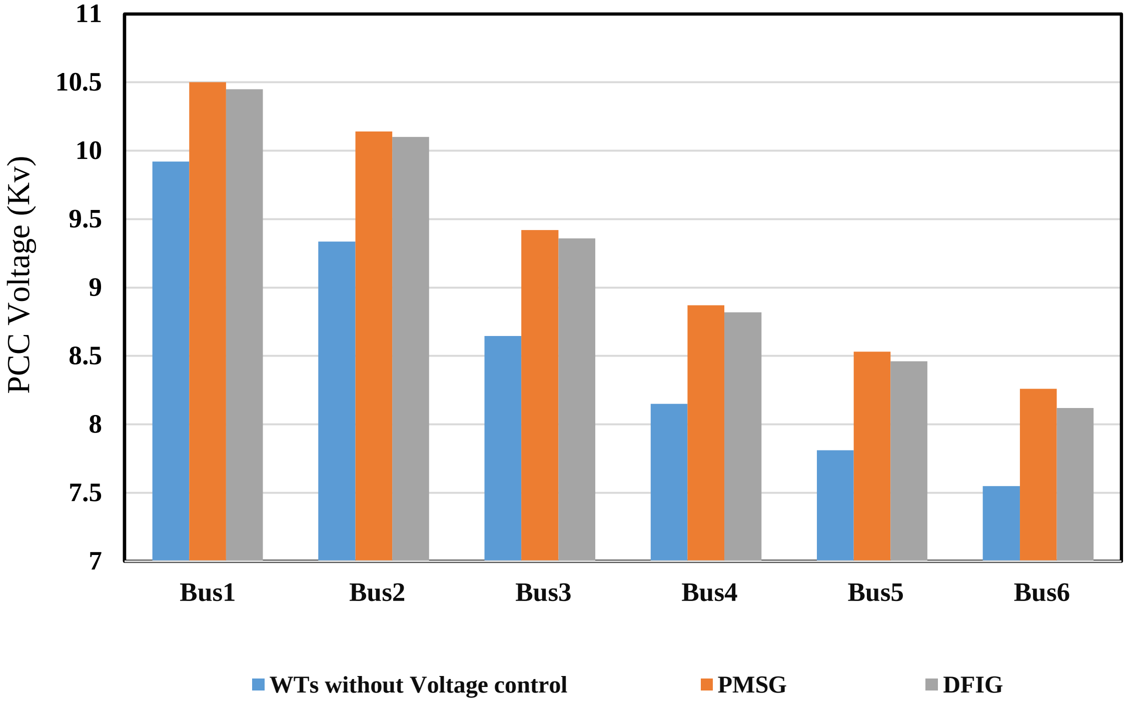

Fig 7-22: voltage across case study buses with and without voltage control

7.6 Response to Voltage Dip

This section examines the way WTs react to a decrease in voltage brought about by a fault in grid. The previous section showed that impedance is connected to case study at PCC so that there is asymmetrical three phase fault that reduces the voltage to almost 90%. This drop extends for 0.5 sec, after which the fault is removed. Both WTs are functioning at rated power when the fault takes place. The way the fault affects electrical and mechanical WTs systems are described in accordance to the simulation findings.

7.6.1 Electrical system respond to voltage drop

This section examines the way voltage decrease affects variable speed WTs electrical system. Fig 7.23 to 7.26 presents the simulation findings, which conform to active power, reactive power, voltage and current respectively. Fault is applied at time 10sec and removed at 10.5sec.

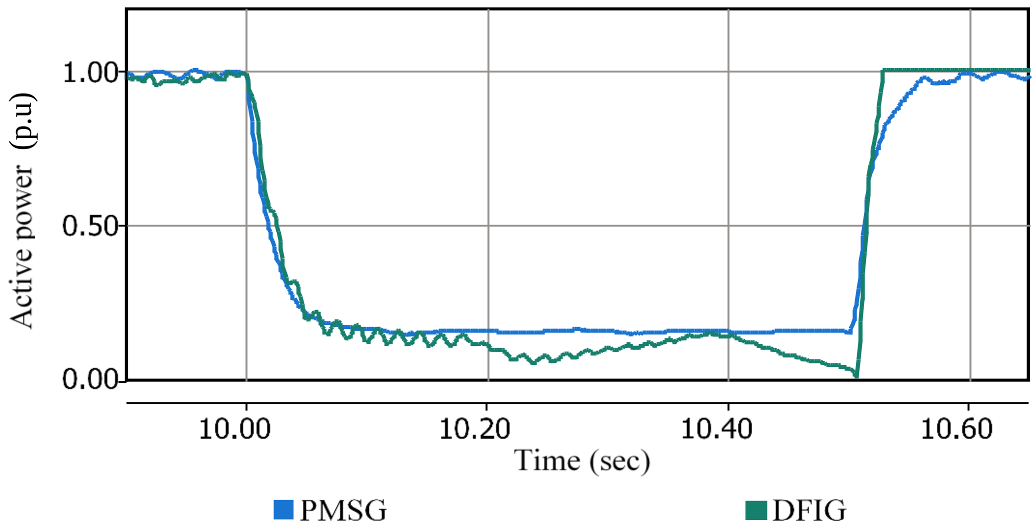

Fig 7-23: WTs active power responds to voltage drop

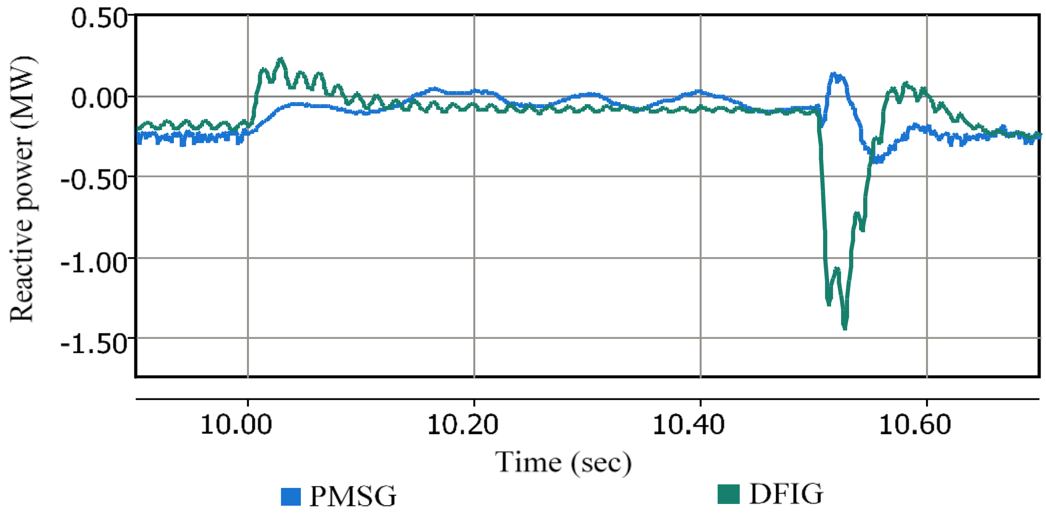

Fig 7-24: WTs reactive power responds to voltage drop

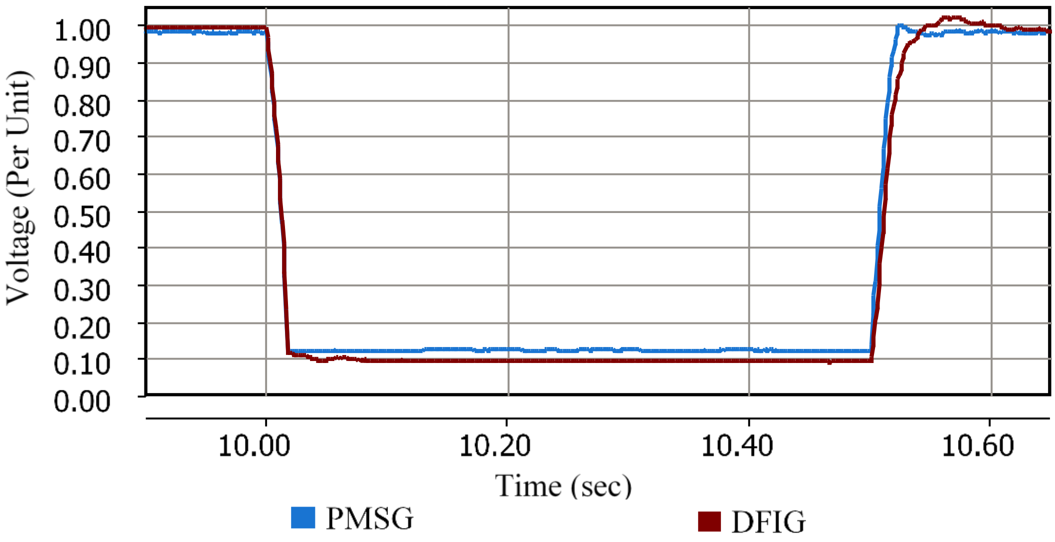

Fig 7-25: WTs PCC voltage respond to voltage drop

Fig 7.23 shows that there is a decrease in active power of the two WTs when the fault occurs, even though the aerodynamic power is still functioning at full ratio. The reason for this is that the WTs terminal voltage falls just like the PCC depicted in Fig 7.26 for PMSG. The inverter is unable to restore the active power to the reference signal.

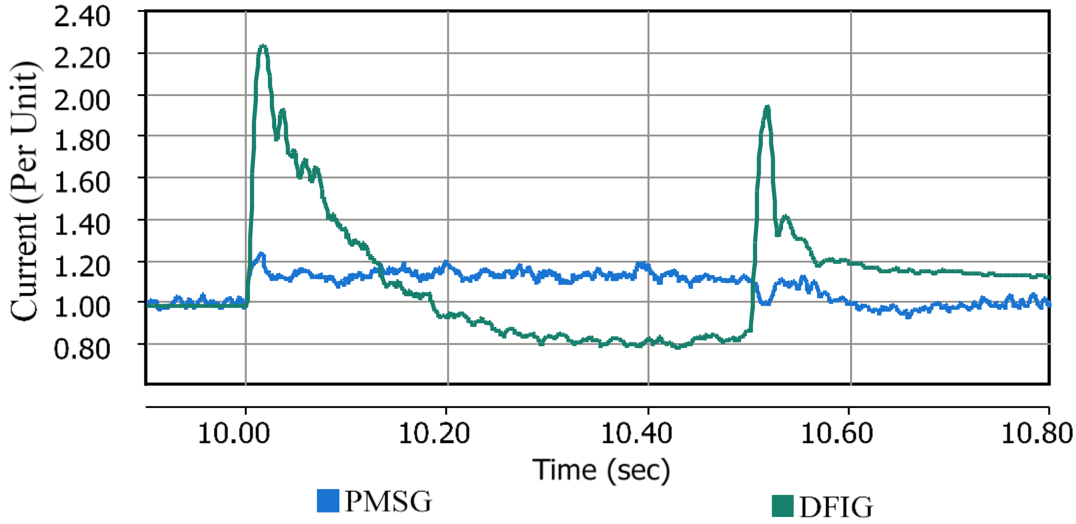

Fig 7-26: WTs current respond to voltage drop

Due to sharp decrease in voltage, the power cannot be delivered whereas the WT is still functioning at full capacity, The unequal power between the converter and the inverter may destroy the DC link, and so, a breaking resistor was included in the DC link so that any additional power is removed through the resistor and the DC link is kept within its limit. With respect to DFIG, due to the decrease in terminal voltage, both the stator and rotor flux are decreased, leading to an electromagnetic torque that causes a significant decrease to active power. The active power of DFIG is comparatively less than PMSG as the PMSG continues to produce power during fault. Fig 7.24 presents the way WTs reactive power functions during a fault. The voltage control is deactivated at this time, and the two systems can reduce the reactive power to zero. However, when there is a fault and at clearing times, the reactive power may exhibit transient values. The simulation findings of WTs current reaction to stark decreases in voltage can be seen in Fig 7.26. It is evident in this figure that there is a large difference in the performance PMSG and DFIG with the current. There is censurable low current in PMSG as the reference current in the inverter (I_d) is normally fixed at 1.1 of its rated value. This is evident in Fig 7.26 when the current remained within its limit. For DFIG, a decrease in voltage causes a decrease in the stator voltage as well because of the direct connection of the stator, causing a decrease in the flux in the stator and the rotor. Therefore, there is a high fault current due to the transient variation in the stator voltage and flux [103].

7.6.2 Mechanical system respond to voltage drop

The Mechanical parameter corresponded in this study are mechanical speed and pitch angle which plotted in Fig 5.27 and 5.28 respectively, the drive train adopted in this simulation is a two-mass system.

It can be seen in Fig 7.27 and 7.28 that the mechanical speed and pitch angle work distinctly. In the PMSG turbine, both factors seem to be stable. This happens due to the integrated breaking resistor which dissipates the extra power in the DC link and hence, manages all the aerodynamic power. In the DFIG turbine, there is a significant decline in the electrical torque during the fault, while the turbine power continued to transfer to the rotor shaft. Hence, the drive train functions as an untwisted torsion spring, increasing the DFIG rotor speed. This is evident in Fig 7.27. The pitch angle also increases, which will stop the turbine rotor speed from increasing, as depicted in Fig 7.28.

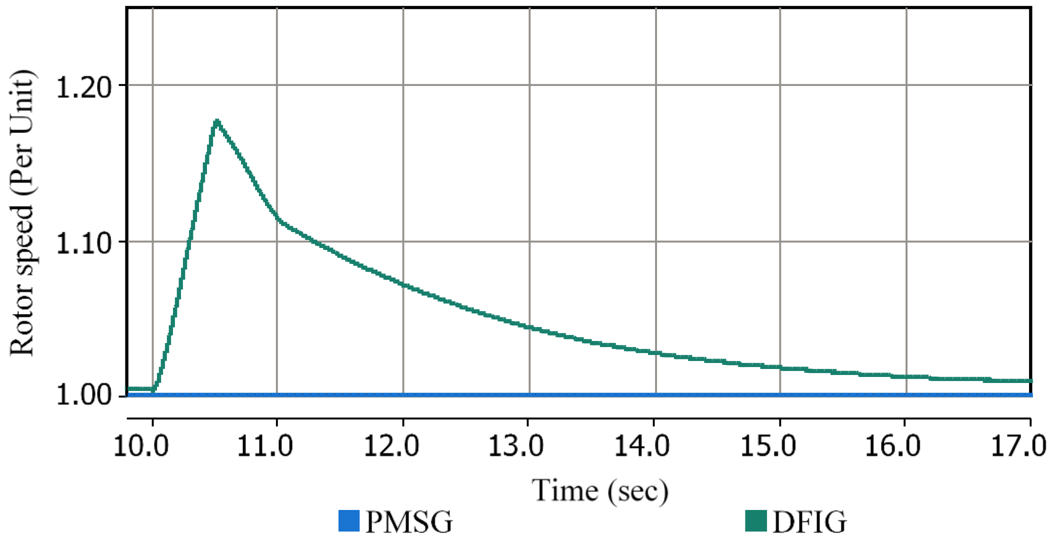

Fig 7-27: WTs mechanical speed respond to voltage drop

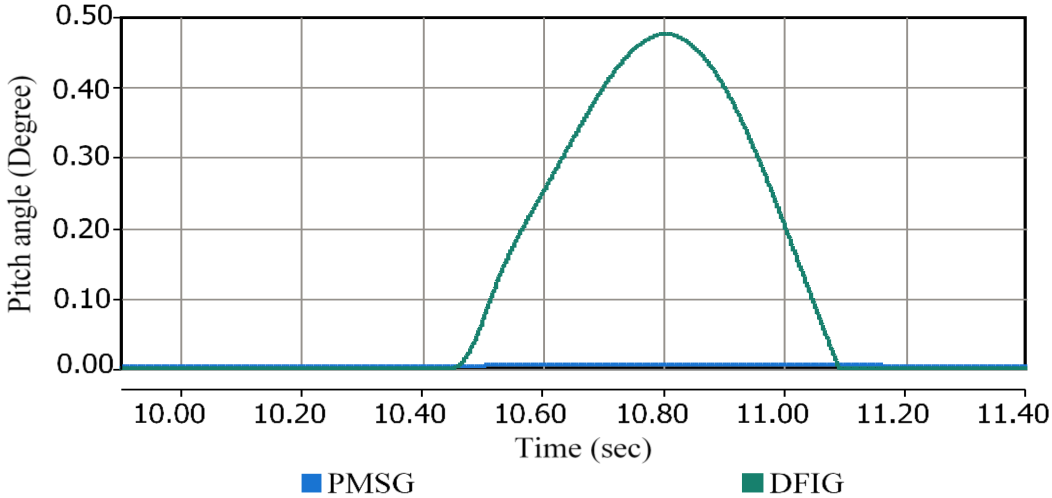

Fig 7-28: WTs pitch angle respond to voltage drop

7.7 Wind Turbine Short Circuit Current Contribution

In this section; the contribution of WTs to short-circuit current is assessed. A sever symmetrical three-phase fault was applied at PCC while WTs were operating at rated power. Fig 7.29 depicts the fault current in KA at PCC with and without WTs, whereas the generators' currents during fault are plotted in Fig 7.30.

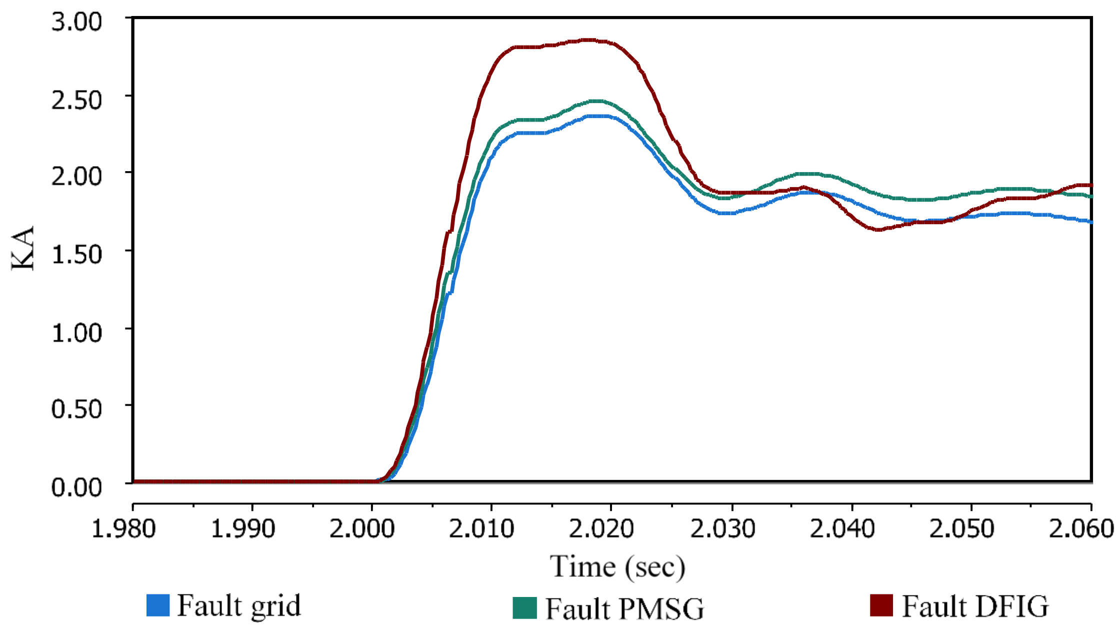

Fig 7-29: short-circuit current of WTs during fault

It is seen in Fig 7.29 that there is greater fault current with DFIG due to direct stator connection. The terminal voltage decreases to zero or almost to zero when the fault takes place. This stops the flux space vector from rotation in the stator, as a result, a DC component exists in the stator flux. In contrast, the rotor-flux continues to rotate (since it is attached to the rotor) and produces alternating component to the stator flux [89]. Voltage is generated by the ensuing flux in the stator at the WT terminals, leading to fault current [91]. The rotor flux causes the oscillation in DFIG current shown in Fig 7.30. The value of DFIG fault current is mainly determined by leakage.

When the stator and rotor transient time are constant, the inductance of the stator and rotor determines the time at which fault current decays. Usually, crowbar protection method is used to secure the converter from high current. The rotor windings is decreased by the crowbar during the fault through set resistors. Using the selected appropriate value of these resistors, the fault current of DFIG can be decreased [89]. In contrast to DFIG, PMSG demonstrates better performance while the fault is in progress, and this is evident in the results. As stated in section 7.5, this is because the GSC can regulate and restrict PMSG current to its rated value, as shown in Fig 7.30.

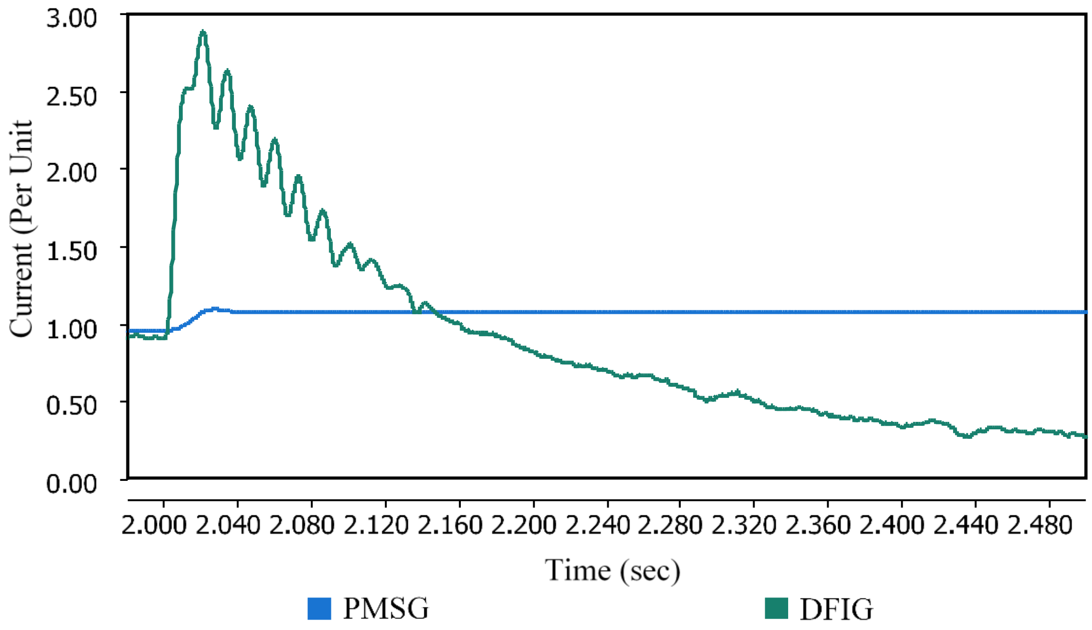

Fig 7-30: PMSG and DFIG current during fault

7.8 **Fault-Ride Through**

In this section, DFIG and PMSG wind turbines ability to conform to fault-ride through based on different grid codes. These include the National grid, E.ON and Energinet.dk, given in Chapter 6. There are three case studies that are performed. In the first one, the National grid code is simulated, followed by the E.ON grid code requirements, and finally, the Energinet.dk grid code. The grid codes' voltage profiles are applied to PMSG and DFIG wind turbine systems. The voltage profile of every grid code is used to the same grid impedance presented by Energinet.dk to allow for comparison. This study concentrates on the fault ride-through as well as voltage support ability. Similar case studies are also carried out for PMSG and DFIG wind turbines.

7.8.1 National grid

This study adopts the National grid voltage profile (see Fig 6.8), in which a fault is created so that the PCC voltage falls to zero. This extends for 140-sec, after which it recovers to 85% in 1.06 sec. The respond of PMSG and DFIG to National grid voltage profile are demonstrated in Fig 7.31 and Fig 7.32 respectively, the quantities depicted in this simulation are: Active power, Reactive power and PCC voltage, all parameters are in per unit. The lower green plot shows that the National grid voltage profile is applied to the PCC, which is plotted with the voltage from wind turbine (blue plot). Furthermore, highest and middle plots demonstrate the active and reactive power generation of the wind turbine respectively.

When the time is 2 sec, the voltage becomes zero. It then increases to 0.15% at 0.140sec, and starts restoring to 80% slowly in 1.06 sec. This continues for 1.3sec, after which it rises to 0.85 and eventually reaches 90% by 15sec.

It is demonstrated in both Fig 7.31 and 7.33 that both WTs conform to the national grid and are capable of remaining stable and connected while there is a decrease in voltage, without having to switch of either of the two WT. In addition, the two WTs can be restored to 90% of the active power once the voltage has been recovered. On the other hand, more rapid and improved behaviour is shown by PMSG to recover and improve the voltage due to inverter controllability, which can provide reactive power, even when facing the fault. However, not the entire reactive power available can be provided because of voltage drop. On the other hand, DFIF rotor circuit is decreased by crowbar in the RSC, after which the power control cannot be attained. Therefore, it works as induction motor that takes in reactive power. At the same time, smaller quantity of reactive power is provided by the GSC (since its size is a lot smaller compared to PMSG GSC). After removing the crowbar, the rotor converter starts regulating the generator power and providing reactive power so that the voltage can be improved. However, restoring the active power restricts the reactive power to the DFIG parameter, which may no longer be generated. On the other hand, PMSG can create the reactive power, even when the active power is at its rated value

7.8.2 E.ON grid code

The simulation outcomes of the PMSG and DFIG wind turbines that have gone through the voltage profile given by the E.ON grid code (see Fig 6.10) are presented in Fig 7.33 and Fig 7.34. Again the lower green indicates the E.on voltage profile, the lower blue plot indicates the PCC voltage, the middle blue plot indicates the reactive power and the top blue plot indicates the active power.

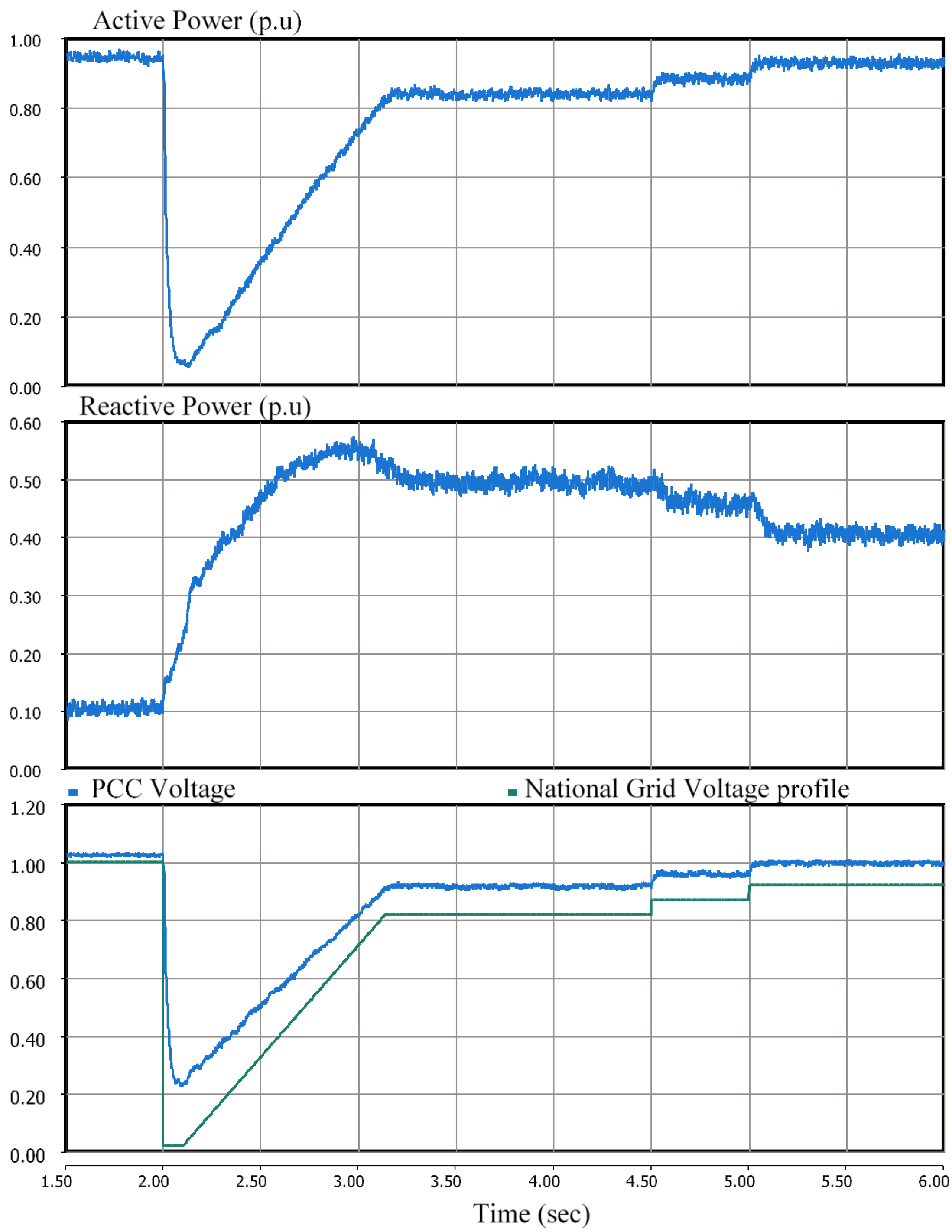

Fig 7-31: **PMSG response to National grid code fault-ride through voltage profile**

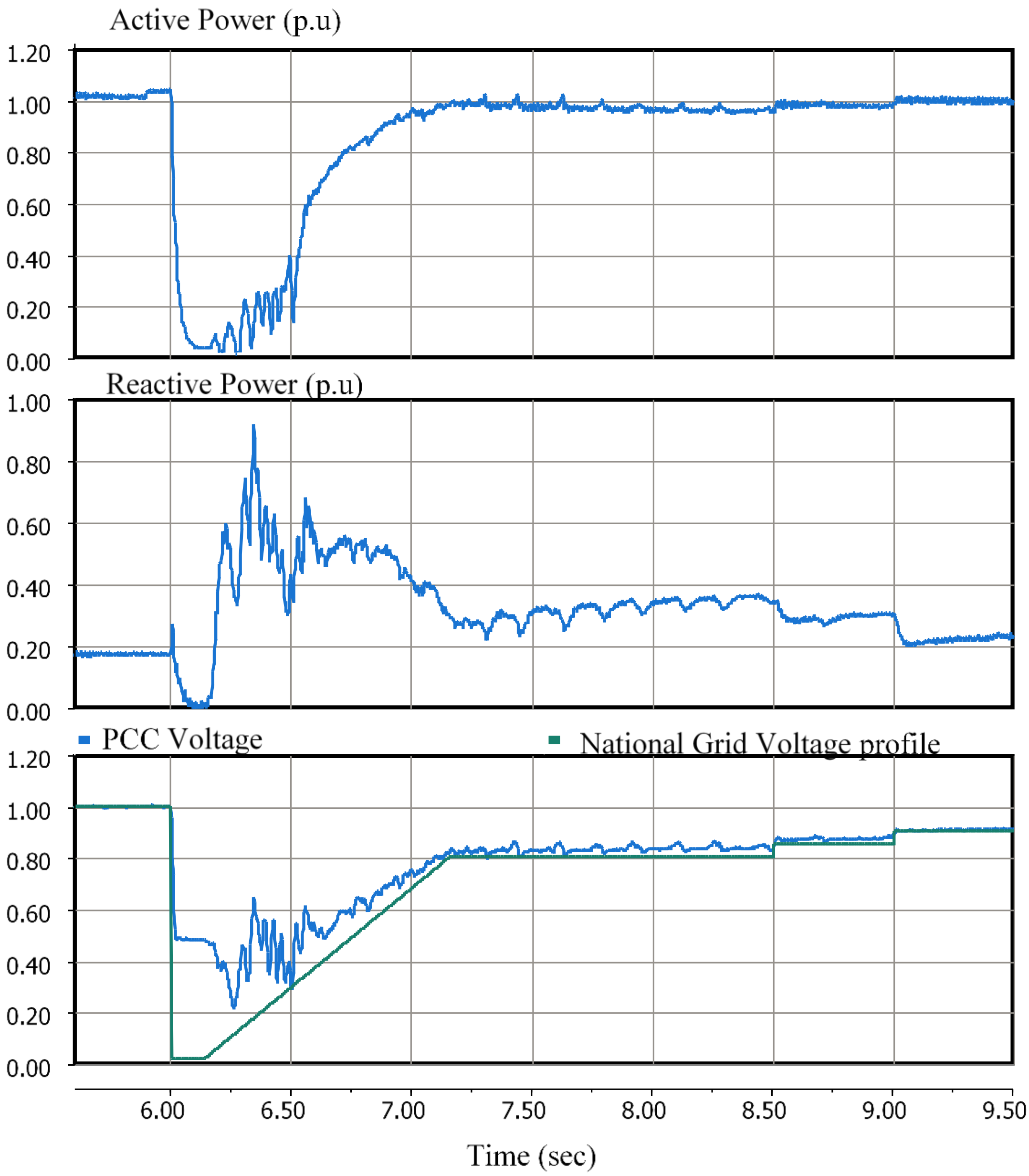

Fig 7-32: DFIG response to National grid code fault-ride through voltage profile

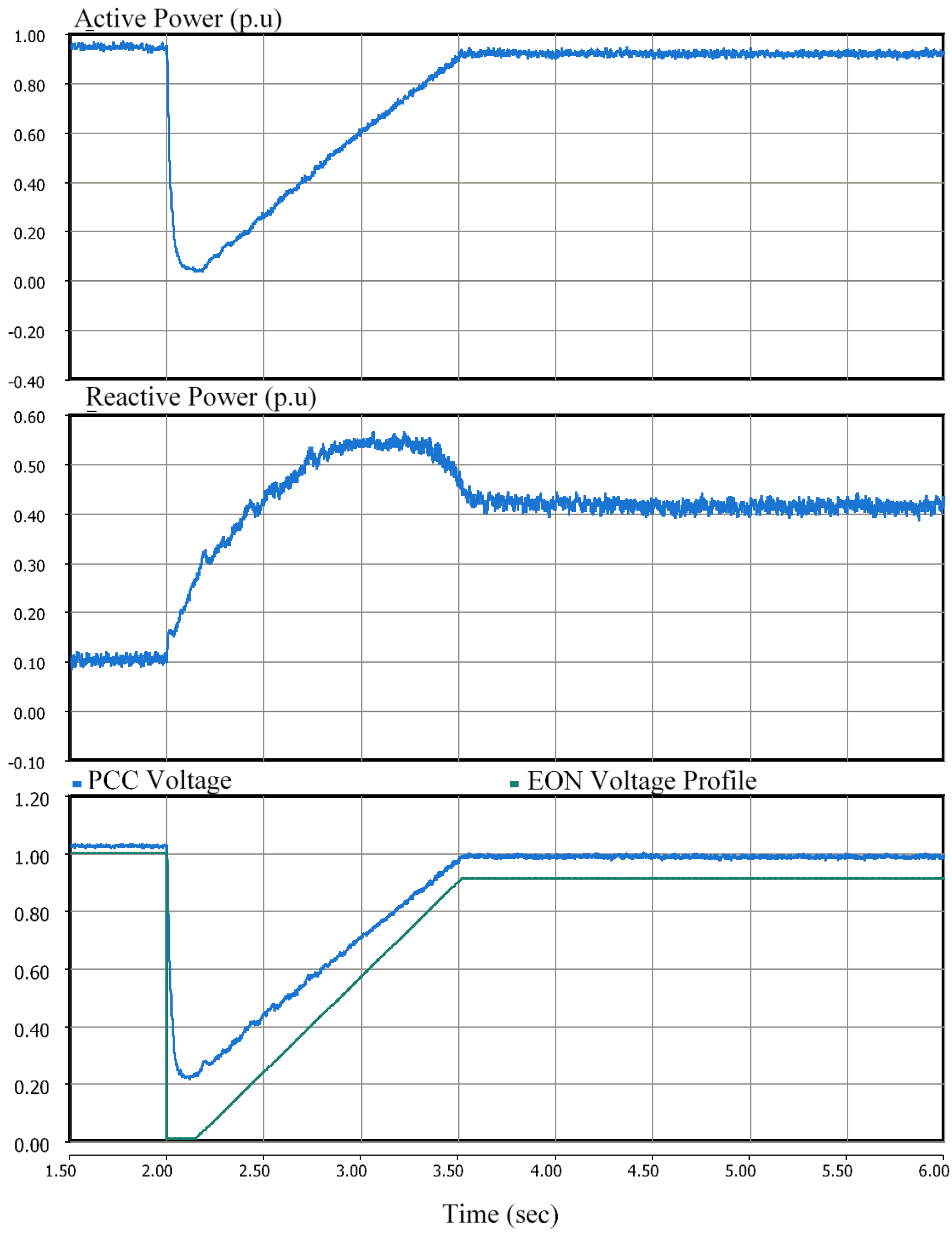

Fig 7-33: PMSG response to E.ON grid code fault-ride through voltage profile

Fig 7.33 shows that E.ON voltage profile is applied on PMSG WT, in which the voltage profile signifies a decrease in voltage to zero when the time is 2 sec, which last for 150 m-sec. The voltage is then start to increase and reach 90% at 3.5 sec, where the active power fully re-established to its nominal value of 1 p.u. The voltage control of E.ON grid code states that the reactive current injection should be applied when there is a decrease in voltage. A full-scale frequency converter is used to connect the PMSG wind turbine, the control can provide highest reactive current to network. The active power becomes zero, and the chopper is used to eliminate the excess power of the turbine. As there is a decrease in the voltage level, the reactive power contribution also decreases. However, there is an increase in the voltage at PCC in contrast to the applied voltage profile. Once the voltage is restored, the turbine can offer the reactive power of 0.6p.u, when the active power is backed up, the producing reactive power decrease to 0.4 p.u because of the inverter size limitation.

Fig 7.34 shows that the E.ON voltage profile specified for fault ride-through is exerted to DFIG, where the voltage falls down to zero for a span of 150 m-sec. Following this, it takes 1.5 s for the voltage to gradually restore to its original value. There is instantaneous coupling of the crowbar at the fault incident because of the intense voltage decrease. Meanwhile, RSC is blocked; however, the GSC offers a minor reactive power to PCC. The crowbar is removed after the voltage recovery, after which the rotor side converter integrates with the reactive power. At this point, the active power falls to zero since the reactive power generation is selected by the RSC control. The DFIG provides its highest reactive power in the simulated case. This causes the voltage level to improve in contrast to the E.ON voltage profile. Nonetheless, when the grid voltage is reduced considerably, the DFIG cannot offer the maximum reactive power. There is a certain limit to which the DFIG wind turbine can offer reactive power. The reasons for this are: 1) active and reactive power generation are not completely independent as compared to a full converter connected generator. When the wind turbines are entirely converter connected, the reactive power included in the grid depends on the grid side converter that is not dependent on the generator’s operational point; 2) as the DFIG’s frequency converter has a smaller size, the rotor current of the DFIG is limited; 3) While crowbar coupling is taking place, reactive power supply occurs solely by the grid side converter, which does not have much capability for supplying reactive power. However, the voltage level is slightly increased by the reactive power supply. The crowbar protection allows for achieving the fault ride-through, which allows the turbine to remain connected.

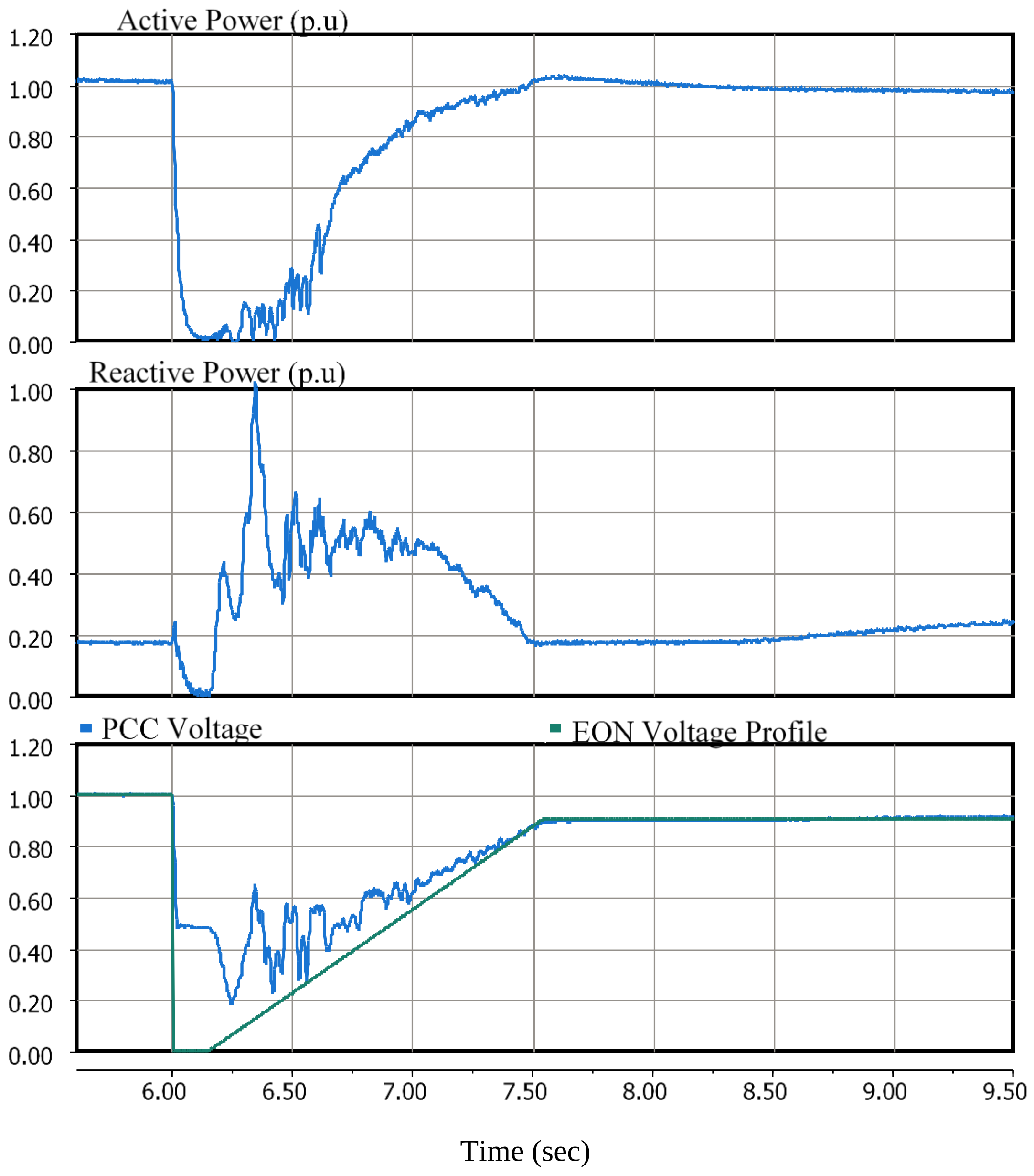

Fig 7-34: DFIG response to E.ON grid code fault-ride through voltage profile

This makes it evident that fulfilling the grid code depends on the precise understanding of the given requirements and acceptance of the responsible grid code

Because of little rotor current capacity, there is limited reactive power generation. Hence, the reactive current infeed is unable to meet the given requirement, and this is the sole issue faced in fulfilling grid code. Nonetheless, the E.ON grid code permits short-term interruption for the simulated voltage profile, after which there is rapid re-synchronisation of the wind turbine. Here, the reactive power would be constrained or interrupted, and the power system

7.8.3 Energinet.dk grid code

In another case study, the PMSG and DFIG wind turbines go through the voltage profiles given in the Energinet.dk grid code (as illustrated in Fig 6.9 in chapter 6). The results resented in figure created from the same generators' quantities, such as voltage at PCC and active and reactive power generation infeed of the wind turbine. As compared to the National and E.ON grid code, Energinet.dk specifies greater voltage profile, however, the voltage decreases to 75%, which continues for a longer time. There is a decrease in voltage to 75% for 100 m-sec, after which the voltage undergoes a linear increase to 75% of nominal value within 750 m-sec.

Fig 7.35 shows that energinet.dk voltage profile is applied to PMSG WT. The turbine quantities, including the voltage at PCC and its active and reactive power are graphed for 4sec following the fault incident. The graph's plots also like previous cases, demonstrate the voltage profile, the active, the PCC voltage, the reactive power and active power as in previous cases.

The Energinet.dk grid code states that it is important to generate active power as given in equation 6.16. Because of the greater converter rating, reactive power can be provided alongside by the GSC of the PMSG. The reactive power instantaneously increases in a small rise time. Reactive power of 0.56 p.u can be offered during the fault, which leads to an increase in the voltage level at PCC. The active power falls as the voltage decreases, when the voltage is backed up, the active power is restored to 80% of its rating, as a result, the reactive power decreases slightly because of converter size limitation. Nevertheless, it is capable to provide 0.5 p.u of reactive power as the converter is sized larger than wind turbine nominal power value. It is can be concluded that PMSG wind turbine can ride-through the given grid fault, and fulfil the grid code specifications given by Energinet.dk.

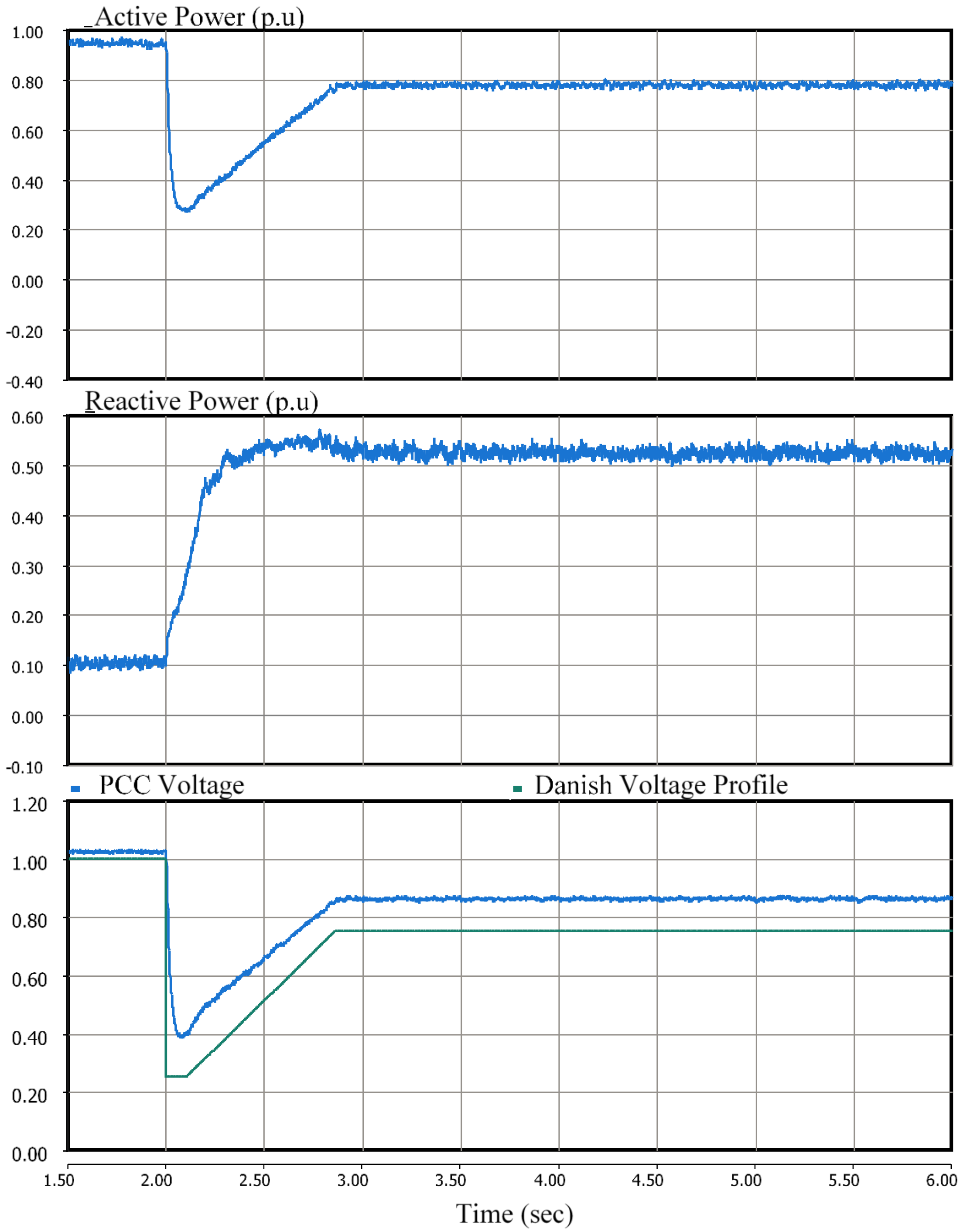

Fig 7-35: PMSG response to Energinet.dk grid code fault-ride through voltage profile

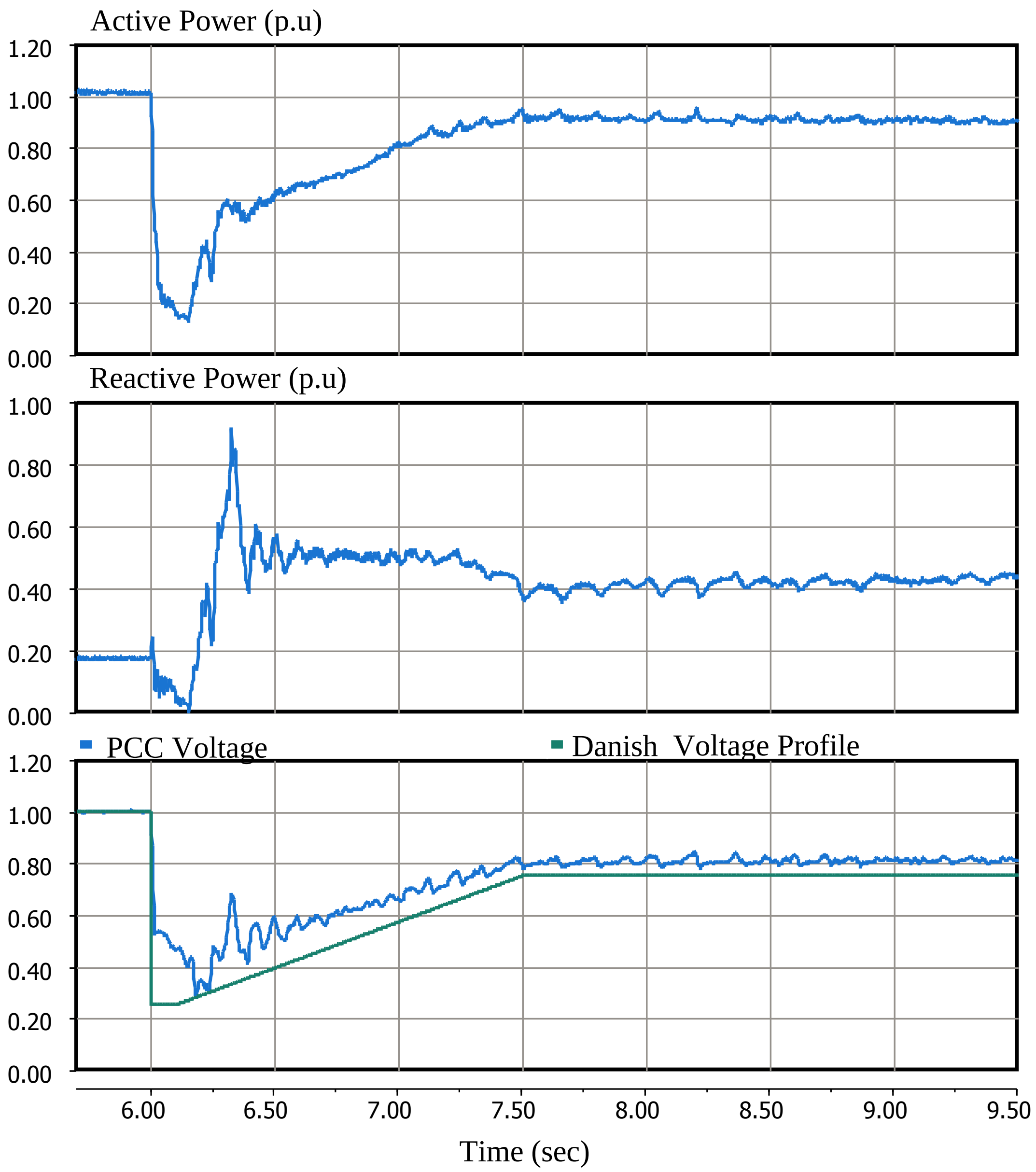

Fig 7-36**: DFIG response to Energinet.dk voltage profile fault-ride through**

Fig 7.36 illustrates the respond of DFIG for Energinet.dk fault-ride through voltage profile. Crowbar coupling occurs once again because of the decrease in voltage. Compared to the E.ON and National grid codes, active power supply is needed by Energinet.dk when the fault is occurring. Equation 6.16 describes the active power reference, and this can be adhered to by the active power from DFIG. In addition, less reactive power is needed; hence, the reactive power ability is not entirely restricted. This suggests that in addition to the active power production needed, the highest possible reactive power and reactive current is offered by the DFIG. However, the specifications for the reactive power feed are not presented in the Energinet.dk grid code. The RSC voltage controller allows the DFIG to provide reactive power so that the voltage magnitude at the PCC can be augmented. It is accepted in this study that fault ride-through for the given voltage profile can be achieved by DFIG wind turbines. In addition, the Danish grid code specifications can be fulfilled.

7.9 Summary

This chapter presented a dynamic simulation of a variable speed wind turbine with PMSG and DFIG. A comprehensive dynamic model of VSWTs and their control were developed and implemented in PSCAD/EMTDC package. Firstly, the VSWTs dynamic performance at normal conditions was examined in order to demonstrate that the control technique presented in chapter 4 and 5 can effectively controls the VSWTs at varying wind speed circumstances. The results guarantee that the power converters enable a variable speed operation, and VSWTs can extract maximum power during different wind speed at or below nominal wind speed, when the wind speed is above its rated value, the blade angle control prevent the WTs from overspeed and then indirectly control the output power to their nominal values. Then, a set of simulations is performed in order to measure and investigate the impact of VSWT on power quality as detailed in chapter 6. The measurement procedure was conducted based on the standard IEC61400-21, the addressed power quality characteristics are: Flicker, current harmonics, active and reactive power and the response to voltage dip. Moreover, the short-circuit current and fault-ride through were also simulated in this chapter based on the grid codes described in chapter 6. Different simulation sets are carried out for the power quality measurements. A flickermeter developed by IEC61000-4-15 is used to measure the flicker level from the WTs terminals voltage, the simulation proved that VSWTs have low flicker lever because the fluctuation in aerodynamic power is not totally transfer to the generators' output power and smoothed out by the power conveter. By the advantages of employing power converter, both VSWTs able to track the controllers' signals for active and reactive power and meet easily the standard requirements. On the other hand, using power converters presents current harmonics for VSWTs, a FFT was used to measure the harmonic and it has been found that both; DFIG and PMSG contains low-order harmonics in their current, which is caused by of power electronics switching devices. The direct connection of DFIG's stator to utility grid make it sensitive to the voltage and large inrush current occurs during voltage dip, on the other hand, PMSG is fully separate from the grid by full-scale power convert which brings the advantage of smooth performance at voltage dip. Likewise, when addressing fault-ride through and short-circuit current PMSG has the advantage of smooth performance because of fully decoupling between the generator and the grid. Furthermore, PMSG has the capability to produce the reactive power during voltage drop whereas DFIG loose the controllability at voltage dip because GSC is blocked by the protection scheme.

The major contribution to the knowledge presented in the current work can be concluded in the following table:

Table 7-8
The characteristics of variable speed wind turbine to power quality issues

WT type / **Power quality issue**	**PMSG WT**	**DFIG WT**
Short-term Flicker	Low Flicker emission (P_{st} = 0.4 at rated speed)	Low Flicker emission (P_{st} =0.2 at rated speed)
Flicker step factor	Low values at starting-up WT at cut-in ($k_{f\,(\psi k)}$ = 0.02) and at rated wind speed ($k_{f\,(\psi k)}$ 0.031)	Higher values at starting-up WT at cut-in ($k_{f\,(\psi k)}$ = 0.06) and at rated wind speed ($k_{f\,(\psi k)}$ = 0.086)
Voltage step factor	Low values at starting-up WT at cut-in ($ku_{(\psi k)}$ = 0.52) and at rated wind speed ($ku_{(\psi k)}$ = 0.51)	Higher values at starting-up WT at cut-in ($ku_{(\psi k)}$ = 1.558) and at rated wind speed ($ku_{(\psi k)}$ = 2.07)
Respond to voltage dip	Dynamic stability	High Inrush current, rotor over-speed and unbalanced reactive power
Active power control	Very fast respond to reference signal	Very fast respond to reference signal
Reactive power control	Very fast respond to reference signal	Very fast respond to reference signal
Harmonics Distortion	Low-order current harmonics, compliment to IEC61000-3-6 standard and maximum THD = 8%	Low-order current harmonics, compliment to IEC61000-3-6 standard and maximum THD = 14.5%
Fault-ride Through	Capable of Fault-ride Through to the given grid codes with significant power quality supply	Capable of Fault-ride Through to the given grid codes with low power quality supply

Chapter 8 Conclusion and Further Works

The integration of wind turbines to the utility grid causes various power quality related issues. Because wind power which is now an emerging and it is expected to be the major renewable source of electrical energy in near future, the study of wind power effect on power quality is then essential. So the problems of power quality emerging from the grid connected variable wind turbines are being studied, this study also addressed the interaction between wind turbines and the connected grids. Via this research, an evaluation process would be run to check the power quality being affected by variable speed wind turbines based on pattern devised by IEC61400-21. Factors fuelling power system stability that includes voltage ride-through and current short-circuits are also revised under the study.

While discussing the modern variable wind turbines available in the recent times, the concept of wind turbine featured by the doubly-fed induction generator (DFIG) is the most admired amongst all. Sorting out the most promising future applications tech, related to the offshore wind turbines, full-scale frequency converter and the multi-pole permanent magnet synchronous generator (PMSG) crowns the list. Being the ultra-modern variable speed wind turbines, DFIG and PMSG wind turbine technologies are were focused in this research. In order to accomplish the objective of this research, the wind turbine concept has been categorized into the electrical, mechanical and control modelling, by constructing inclusive dynamic simulation models of wind turbines mutually, utilizing the PSCAD/EMTDC tool which possesses expertise in analysing power system.

The mechanical model is represented by the aerodynamic and the drive train model, two-mass spring model is adopted for the drive train. The model of the wind turbine's mechanical part, valid for both concepts. The modelling of electrical system for every concept is different. Tool box library makes various tools available in varying proportions such as the switching devices, generators, capacitor, loads, transformers and the coils, which collectively make up the models of the electrical system. Certain particular manufacturer doesn't describe the strictures of wind turbines and generators but they do play a role of generator and turbine envoy being adopted in a modern 3 MW pitch-controlled variable speed wind turbine.

Power controller and the speed controller are the two coordinated controllers that work mutually in achieving wind turbine with its control. Both of the DFIG and PMSG wind turbines works on the same control standard; Convertor has a direct control of the turbine power, on the other hand pitch angle control is responsible for preventing the generator from over-speed. Given the normal operational circumstances, it can be inferred from the Simulations that the variable wind speed wind turbines were mainly controlled by the developed control method. When wind speed is below than rated value; the task of the converter is to capture maximum power according to the MPP-tracking. During the heavy wind blows, convertor and speed controllers make it calm and utilize their full potential to avoid any damage, either its mechanical stresses or the turbine's mechanical system. The generator power is kept constant by the convertor while generator speed is varied a little by speed controller.

The power quality parameters given by IEC61400-21, current short-circuits and voltage ride-through were measured and discussed in this research. IEC61400-21 power quality aspects include voltage flicker, current harmonic, voltage dip, active power control and reactive power control.

PMSG and DFIG grid-connected wind turbines were simulated to study the flicker emission during continuous and switching operations. Factors such as grid conditions (short circuit capacity, grid impedance angle) and wind characteristics (mean speed) were found to affect the flicker level. In general, both generators produced low value of flicker emission and they were compliant to flicker limit stated by the standard IEC61000-3-7. DFIG has less flicker emission whereas PMSG show better results during switching operation because of grid-isolation of full power convert.

It was found that the current harmonic depends on wind turbines' operation with noticeable different behaviour for every wind turbine type, in DFIG case, the current harmonic caused by rotor and grid side converter, the rotor-side regulates the generator speed range operation by changing rotor voltage which is a function of slip, this make the magnitude of the stator harmonics is proportional to the slip value regardless of the slip direction. On the other hand, current harmonic of PMSG is emitted by the inverter only and it is proportional to the out power of wind turbine

The active power is mainly determined by the wind turbine current, and within the given range, active power output can be controlled in diverse modes. It has been found that variable speed WTs with PMSG and DFIG have the ability to follow a given set point as specified by IEC 61400-21 very quickly and precisely.

From the results we can incur that both of the WTs possess the ability of coming along with the exact reactive power reference stated by IEC 61400-21 while trailing it. Switching from inductive to capacitive mode is a matter of less than a second for PMSG and DFIG WTs providing WTs with an advantage of backing up the stability of voltage during disturbing situation.

PMSG and DFIG, due to their defined structural and grid integration distinctions, are performing in different ways to voltage dip. As a consequence of voltage drop, the active power trim down during voltage dip, in PMSG integration while WT's still generate full power, the excessive power of which fritter away throw breaking resistor in the DC link. Meanwhile, the reactive power and the current is controlled by the grid-side converter up to their reference values, the current is usually set to 1.1 p.u and the voltage drop is compensated by reactive power whose signal is given by extended voltage control. In the case of DFIG, the active power drops because of voltage reduction and an inrush current occurs due to the direct stator grid connection. In the interim the stored magnet field is demagnetised by the stator stimulating a momentary rise in reactive power. As soon as the fault removed, the stator begins to recharge which request a large transient current. As a comparison between PSMG and DFIG, we can suggest that PSMG functions smoothly when it comes to voltage dip issue.

Short-current circuit contribution of WTs was assessed to sever symmetrical three-phase fault. It has been revealed that DFIG has much higher fault current because of direct connection of the stator to the grid. The magnitude of DFIG fault current depends mainly on leakage inductance of the stator and rotor, the stator and rotor transient time constants determine the time of fault current decay. Typically, DFIG is equipped with crowbar protection scheme to protect the converter from high current. The crowbar shortens the rotor winding during the fault by set resistors. On the other hand, PMSG shows a better performance during the fault, the stator terminal is fully decoupled from the grid by GSC which can control and limit PMSG current to its rated or a given value.

This work implements a voltage ride-through, determined by British, German and Danish grid codes. The simulation results exemplify how DFIG and PMSG perform during voltage profiles given by these grid codes and have been found that both generators are capable of staying connected when and capable of FRT. It can be seen that both WTs have the ability to restore their active power after voltage recovery. PMSG distinguishes itself due to its capacity of distributing reactive power when the voltage is low. On the other hand, DFIG has different performance, the rotor terminals is blocked by RSC which result to no longer power control is feasible, hence, it conducts like induction motor, demanding reactive power instead. Conversely, reactive power of GSC is formed by DFIG but its spontaneous power contribution is much less than PMSG due to the limitation of convertor to 30% of wind turbine power. Financially befitting partial scale converter comes out to be technically unbeneficial when addressing voltage fault, because it demands protection scheme to prevent high transient currents and voltages.

In conclusion, the choice of which type of electrical generators is best to be employed in wind turbines is critical, DFIG is the preferred solution when considering the cost and the weight. Nevertheless, the PMSG is more attractive in term of reliability, the efficiency and the robustness. Moreover, the simulation results in this work figured out that the select of PMSG with full-power converter is the most efficient in terms of power quality, and it can be concluded that PMSG WT is the best choice among all the variable speed wind turbines

Further Works

There are other issues concerning the power quality of wind turbines and grid integration of wind power exists and should be studied. Below, some of selected concerns which should be targeted by future research:

- The response of variable speed wind turbines' frequency should be studied, as the rotor speed wind turbine varying according to weather condition, the effect of rapid change in wind speed e.g. strong gust which result in change in rotor speed, may affect the grid frequency. Furthermore, after voltage dip, the effect of restoring of active power and voltage on frequency should be evaluated.

- How power quality might be affected by replacing the currently studied wind power diffusion from a large wind turbine can also be revised in upcoming studies. The influence of group of wind turbine on some power quality problems (as explained in chapter 6) differs from a single unit e.g. flicker and harmonics. Today wind turbine is installed in high number either shore or offshore, thus it worth to evaluate the power quality of wind turbine as large wind farm.

- If probable, the simulation results in this thesis should be verified by carrying out a field test.

- The interharmonics should be studied since they appear in variable speed wind turbine current, the interharmonics play a significant role in current waveform distortions. However, interharmonics are not considered in this research because of software inability.

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Appendix

A. Wind turbine parameters

Wind turbine type	**Horizontal axis**
Number of blades	**3**
Rated power (MW)	**3**
Rotor diameter (m)	**82**
Hub height (m)	**100**
Blade control	**Pitch**
Speed control	**Variable**
Generator type	**PMSG/DFIG**
Frequency converter type	**Back-to-Back**

B. PMSG parameters [155]

Parameters	PMSG	Unit
Rated power	3	MW
Rated speed	12	m/s
Voltage/Frequency	690/50	V/HZ
Stator resistance	0.006	p.u
d-axis inductance	0.00415	p.u
q-axis inductance	0.0015	p.u
DC voltage	1000	V

C. DFIG parameters [155]

Parameters	DFIG	Unit
Rated power	3	MW
Rated speed	12	m/s
Voltage/Frequency	690/50	V/HZ
Stator resistance	0.023	p.u
Rotor resistance	0.016	p.u
Stator resistance	0.018	p.u
Rotor leakage resistance	0.016	p.u
Mutual inductance	2.9	p.u
DC voltage	1000	V

D. Case study details [154]:

PM Generator

Nominal power	3 MW
Nominal Voltage	690 V
Nominal frequency	33 HZ
Stator resistance	0.017 p.u
Quadrature-axis reactance	0.5 p.u
Direct-axis reactance	0.5 p.u

Transformer (T1)

Rated power	5 MW
Rated frequency	60 HZ
Connection	Y/Y
Primary voltage (L_L/rms)	138 kV
secondary voltage (L_L/rms)	11kV

Transformer (T2)

Rated power	3 MW
Rated frequency	60 HZ
Connection	Y/Δ
Primary voltage (L_L/rms)	0.69 kV
secondary voltage (L_L/rms)	11kV

Transformer (T3)

Rated power	5 MW
Rated frequency	60 HZ
Connection	Y/Y
Primary voltage (L_L/rms)	138 kV
secondary voltage (L_L/rms)	11kV

Hybrid Loads

Linear loads (L .L)

Active power	1.2 MW
Reactive power	0.9 MVAR

Nonlinear loads ()

Active power	1.6 MW
Reactive power	1.2 MVAR

Distribution Feeder

Length	3 km/section
Resistance	0.25 ohms/km
Inductance	0.93 mH/km

Motorised loads

Nominal power (based)	0.6 MVA
Nominal Voltage	4160 V
Nominal frequency	60 HZ
Stator resistance	0.019 p.u
Stator inductance	0.06 p.u
Rotor resistance	0.019 p.u
Rotor inductance	0.06 p.u