# Grid Code Testing by Voltage Source Converter

*Master's Thesis in the Master Degree Programme, Electric Power Engineering*

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# Abstract

The wind power penetration is increasing tremendously and according to EWEA that wind will contribute up to 230 GW – 260 GW by 2020 in Europe and total wind power generation in Europe would be 400 GW by 2030. To integrate this huge amount of contribution from wind power into our current electrical system is a big challenge for both power system planners and operators because of different behavior of wind power plants than the conventional power plants. It is required from the wind power plants that it should contribute in grid support such as frequency, voltage and reactive power control and it should behave as a conventional power plant during normal and abnormal conditions. For this reason transmission system operator's (TSO) of different countries have issued grid codes for wind power plants to operate them in conventional way.

In this project, a design of a voltage source converter (VSC) based test equipment has proposed which can be capable to test a single wind turbine for the compliance of grid codes to the wind turbine. The main objective to design this kind of test equipment is to investigate the design and performance of a voltage source converter based test equipment to test a single wind turbine and to set a base model for future discussions on grid codes compliance to wind farms. The VSC based test equipment is found to be very unique as it exhibits the characteristics of a grid and it can vary both frequency and voltage independently. The most important factor that should be considered while designing this kind of test equipment is the current and voltage ratings of the converter and the maximum fault current provided by the wind turbine during short circuit test that the equipment has to handle as this fault current can be several times higher than rated current of wind turbine. It is also shown from simulation results that the test equipment can be used successfully to verify the grid codes by creating different voltage and frequency variations and can apply abrupt changes in voltage to exhibit short circuits leading to voltage dips in the grid.

Keywords: Grid codes, voltage source converter, point of common coupling (PCC), fault ride through capability.

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*Dedicated to our beloved parents*

# TABLE OF CONTENTS

# Chapter 1

# Introduction

Energy is the major driver in the development of a society. As the world is developing day by day, ultimately we have to find new energy resources to fulfil the demand to carry on this development of the society. We cannot completely rely on our current energy sources like thermal, nuclear and hydro because the fuel reserves for these sources are declining rapidly and their environmental effects are quite alarming for the society. There exists a solution to this problem is to use renewable energy sources i.e. wave and tidal power, solar power and wind power. Their contribution to meet the demand is quite modest till now because the major disadvantages of these renewable energy sources are that they are quite expensive and less flexible as compared to conventional power plants. But many governments tend to value the benefits of renewable energy sources more than the conventional generating plants .Hence they support the expansion of renewable energy sources in various ways which basically means to overcome the disadvantages associated to them. Among the renewable energy sources, wind power is the most effective one and it is growing more rapidly due to its advantages over the other renewable energy sources i.e. there is a lot of technology available to harness it and technology is quite developed .People are using wind power for hundreds of years and there are also quite a large number of wind power companies in the world.

## 1.1 History of Wind Energy

Wind power is being used by humans for hundreds of years. It is the evolution from the use of simple light devices driven by aerodynamic drag forces to heavy, material intensive drag devices. At first wind power was used to sail boats and later on this led to development of sail – type wind mills. In the start windmills were made for grinding grains, pumping water and the design was known as vertical axis system. Wind energy used to generate electricity for the first time by Charles F. Brush in 1888. Paris – Dunn and Jacobs were the pioneer companies for small electrical output wind turbines simply used modified propellers to drive d.c generators. In 1979, the modern wind industry started when Danish manufacturers started producing wind turbines. Although at that time they were small in size 20 – 30 KW but now with the passage of time they have increased greatly up to 7 MW. Figure: 1.1 below represents that how wind power development took place from simple grinding speed or driving machines to wind parks [1].

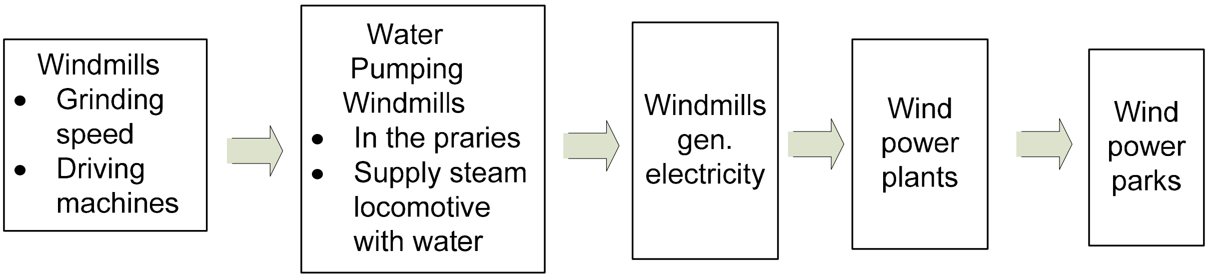


Figure: 1.1 Development of Wind parks.

## 1.2 Wind Energy Mechanism

The sun does not heat the earth in an evenly manner such that the poles get less heat than the equator and moreover dry land gets heat up and cool down more quickly rather than sea. Therefore, some patches gets warmer than others rise, air blows in to replace them and we feel blowing wind. We can say that it is a form of solar energy as wind is produced by uneven heating of sun. The basic mechanism of wind energy is that it converts the kinetic energy of wind into mechanical power by using turbines. Wind turbines are available in different sizes according to different power ratings. Its mechanism is opposite to fan that rotates to generate wind while wind turbine itself rotates by the wind to produce kinetic energy. There are two types of wind turbines,

(i) Horizontal Axis Wind Turbines

(ii) Vertical Axis Wind Turbines

Betz Law is used to calculate maximum amount of power that can be extracted from a wind power plant. It gives the maximum theoretical power but the original power that is extracted from generator is lower as there are some transformation losses from mechanical to electrical energy. Currently the most effective power plants have efficiency of about 50% and now the consideration is to make more cheaper, more reliable and more flexible wind power plants [1].

The power in the airflow is given by,

$$P_{\text{air}} = \frac{1}{2}\,\rho\,A\,\nu^{3} \tag{1.1}$$

Where,
$\rho$ = air density (approximately 1.225 $\text{kgm}^{-3}$)

A = swept area of rotor, $m^2$
$\nu$ = upwind free wind speed, $ms^{-1}$

Equation (1.1) gives the power that is available in the wind but the original power transferred to wind turbine rotor is reduce by the power coefficient, Cp.

$$C_p = \frac{P_{\text{wind turbine}}}{P_{\text{air}}} \tag{1.2}$$

Betz limit defines the maximum value of Cp that a turbine cannot extract more than 59.3% power from air. In real its value varies between 25% – 45%. [1]

The tip speed ratio $\lambda$ is an important parameter while designing a wind turbine as it measures that how fast blades rotate with the wind speed.

$$\lambda = \frac{v_{\text{blade}}}{v_{\text{wind}}} = \frac{\omega_r}{v_{\text{wind}}} \tag{1.3}$$

Where,
$\lambda$ = Tip speed ratio
$v_{\text{blade}}$ = Tip speed of the blades (m/s)
$v_{\text{wind}}$ = Wind speed (m/s)
$\omega$ = angular velocity (rad/s)
r = radius of the rotor (m)

## 1.3 Wind Power Plant Components

Wind power plants can have different architectures of electrical systems. Components are chosen with respect to generator type to make more efficient and reliable wind power plant [1].

**(1) Generators:** Wind power plants can be equipped with any type of generators whether it is ac or dc as it can be complied with the power electronics to synchronise it with the grid. Mechanical construction of synchronous and asynchronous generators is same. A generator consists of two main components, a rotor and a stator. Rotor consists of permanent magnets or windings that generate a magnetic field when current flows into the rotor. As the rotor rotates, a rotating magnetic field arises. When this magnetic field moves into stator windings, voltage is induced in these windings. Mostly generator generates alternating current. With every revolution of rotor current and voltage changes its direction accordingly. There are different kinds of generators and they are categorized in figure 1.2.

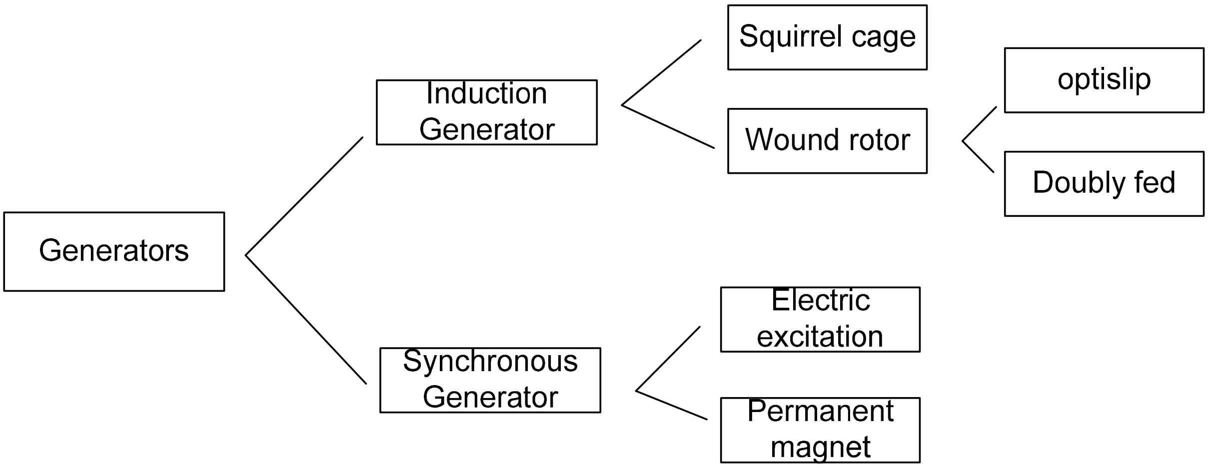


Figure 1.2 Different types of generators

**(2) Rotor brake:** It is used to lock the rotor when maintenance is required and to keep the rotor in position when it is not rotating or to brake the rotor when the wind speed is too high. Normally disc brakes are used and dimensions are calculated by measuring the maximum possible wind speed in that location. The size of the disc brake is directly related to rotor size and they can be installed either on low speed shaft or high speed shaft but mostly it is connected to high speed shaft. High speed results in low torque so diameter of disc should be kept as small as possible [1].

**(3) Gearbox:** It contains two cogwheels, a large and a small. A shaft connected from turbine to large cogwheel, called low speed shaft. Large cogwheel runs the small one. The smaller cogwheel is connected to generator by high speed shaft. Its function is to convert the low speed from the turbine to high speed that is suitable for generator [1].

**(4) Frequency Converter:** It is installed to synchronise the generator's frequency to the grid. It consists of inverters and rectifiers. There are different kinds of frequency converters that are used depending on type of wind power plants. Inverter can be chosen arbitrarily but rectifier must be chosen in accordance with generator [1].

**(5) Capacitor Bank:** If the system is not provided with a component that provides reactive power to generator, the system would consume reactive power from the grid which is not preferable as induction generators require reactive power to operate. This is the reason the system is equipped with capacitor banks. It operates according to the requirement of the reactive power needed in the system [1].

**(6) Soft Starter:** During the start up of generator, high in-rush current flows, and soft starter is used to limit that current. It contains a set of thyristors connected in parallel in opposite directions from each other. It is connected between generator and the grid and when the generator is connected to grid, the maximum in-rush current should not exceed the generator's nominal current. This current is about 6 to 8 times high than the rated current if there would be no soft starter in the system [1].

## 1.4 Development in Wind Energy

Wind energy growth in Europe has increased rapidly over the last few years. Almost 4.8% of total energy consumption in Europe is provided by wind now days [8]. Main reason for this rapid growth in Europe is that they are looking for a secure source of energy that is independent of external source like oil and gas and the other factor is a major reduction in green house emissions. Wind energy is playing a vital role as clean renewable resource and will continue to play as emissions that are polluting atmosphere reduced tremendously.

Both these factors are the major reasons why Europe is more focused on this. Reason for wind power that is expanding so rapidly is due to wind power technology that is evolved significantly. Turbine size increased from 50 KV to more than 3 MW [19]. Rotor diameter has also increased from 15 m to 100 m or more. Installation cost has also reduced with the time that made it more attractive. Wind power capacity increased about 100 times in Europe over last twelve years from 4753 MW in 1997 to 74767 MW in 2009 [8]. Almost 39% of all new electricity that has been added to system is getting from wind can be seen in Table 1.2 .

European countries like Germany , Spain , Denmark , Italy , France , Portugal , Netherland , Sweden , Ireland , Greece and UK are playing the leading role in the development of world wind energy technology. Among them Denmark, Spain, Portugal, Ireland and Germany have managed more than 5% of total energy from the wind to meet their electricity demand [8]. As the availability of wind energy resources varies from country to country and it will not be equally important in all countries. There are some factors like ability of current transmission networks and other generation plants to achieve large amount of wind energy considering the strategic planning of wind farm development in the Europe.

Table 1.1 Top Ten Wind Power Countries [3]

| Country | Wind Power Capacity MW |
|---|---|
| China | 44,733 |
| United States | 40,180 |
| Germany | 27,215 |
| Spain | 20,676 |
| India | 13,066 |
| Italy | 5,797 |
| France | 5,660 |
| United Kingdom | 5,204 |
| Canada | 4,008 |
| Denmark | 3,734 |

Table 1.2 Top Ten Electricity Generation European Countries [3]

| Country | Wind Power Electricity Production GWH |
|---|---|
| Spain | 42,976 |
| Germany | 35,500 |
| United Kingdom | 11,440 |
| France | 96,00 |
| Portugal | 8,852 |
| Denmark | 7,808 |
| Netherlands | 3,972 |
| Sweden | 3,500 |
| Ireland | 3,473 |
| Greece | 2,200 |
| Austria | 21,00 |

## 1.5 Offshore Wind Energy

Offshore wind energy has added more attraction in this sector due to less environmental effects and truly speaking resources for wind energy generation are more than the centres of electricity demand. At off shore, wind speeds are quite high so increased the energy production level because wind speed is directly proportional to potential energy produced by wind by its cube so a small increase in wind speed would make a significant change in energy output. The average increase of wind energy at off shores is about 10 – 20 % [18].

Many countries have installed the off shore wind turbines to harness the wind energy of the oceans to generate electricity as wind speeds on off shores are relatively much higher than on shores. Many off shore areas have ideal conditions for wind energy production .Denmark and UK have installed a number of off shore wind turbines to harness wind energy. Up till now just 600 MW of off shore wind energy is installed but now from 2010 it would be more than 11000 MW of which 500 MW each would be in United States and Canada and rest is in Europe and Asia [18]. The development in offshore wind energy would be 22 % of total installed capacity in Europe by 2020 and for around 12% in China. China is emerging rapidly in offshore industry [1].

## 1.6 Grid Management

To integrate wind power plants to our current electrical system is a big challenge for both power system planners and operators. This is due to the different behaviour of wind power plants than the conventional plants. Wind power varies with the speed of wind and it cannot be transmitted in a traditional way. Normally, induction generators are used for wind power require reactive power for excitation and substations that are connected to the wind power system have to include capacitor banks for power factor correction. Each wind turbine will behave differently during grid disturbance so more dynamic modelling of wind farms is required by TSO to ensure stability of system during faults.

## 1.7 Thesis Objective

The main objective of the project is to develop a testing method for a single wind turbine by using voltage source converter in order to make the grid codes compliance to the wind turbine and to make wind turbines more efficient during normal and fault conditions in the grid. The project will mainly work with the question that to what extent can a voltage source converter can be used to test the grid codes for wind turbines. Project will carry out methods and simulations for grid code tests with voltage source converters. The test object would be a full power converter wind turbine.

A broad literature study will be done to clearly understand the dips and swells occurring in grid voltage. Voltage dips would be created deliberately during the test by inducing a short circuit in the grid side. Simulation of the complete testing system with the wind turbine and voltage source converter will be done in PSCAD and then by creating different frequency and voltage situations according to grid codes, their effect on the wind turbine will be investigated.

## 1.8 Structure of Thesis

This thesis report consists of six chapters. Chapter 2 gives a brief description about different types of wind turbines and their operating mechanisms and different sizes of wind turbines available in the market.

Chapter 3 gives an understanding about voltage source converters and its different types.

Chapter 4 gives an overview of existing grid codes for wind farms issued by different transmission system operators.

Chapter 5 describes the design and control strategy of the complete system i.e. test equipment, test object, filter and transformer that has been designed in PSCAD.

Chapter 6 is about the simulation results. In this chapter results have been analysed and summarised and then suggestions for future work has been presented.

# Chapter 2

# Wind Turbine Architectures

Large number of choices of architecture is available to wind turbine designers. For electricity generation currently horizontal axis, three bladed, upwind turbines are normally used. Large machines operates at variable speed while the small ones at constant or fixed speed. Modern wind turbines are equipped with three blades upwind rotor while earlier two bladed and even one bladed rotor were used commercially. By the reduction in number of blades now the rotor has to rotate at higher speed to extract more power from the wind. Other important aspect is that three bladed rotors are visually more attractive than the other designs that is also a reason that now they are always used on large wind turbines [4].

Wind turbines are normally classified into two types,

- Fixed Speed Wind Turbines.
- Variable Speed Wind Turbines.

## 2.1 Fixed Speed Wind Turbines

Fixed speed wind turbines are electrically quite simple devices normally equipped with an aerodynamic rotor that drives a low speed shaft, a gear box, a high speed shaft and an induction generator (often called as asynchronous generator). In the electrical aspect they are considered as large fan drives with torque applied to low speed shaft from the wind flow [4].

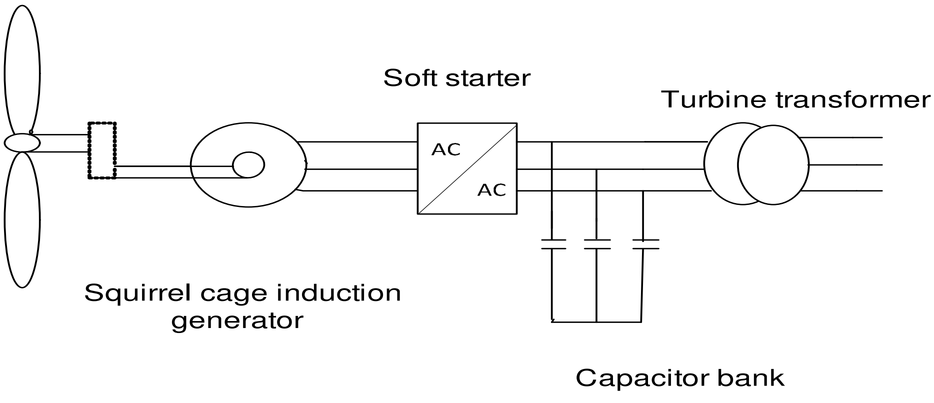


Figure 2.1 Schematic of a fixed-speed wind turbine

Figure 2.1 describes the working mechanism of fixed speed induction generator (FSIG) configuration for wind generation. It consists of a squirrel cage induction generator connected to grid by a turbine transformer. When the operating power level changes, the operating slip of generator changes slightly with it. Although this variation is quite small i.e. less than 2% so it is normally referred to as fixed speed.

As it is the characteristic of squirrel cage induction generator that it consumes reactive power so it is obligatory to install capacitors at wind turbine for power factor improvement. The purpose of soft starter is to create magnetic flux slowly and during energization of generator minimizes transient currents [4].

## 2.2 Variable Speed Wind Turbines

With the increase in size of wind turbines, the technology has moved from fixed speed to variable speed. The purpose behind this transformation is to comply it with the grid codes connection requirements and other advantage is the reduction in mechanical loads. Variable speed wind turbines rely on pitch control rather than stall control. Rotor is allowed to speed up with the wind gusts and thereby reducing the variations in active output power. Variable speed wind turbines has many other advantages over fixed speed wind turbines like stress on mechanical structure is reduced and the noise produced at low wind speeds would be less and reactive power can be controlled at grid connection[4].

Most common variable speed wind turbines configurations are,

- Doubly Fed Induction Generator (DFIG) wind turbine.
- Full Rated Converter (FRC) wind turbine.

### 2.2.1. Doubly Fed Induction Generator Wind Turbine

The typical configuration of a DFIG is shown in figure 2.2

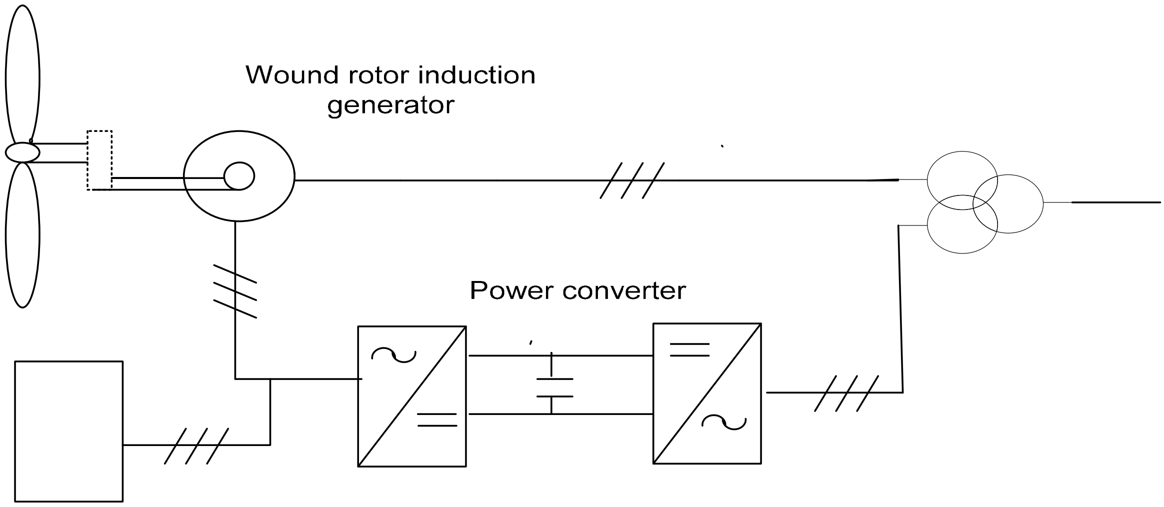


Figure 2.2 Typical configuration of DFIG wind turbine.

It uses a wound rotor induction generator with the slip rings to transmit current between converter and rotor windings and to obtain a variable speed operation; a controlled voltage is injected into the rotor at desired slip frequency. A variable frequency power converter based on two AC/DC IGBT- based voltage source converters (VSCs), linked through a DC bus is used to feed rotor winding. The variable frequency rotor supply from converter enables the rotor mechanical speed to decouple from synchronous frequency of electrical network, so allows the variable speed operation. The protection of generator and converters is done by voltage limits and an over current crowbar. A DFIG wind turbine delivers the power to grid through both stator and rotor. When the generator operates above the synchronous speed, the power will be delivered from rotor through converters to the network. When the generator will operate below synchronous speed then the rotor will absorb the power from the converter [4].

### 2.2.2. Fully Rated Converter Wind Turbine

Wind turbine manufacturers are now considering the induction or synchronous generators with fully rated voltage source converters to give converter controlled, full power, variable speed operation to fulfil present grid code requirements. The typical configuration of a full power converter turbine is shown in figure 2.3,

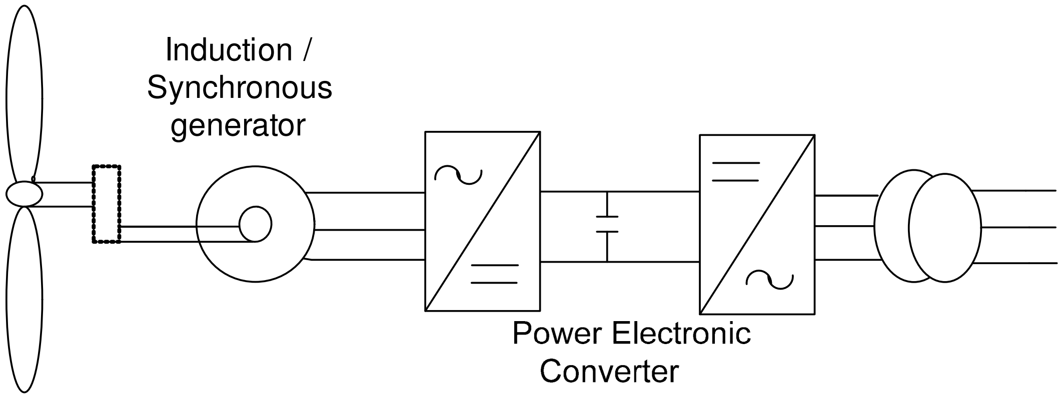


Figure 2.3 Typical configuration of fully rated converter-connected wind turbine.

This type of wind turbine may or may not have gearbox and wide range of electrical generators can be employed such as asynchronous , conventional synchronous and permanent magnet . Since all the power from the turbine goes to power converter, the specific characteristics and dynamics of electrical generator are effectively isolated from power grid. Hence with the variation in wind speed the electrical frequency of generator can vary but the grid frequency remains same and hence allowing variable speed operation. Rating of power converter in this type of wind turbine relates to rating of generator. There are many ways of arranging the power converters. Generator side converter can be a diode rectifier or a voltage source converter while the grid side converter is typically a Pulse width modulated VSC. The control scheme for the operation of generator and power flowing to grid depends on converter arrangement. Torque applied to generator is controlled by generator side converter while the grid side converter is used to maintain the DC bus voltage or vice versa. Each of the converters has the ability to absorb or generate the reactive power independently [4].

## 2.3 Wind Turbine sizes

Turbine sizes are classified into three categories

**(1) Utility Scale:** The turbines in this category range from 900 KW to 2 MW per turbine. They are used for generating bulk amount of power to sale in power markets. They are normally installed in large wind energy projects but can also be used sometimes on small scale for distribution lines [19].

**(2) Industrial Scale:** These are also called medium size turbines and normally range in between 50 KW to 250 KW. These are normally used in remote areas for grid production often in conjunction with diesel generation [19].

**(3) Residential Scale:** These are very small scale turbines typically ranges in between 400 watts to 50 KW and normally used for remote areas , for battery charging or net metering type generation [19].

# Chapter 3

# Voltage Source Converters

## Introduction

The power electronic converter process and controls the flow of electric energy by supplying voltages and currents in a form that is optimally suited for the user loads. Due to better controllability and improvement of semiconductor and microelectronic technology the use of power electronic converters is increasing rapidly in domestic and industrial applications in the last two decades .A power electronic converter consists of a power circuit which can be handled by different types of switching pattern of power switches (GTO, MCT, BJT, MOSFET, IGBT) and passive components (filter, shunt capacitor) and a control/protection system. Based on the type of electrical subsystems the converters can be classified as AC to DC, DC to DC or DC to AC converters [5]. A rectifier is a kind of converter where the average power flow of the circuit is from the AC side to the DC of the converter. For the case of an inverter it is completely opposite to the rectifier. But the bidirectional power flow in the system can be possible by the implementation of specific classes of converters, where they can operate either as rectifier or inverter, and this can be identified by the direction of load current that is connected with the converter[5].

The following illustration describes the reasons of choosing voltage source inverter instead of current source inverter in most of the High voltage direct current (HVDC) cases. Further, it explains voltage source inverter (VSI) and its different types. Latter, it describes a bit about the switching techniques of inverter.

## 3.1 Voltage source and Current source converter

In conventional HVDC transmission system, current source converter (CSI) with line commutation is implemented. A synchronous voltage source is needed to operate this type of converters. The filters, series capacitors or shunt blocks, provide reactive power support in the converter station during conversion process. If there is any kind of variation in reactive power the ac source is responsible to adjust it. Reactive power variation needs to be kept small, to maintain the ac voltage within the acceptable limit .The weaker the system or the further away from generation, the tighter the reactive power exchange and must have to stay within the desired voltage tolerance [6]. To hold the ac voltage within a fairly tight and acceptable range, proper control and associated reactive power support is needed from the converter. The conventional HVDC converters cannot bear much dynamic voltage support to the ac network like a generator or static var compensator (SVC). Using Voltage source converter in HVDC conversion technology can provide control over the power flow and at the same time it can also provide dynamic voltage regulation to the ac system [6].

## 3.2 Single phase half bridge Voltage Source Inverter

Figure.3.1 shows a half-bridge voltage source inverter, where two capacitors are connected in series in such a way that they can share the dc link voltage equally, i.e. $\frac{V_d}{2}$. Assume the capacitors are large enough to provide the constant voltage at point O with respect to the negative dc bus N. During the ON stage of upper switch T1, the direction of current io decides whether to conduct T1 or D1.This current is equally distributed through the two capacitors C1 and C2. Similarly the current io decides the conduction of T2 or D2, when the switch T2 is in ON state. As the current have to flow through the capacitor C1 and C2 in the steady state, io can not have any dc component. Thus the capacitors are acting as dc blocking capacitors [7].

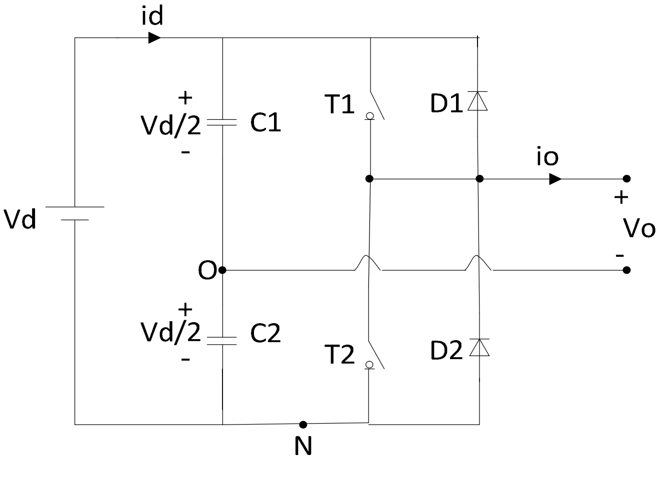


Figure 3.1 Half bridge inverter

## 3.3 Single phase full bridge voltage source inverter

The circuit arrangement of a full power converter is shown in figure 3.2. From the figure it is clearly seen that a full bridge converter is the composition of two half bridge converters. The maximum output voltage of this converter is double that of half bridge converter with same input, i.e. Vd [7].

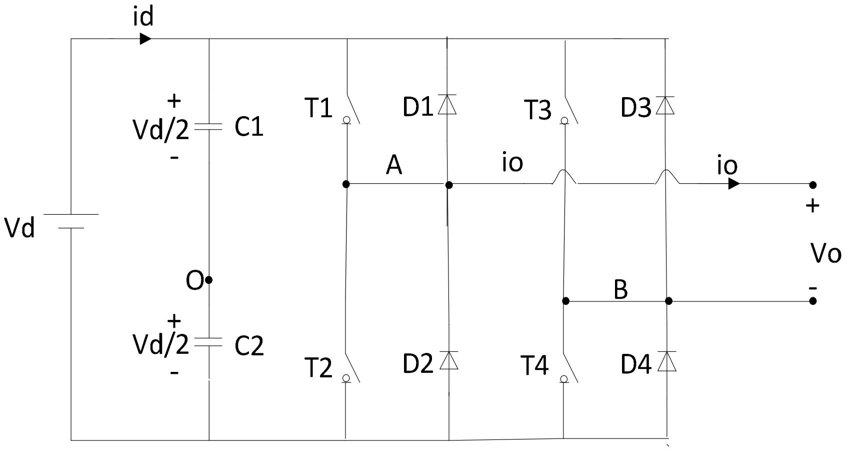


Figure 3.2 Single phase full bridge inverter

## 3.4 Three phase voltage source inverter

The most commonly used three phase inverter circuit consists of three legs, one for each phase (conducts for120°), as shown in figure 3.3. Each inverter leg of the three phase inverter can be explained from the figure 3.3 separately. Where the inverter output voltage depends on the switching state and current sign. Leg A of the converter consists of upper and lower power devices T1 and T4, and reverses recovery diodes D1 and D4 [7].

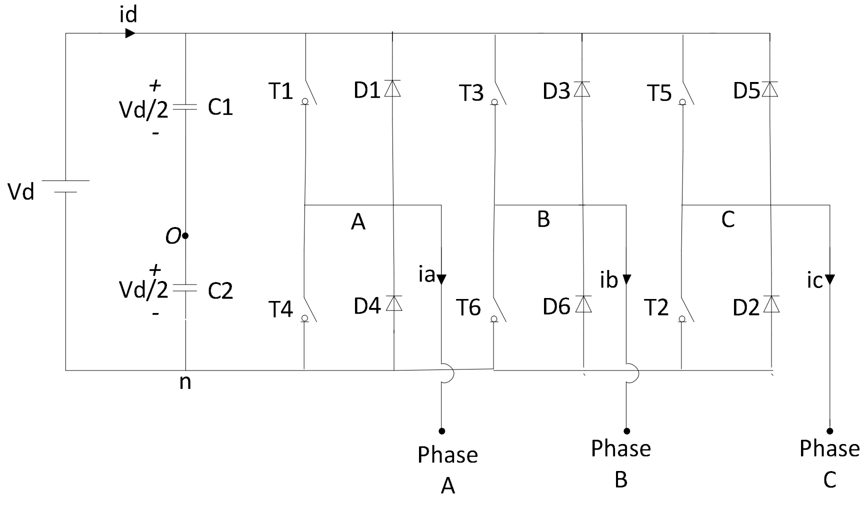


Figure 3.3 Three phase voltage source inverter

When T1 is turn on, a voltage $\frac{V_{dc}}{2}$ is applied to the load. If the load draws positive current, it will flow through T1 and delivers energy to the load. Conversely, if the load current ia is negative, the current flows back to the dc source through D1.

Similarly if T4 is on or T1 is off, a voltage - $\frac{V_{dc}}{2}$ is applied to the load. If ia is positive, energy returns back to the dc voltage source through D4. A negative current conducts T4 and provides energy to the load.

So, the voltage of each leg switches between $\frac{V_{dc}}{2}$ to - $\frac{V_{dc}}{2}$, respectively. The other phases can be explained in the similar way [7].

## 3.5 Switching technique of voltage source inverter

There are basically to types of modulation techniques used for the switching of VSI, which are

- Pulse width modulation (PWM) inverter
- Square wave inverter

For the case of Pulse width modulated inverters, the input dc voltage is maintained constant in magnitude. So, the ac output voltage magnitude and frequency are controlled by the PWM section of the inverters.

In square wave inverter, the magnitude of the output voltage is controlled by varying the input dc voltage, and the inverter has to control the frequency of the output voltage. The output ac voltage in this case is similar to a square wave, and hence the inverter is called square wave inverter. The control of the square wave inverter is simple .The switching loss of this type of converter is less but significant energies of lower order harmonics and large distortions in current wave need large low-pass filters. A controlled rectifier is needed to control the voltage, which added some additional costs of the inverter. So this is one of the big reasons for choosing PWM technique instead of square wave operation [7].

### 3.5.1. PWM inverter

In pulse width modulation technique a carrier signal $\widehat{V}_{carrier}$ is compared with a control signal $\widehat{V}_{control}$ to generate the switching pattern of the inverter. The control signal is basically a sinusoidal signal and chosen carrier signal is a triangular signal of very high frequency compared with the control signal chosen for VSI. The frequency of the modulation signal defines the fundamental frequency of the desired output signal of the inverter and the frequency of the carrier signal decides the switching frequency of the inverter switches [7]. For the case of three-phase inverter a three phase controlled voltage signal is compared with the carrier signal as shown in figure 3.5. In this case three phase voltages are separately compared with same triangular carrier signal in three separate comparators. Each comparator output generates the switching signal for the corresponding inverter leg.

The ratio of the control signal magnitude to that of the carrier wave is called modulation index $\mathrm{m_a}$.

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{carrier}} \tag{3.1}$$

Where $\hat{\mathrm{V}}_{\mathrm{control}}$the peak value of the control is signal and $\hat{\mathrm{V}}_{\mathrm{carrier}}$ is the peak value of the carrier signal.

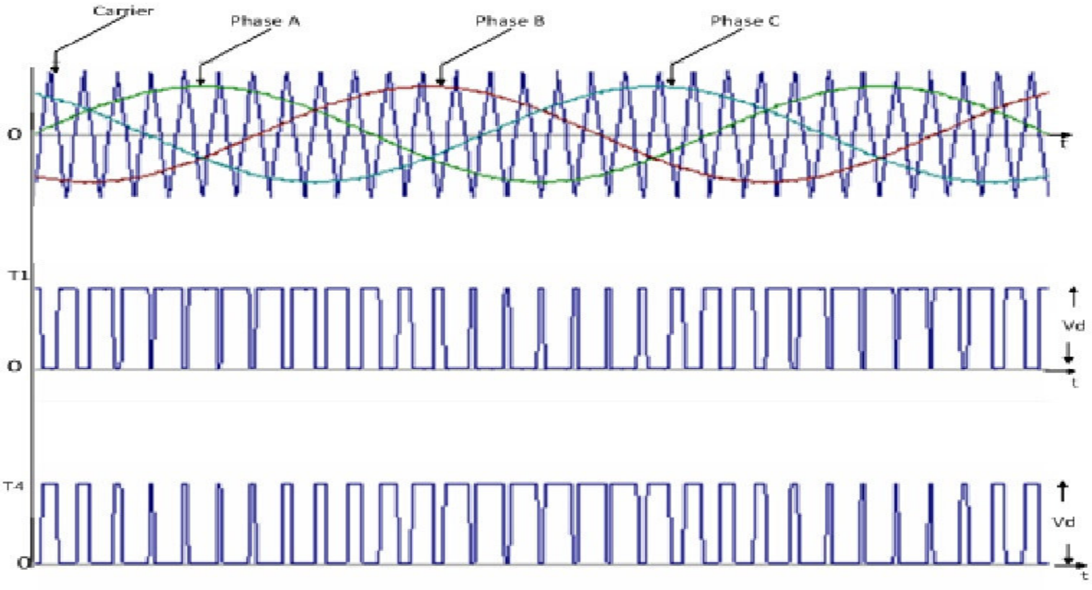


Figure 3.5 PWM Pattern

Considering the linear range of operation (m ≤ 1), the fundamental component of the output voltage in one of the legs of the inverter is,

$$\left(\hat{\mathrm{V}}_{\mathrm{An}}\right)_1 = \mathrm{m_a}\frac{\mathrm{V_d}}{2} \tag{3.2}$$

So, the line to line rms voltage at the fundamental frequency can be written as

$$\begin{aligned}(\mathrm{V_{L-L}})_{\mathrm{rms}} &= \frac{\sqrt{3}}{\sqrt{2}}\left(\hat{\mathrm{V}}_{\mathrm{An}}\right)_1 \\ &= \frac{\sqrt{3}}{2\sqrt{2}}\mathrm{m_a V_d} \\ &\cong 0.612\mathrm{m_a V_d} \qquad (3.3)\end{aligned}$$

If the value of modulation index ma is allowed to increase more than 1, then the control signal peak value exceeds the peak value of the carrier signal and the PWM shifted to over modulation range. After that it is allowed to increase the ma more then, the PWM will act as square wave operation where the maximum line to line rms voltage is equal to 0.78Vd. More explanation about modulation techniques can be found in[7].

# Chapter 4

# Grid Code Requirements for Wind Farms

## Introduction

As the wind power penetration is increasing tremendously and according to EWEA that wind will contribute up to 230GW – 265GW by 2020 in Europe of which 40GW-55GW would be offshore and total wind power generation in Europe would be 400GW by 2030 [8].By expecting this huge contribution it is also required that wind power should also contribute in grid support such as frequency, voltage and reactive power control and it should behave as a conventional power plant in normal and abnormal conditions as these generators has quite different physical characteristics compared to synchronous generators used in conventional power plants. For this reason, there is a need of some specified technical documentation that wind power plants should meet and for this reason transmission system operators (TSO) of different countries has issued grid codes for wind farms to operate them in a conventional way [9].

Grid codes are the technical specifications for defining the parameters of a power plant that it has to fulfil to ensure proper functioning of electrical grid.

Grid code can be the collection of transmission code, distribution and metering code, operation code and scheduling and dispatch code, data regulation code and all kinds of other aspects. Following benefits can be achieved using grid codes for the system:

- The TSO can dispatch the power in a safe way regardless of the generation technique.
- The number of project-specific technical negotiation with the TSO can be reduced.
- The wind turbine manufacturer can design their equipment knowing the requirements properly and they will not need to change without warning or consultation.

Normally Grid code requirements are steady-state and dynamic active and reactive power capability, continuously acting frequency and voltage control and fault ride-through (FRT) capability.

In this chapter we have analysed grid code requirements for wind power generating units by five different transmission system operators due to their great contribution in wind energy ,

(i) Svenska Kraftnät, Sweden [10]
(ii) E.ON Netz, Germany [11]
(iii) Energinet, Denmark [12]

(iv) National Grid Electricity Transmission plc, UK [13]
(v) ESB National Grid, Ireland [14]

Grid codes are divided into static and dynamic requirements. The static part relates to the continuous operation of wind power plants and contains the requirements like voltage control, quality of voltage, power factor requirements, power curtailment, frequency and flicker. Dynamic part constitutes of the requirements regarding to operation of wind turbine during faults and disturbances in grid i.e. fault ride through capability [15].

In this chapter we will discuss the most restringing conditions that we analysed in our thesis work to give an idea about technical requirements that should be satisfied by a wind power plant.

- Voltage control
- Frequency Control
- Fault Ride Through Capability

## 4.1 Voltage Control

Voltage control is required in order to keep the voltage with in specific limits to get rid of voltage stability issues. This can be achieved either by reactive power compensation or by using automatic voltage regulator. In some grid codes it is made mandatory that wind farms should be equipped with tap changing transformers [15].

### 4.1.1. Reactive Power Compensation Requirements

According to Svenska kraftnat [10], wind farms should be provided with automatic voltage controller that can vary at least ±5% of nominal voltage. Reactive power compensation requirements for this are shown in figure 4.1a which shows that reactive power exchange to the system should be zero. It states that the wind power should have the ability of compensating the reactive power requirement within the farm only nor for the grid [10].

Figure 4.1b shows the reactive power compensation for EnergiNet which states that 10 seconds average reactive power exchange at common connection point must be able to withstand within the control band. P-Q diagram showing the reactive power regulation must be provided by the plant owner. It should be made clear for transmission system operator that how much reactive power plant can take or supply to meet reactive power requirements [12].

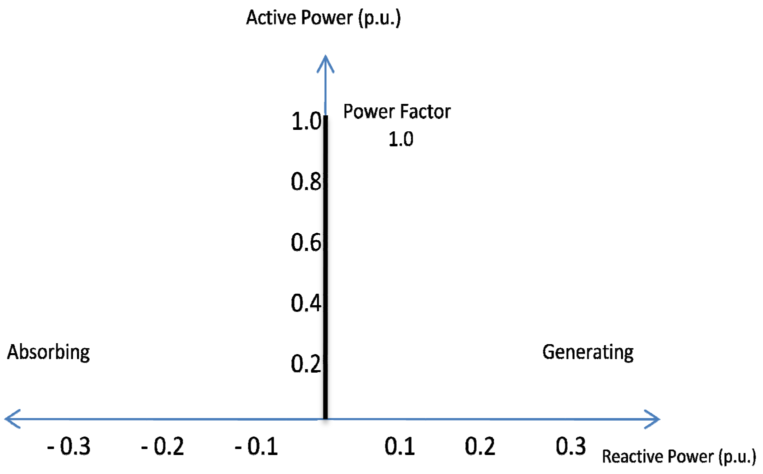


Figure 4.1a Svenska KraftNat.

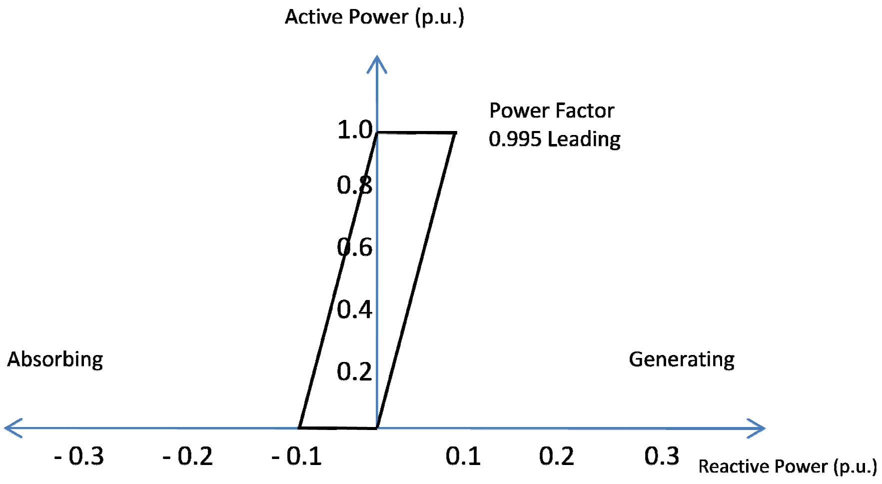


Figure 4.1b EnergiNet.

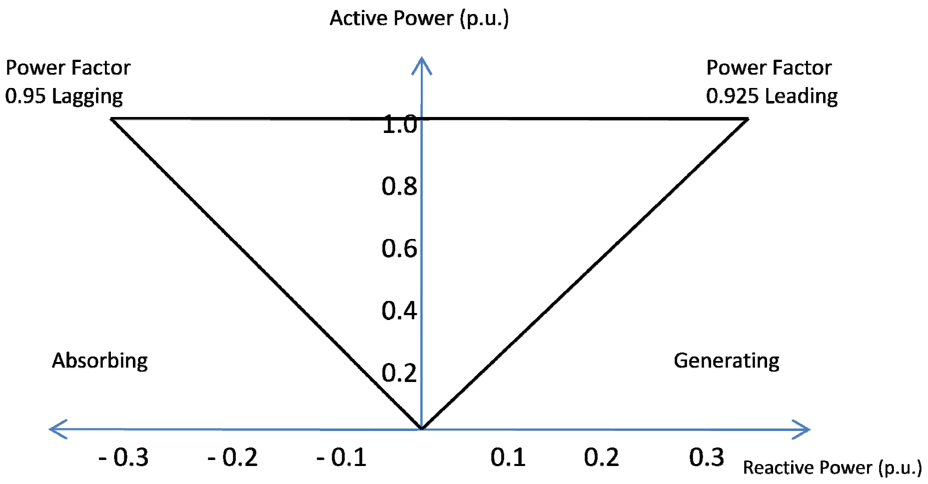


Figure 4.1c E.ON .

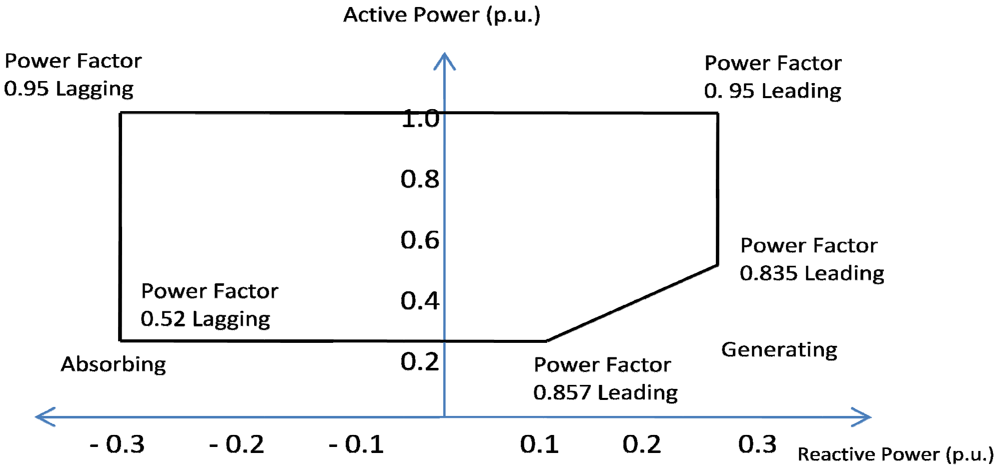


Figure 4.1d NGET.

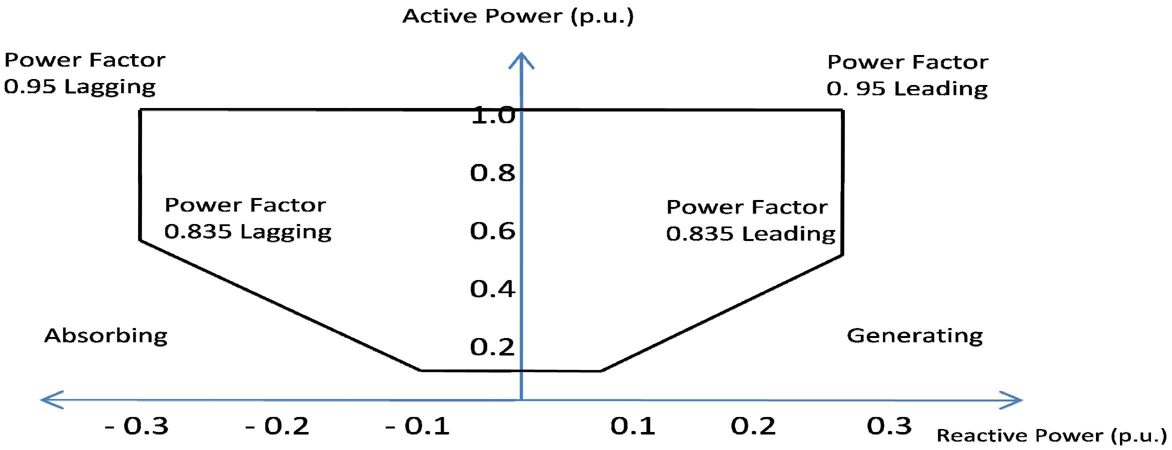


Figure 4.1e ESBNG.

According to figure 4.1c and 4.1d for E.ON and NGET, the wind farm should be capable of providing reactive power to the grid within that defined area [10] [13]. Figure 4.1e shows the reactive power compensation requirements for ESBNG and unlike to others it applies its requirements on low voltage side of grid connected transformer [14]. It can said that the reactive power requirements by Svenska Kraftnat and EnergiNet are quite mild while to fulfil NGET and ESBNG reactive power compensation requirements would be a challenge for wind power industry to meet.

### 4.1.2. Voltage Range

Power system planners should make the system capable to run at a rated voltage in addition to the specified voltage. This voltage range depends on the level of voltage on transmission line and it varies from country to country. Table below shows the continuous operating voltage with respect to nominal network voltage. Normal operation of wind power plants is only possible within these specific limits and for particular time periods [15].

Table 4.1 Allowed Voltage Ranges[15]

| Voltage Range | | | | | | |
|---|---|---|---|---|---|---|
| | Germany | | Denmark | | UK | |
| continuous | -8% --->10% | 400KV | -10% --->5% | 400KV | -10% --->5% | 400KV |
| | -13---->12% | 220KV | -3% --->13% | 150KV | ±10% | 275KV |
| | -13%-->12% | 110KV | -5% --->10% | 132KV | ±10% | 132KV |
| Limited time periods | X | | -20% -->10% | 400KV | ±10% | 400KV |
| | | | -10% -->20% | 150KV | ±10% | 275KV |
| | | | -10% -->18% | 132KV | ±10% | 132KV |

While Svenska Kraftnat as compared to other grid codes has minimum requirements on voltage deviations. The region of continuous operation varies from 90% to 105% of nominal voltage and there will always be reduction in active power output outside from this region [10].

## 4.2 Frequency Control

Wind Power Plants should be equipped with frequency control. For safe operation of grid, it is required that power generation should match with power demand. One key factor for this balance is system frequency. System frequency would be exactly equal to rated frequency when the power generated is equal to power demanded by the system. If this supply and demand does not match i.e. due to load loss, short circuits or outage of power plant, there would be a change in system frequency. Generators would speed up if the generated power is more than power demand or vice versa. For smooth operation of system, it is required that system frequency should be in predefined limits [15].

Frequency control constitutes of primary and secondary control. Active power output should be adjusted automatically by the generators having responsibility of primary control till the frequency stabilizes. Secondary control is always required because the frequency stabilization by the primary control normally does not occur at nominal frequency. It is also required that all generators should operate with a reserve margin of 1.5% and they are not paid for this. There is another solution to this problem that frequency control can be obtained from some other sources. By doing so wind power plant owners get escape from this obligation to equip the system with frequency control as it is quite expensive for wind power plants [11].

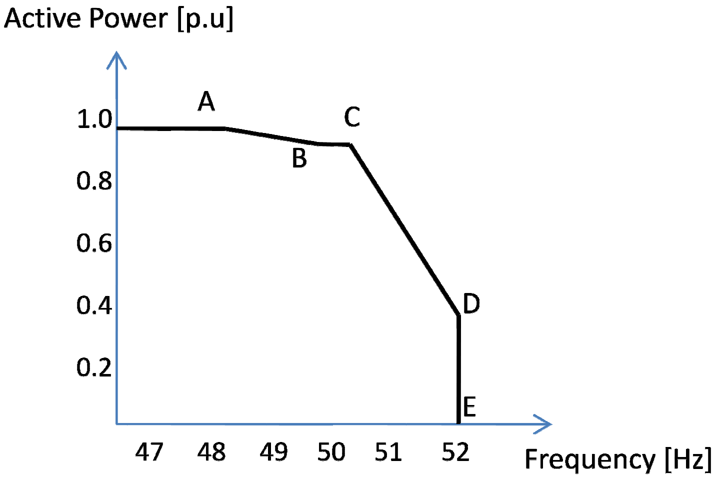


Figure 4.2 Frequency set points by ESBNG [14].

Grid Codes of following countries demand that wind power plants should have the capability of curtailing active power.

| | |
|---|---|
| Germany | with ramp rate of 10% of grid connection capacity per minute [11] |
| Ireland | with ramp rate 1-30 MW per minute [14] |
| Nordic | with ramp rate of 10% of rated power per minute [15] |
| Denmark | with ramp rate of 10-100% of rated power per minute [12] |

Table 4.2 Frequency Range Requirements[15]

| Frequency Range | | | | | |
|---|---|---|---|---|---|
| Frequency (Hz) | Sweden | Germany | Denmark | UK | Ireland |
| 52Hz to 53 Hz | % | % | 3 min | % | % |
| 51.5Hz to 52Hz | 30 min | % | 30 min | continuous | 60 min |
| 51Hz to51.5 Hz | 30 min | % | 30 min | continuous | 60 min |
| 50.5Hz to 51Hz | Continuous | continuous | 30 min | continuous | 60 min |
| 49.5Hz to 50.5Hz | Continuous | continuous | continuous | continuous | Continuous |
| 49.5Hz to 47.5 Hz | Continuous | continuous | 30 min | continuous | 60 min |
| 47.5Hz to 47Hz | % | % | 3 min | 20 sec | 20 sec |

## 4.3 Features of voltage and frequency change requirements

The ability of the wind power unit to cope with variations in the grid voltage and frequency at the connection point is described in the Grid Code SvK 2005:2 and is recalled in the Nordel 2007 grid code [16]. Although the Grid Code is planned for wind power plants but it can be implemented in simulation model of single wind turbine.It can be explain from the figure4.3.

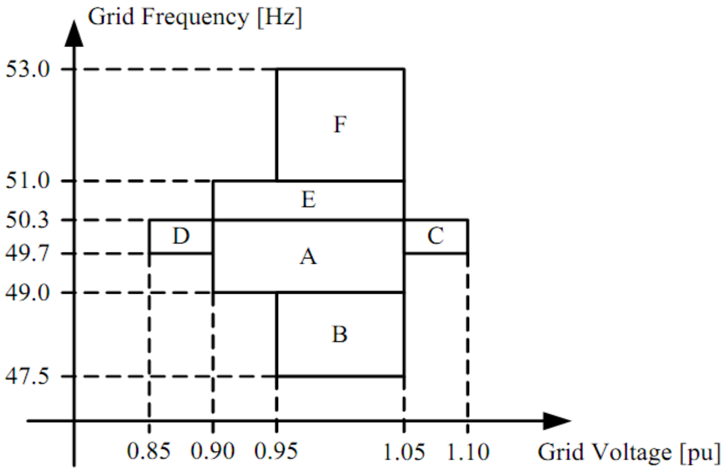


Figure:4.3 Voltage and frequency requirement in Nordel Nordic Grid Code[16]

Each of the rectangles of voltage and frequency has its own requirement for the wind power unit to fulfill. The rectangles represented in the figure can be explained by the following way:

A. This condition represents the continuous operation mode. The wind power unit must be able to operate within this range with no variations in the active and reactive power capability [16].
B. In these operating conditions, the wind power unit shall be able to operate continuously for at least 30 minutes. Active power reduction is allowed. In particular, the active output power can decrease as a linear function of the frequency from zero (49 Hz) to 15% (47.5 Hz) [16].
C. In these operating conditions, the wind power unit shall be able to operate continuously for at least 60 minutes. Active power reduction of 10% is allowed [16].
D. In these operating conditions, the wind power unit shall be able to operate continuously for at least 60 minutes. Active power reduction of 10% is allowed [16].
E. In these operating conditions, the wind power unit shall be able to operate continuously for at least 30 minutes. The Grid Code does not specify the percentage of reduction allowed, but just mentions a "slight reduction" [16].
F. In these operating conditions, the wind power unit shall be able to operate continuously for at least 3 minutes. Active power can be reduced at any level, but the wind power unit must be able to remain connected [16].

## 4.4 Fault Ride through Capability

With the increase in installed wind capacity in the transmission system makes it necessary that wind generators should be connected to the system in case of network disturbance. Therefore grid codes demand that wind farms should be able to withstand the voltage dips for specific period of time and to a certain value of nominal voltage. Such a demand or requirement is called Low voltage fault ride through or Fault Ride Through and it is shown by voltage versus time characteristics. All countries have fault ride through capability figures and it is only concerned with short circuit fault in transmission system not in the wind farm [15].

For the wind turbine generators to be connected to the transmission network, they should be capable of providing active power in proportion to retain voltage and without exceeding the generators limits must be capable to maximize the reactive current to transmission system in case of voltage dips in transmission network.

Figure 4.3 represents the fault ride through requirements for Svenska Kraftnat. It has different requirements for wind farm having rated active output power of 100MW and different for those that varies in between 1.5MW and 100MW. Figure 4.3a with rated power of 100MW shows that wind farm should remain connected to system during voltage dip down to zero voltage during

250ms and then increase linearly from 25% to 90% in 500ms. The wind farms with rated power in the range of 1.5MW and 100MW requires that the wind farm should remain in contact with the system during a voltage dip down to 25% and then there would be a step in voltage up to 90% at 250ms as shown in figure 4.3b [10].

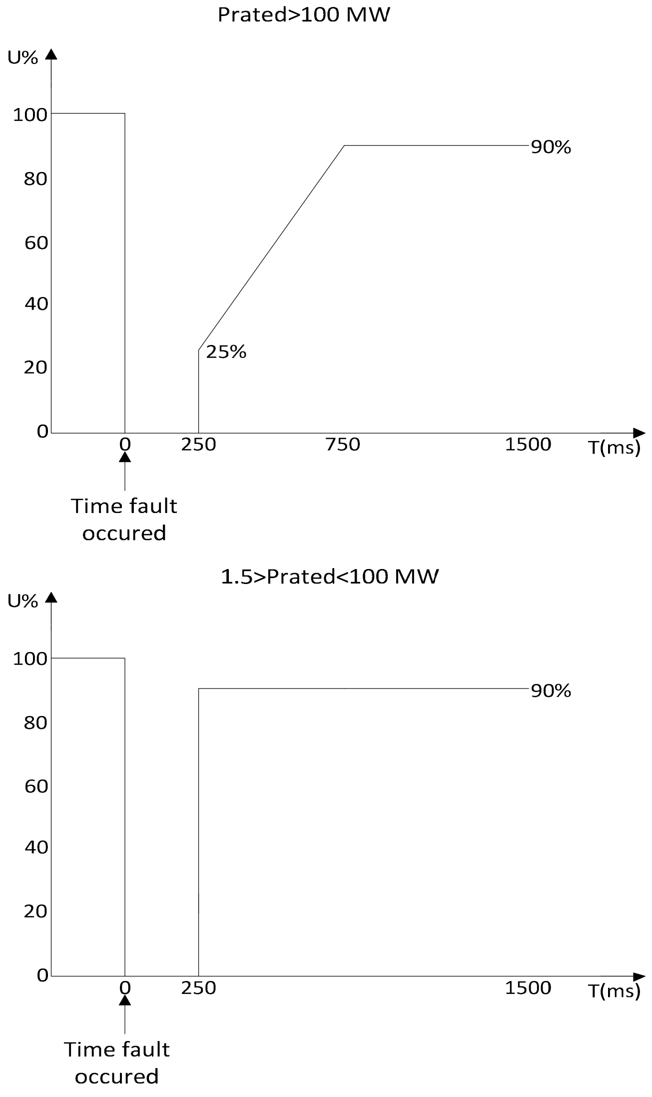


Figure 4.3(b) SvK Fault Ride through Requirements.

Figure 4.4 represents the fault ride through requirements by E.ON. It states that wind farm should remain connected to system during a voltage dip down to zero voltage during 150ms and there would be a step in voltage up to 70% and it will remain for 550ms and then there would be a linear increase in voltage till 90% in 800ms.

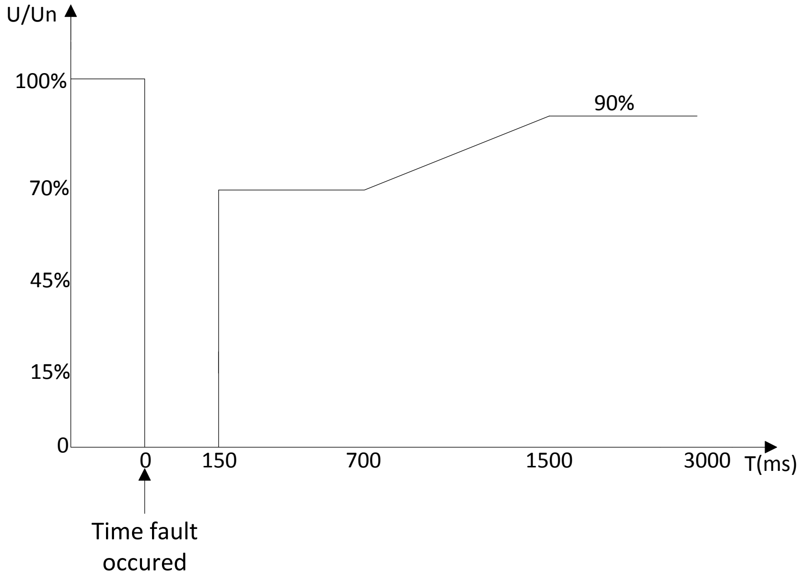
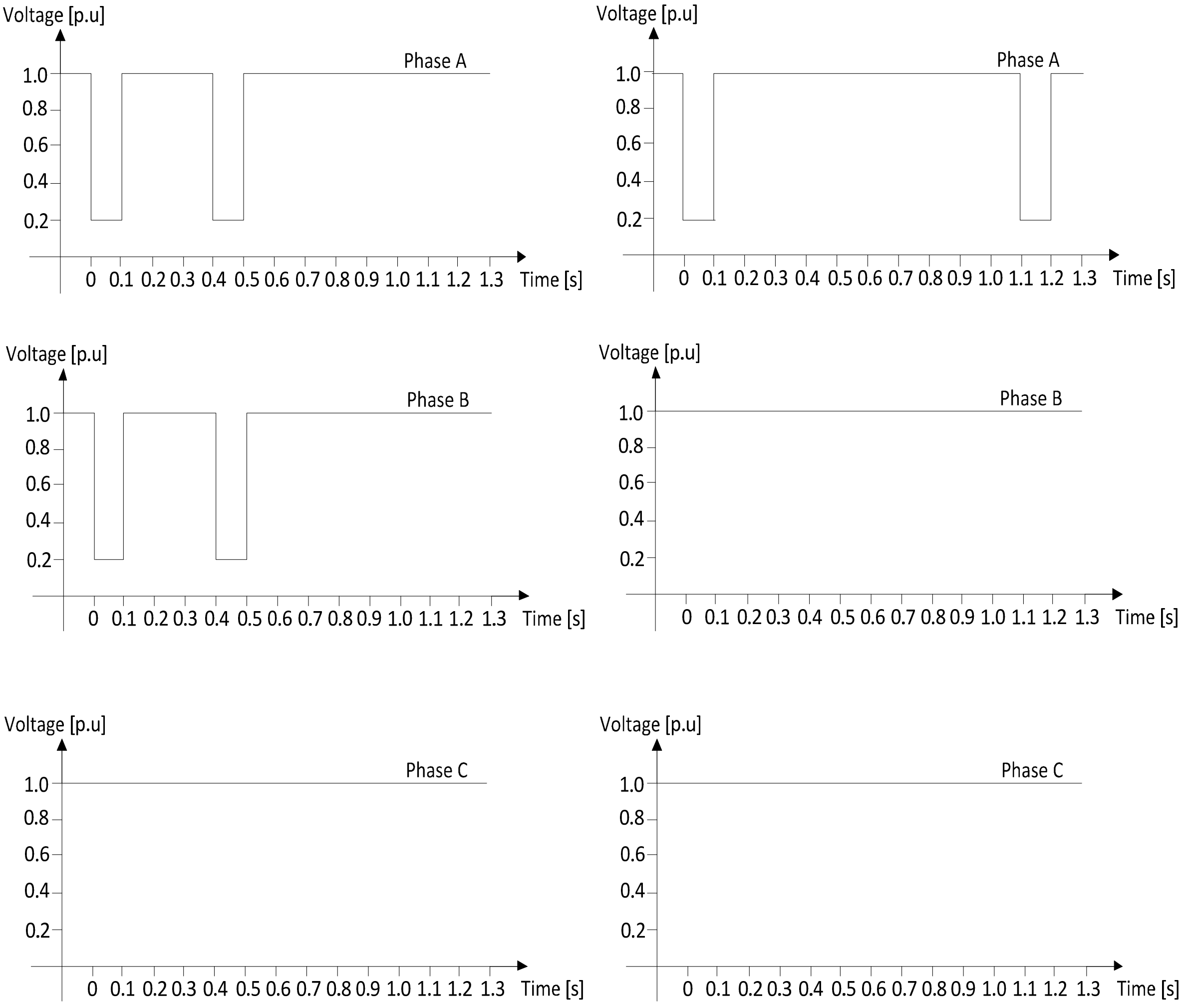


Figure 4.4 E.ON Fault Ride through Requirements.

## 4.5 Impact of unsuccessful re-closure

The Swedish Grid Code does not take into account the case of unsuccessful re-closure procedure after a voltage dip. This condition is instead considered in the Danish Grid Code [12]. In particular, according with the Danish Grid Code the investigated wind power unit must be able to withstand two-phase and single-phase voltage dips with unsuccessful re-closure, as depicted in Figure 4.6 [12] .



(a)

(b)

Figure 4.6 (a)Two Phase fault and (b)Single Phase fault, according to Danish Grid Code.

# Chapter 5

# Design and Control Strategy

This chapter will give an overview of the design characteristics of proposed testing method for the verification of grid codes for a single wind turbine. The test equipment consists of a voltage source converter that typically behaves like a grid, connected to the test object i.e. a wind turbine, through a low pass filter that consists of a capacitor and an inductor as shown in figure 5.1. The proposed test equipment is designed in PSCAD/EMTDC which is a powerful tool for investigating the dynamic performance of power systems.

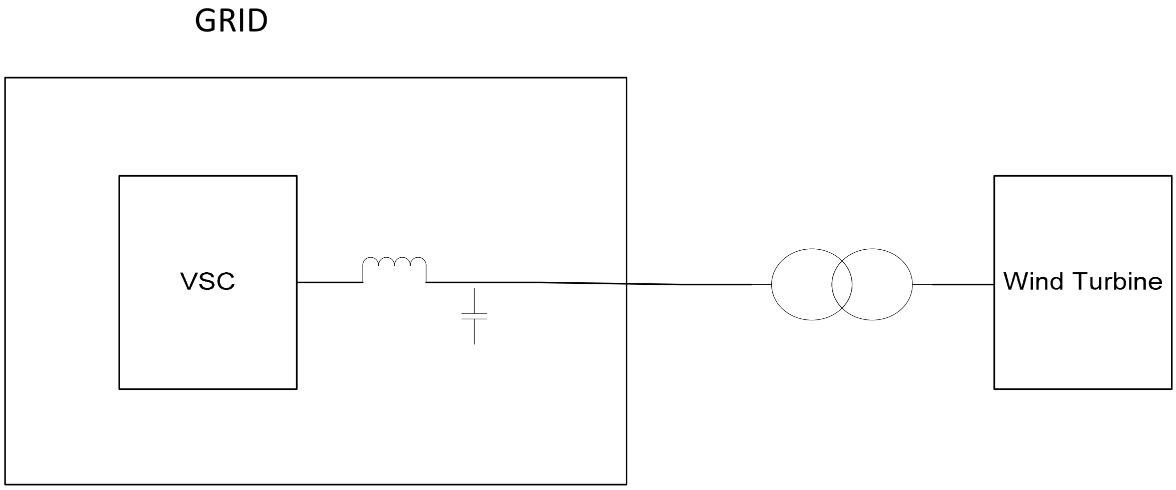


Figure 5.1 Single line diagram of proposed test equipment

It can be seen in the figure that proposed test equipment is connected to high voltage side of transformer in order to reduce the current ratings of converter. Although this system is quite expensive but it is more flexible as it depicts different grid characteristics for different short circuit powers and can also be used for frequency and voltage variations and not only for voltage dips but can also be used for voltage swells or over voltages.

## 5.1 Design procedure of the proposed test equipment

There are different factors that needed to be considered during the design of test equipment. The design is composed of different components and the following steps will describe them.

### 5.1.1. The control scheme of the VSI

The first step in the design is to gain control of the inverter. The inverter should be designed in in such a way that it act as a grid for the test object. The grid should be totally independent from the load. So for this project open loop control of the inverter is chosen, which can be seen from the figure 5.2.

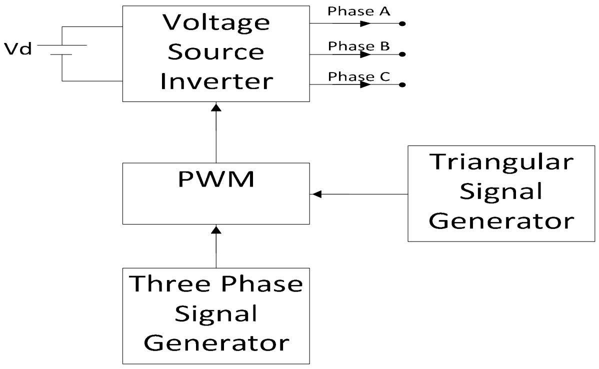


Figure 5.2 Open loop arrangement of the test equipment

### 5.1.2. The inverter size and DC link voltage

It is very important to select the current and voltage ratings of the inverter because the power rating is determined from the maximum current and maximum voltage handled by device. Generally, the valves of the power-electronic equipments are very sensitive to high currents as compared to passive components [16]. To design the test equipment in PSCAD, the three phase inverter arrangement has chosen, which is described in chapter 3 can be seen from the figure 5.3. The test equipment is designed for 50 kVA system which is quite simple to implement in the lab. The DC link voltage of the converter is chosen as Vdc= 654 V, that is taken from a DC voltage source.

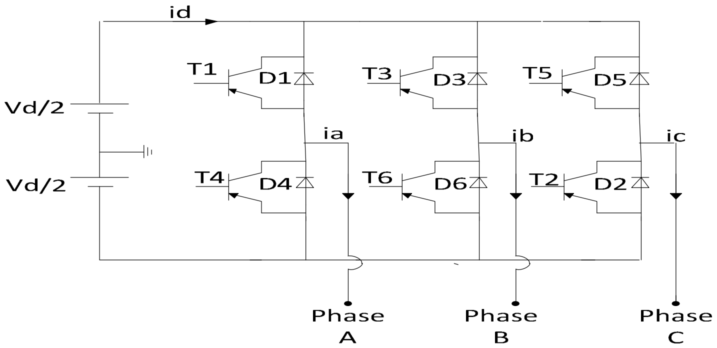


Figure 5.3 General circuit diagram of the three phase voltage source inverter

### 5.1.3. Design of the PWM block

In this design scheme the output of the converter can be changed with the switching pattern of the IGBT's that can be achieved from the PWM block. For this two types of input is needed in the PWM block. Firstly, a triangular signal, that acts as the carrier signal. Secondly, a three phase signal, which will act as the control signal for the PWM block, as mention in the section 3.4. These two signals are compared in the comparator to generate the switching. The frequency of the triangular signal is chosen as 1527 Hz, which represent the switching frequency of the inverter. To get an output of 400 V line to line (rms) from the inverter with 50 Hz frequency, the control signal is generated as 400 V line to line (rms) with 50 Hz. For this case the modulation index is chosen as $m_a$= 1 according to expression 3.3.

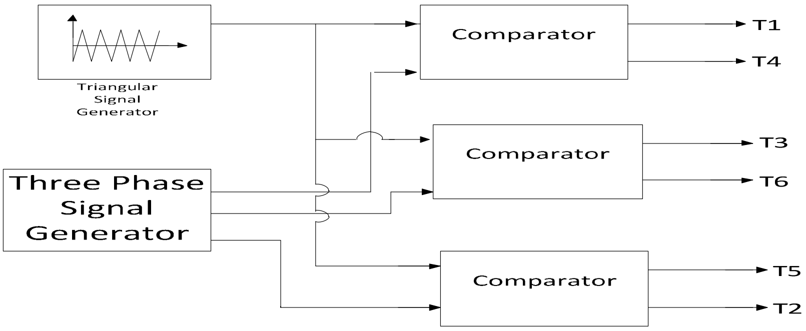


Figure 5.4 PWM signal generator

## 5.2 Filter Design

The output of converter consists of number of harmonics that should be eliminated and for this reason the filters are used. The main purpose of the filter is to eliminate the high frequency harmonics that are generated by the switching of the valves of converter and to lessen the stress on the valves of converter and wind turbine transformer as this filter connects the converter to transformer. Reactance $X_L$, of the filter is chosen as 0.2 p.u of $Z_{Base}$ of converter and having internal resistance of 0.1 times of XL. The cut-off frequency of low pass filter is determined as,

$$w_{\mathrm{cut-off}} = \frac{1}{2\pi\sqrt{LC}} \qquad (5.1)$$

In this project the cut-off frequency of LC filter that is connected at the output of converter is chosen 10 times below the selected switching frequency. Switching frequency is chosen by doing a trade off between quality of output voltage and losses.

## 5.3 Transformer

In this project a built in model of transformer is used that is taken from PSCAD library. It transfers the extracted power from wind to the grid by boosting the voltage level. In this project a 1:1 transformer with the following parameters is selected,

Table 5.1 Parameters of Transformer

| **Transformer Parameters** | **Ratings** |
|---|---|
| Transformer MVA | 0.05 MVA |
| Operating Frequency | 50 HZ |
| Primary Voltage | 0.4 KV |
| Secondary Voltage | 0.4 KV |
| Primary Winding Type | Y |
| Secondary Winding Type | Δ |
| Positive Sequence Reactance | 0.1 P.U |
| No Load Losses | 0 |
| Copper Losses | 0 |

## 5.4 Design of test object

The test object of the system is a single wind turbine with back to back full power converters. The wind turbine basically injects active power and as it is connected with the full power converter it can exchange a certain amount of reactive power also.

The aim of the thesis is to test a wind turbine system through the designed VSI which should be capable of providing the nature of grid. To design the test object is not the thesis goal. As there is no built in model of the test object so for this project the test object is modelled in a simple way but it should provide the similar types of effects as the conventional converter based wind turbine. In wind turbine the generation of power varies with wind speed. But it is expected that at the PCC the wind turbine should provide a fixed amount of power. If it is a full power converter based wind turbine then the task is performed by the grid side converter. That means the grid side converter try to inject the power at PCC in a controlled way. It means a reference value of power at PCC have to be selected that the grid side converter should provide and the converter tries to reach the task by its controllability. The P-Q controller based system can do the things in the similar way. Where a reference value of power is selected and it tries to achieve that by the help of its controller. For this case a P-Q controller based load has modelled. This can exchange a given amount of real and reactive power at the point of common coupling. The figure 5.5 shows the connection of load to the point of common coupling (PCC).

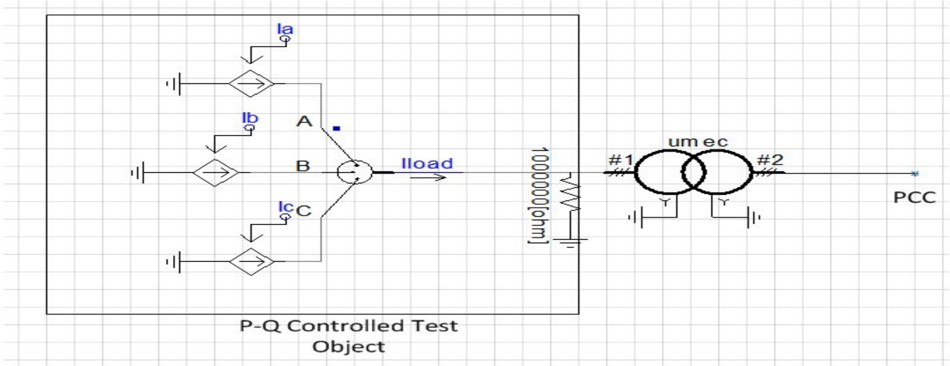


Figure 5.5 P-Q Controlled test object with PCC

### 5.4.1. Design principle

As it is mentioned in the earlier section that the load is P-Q controlled, it is needed to control the active power and reactive power exchange at the point of common coupling (PCC). At the PCC the voltage is to be maintained constant, so the power at that point can be controlled by controlling the current through that point or vice verse. The design block is shown in figure 5.6.

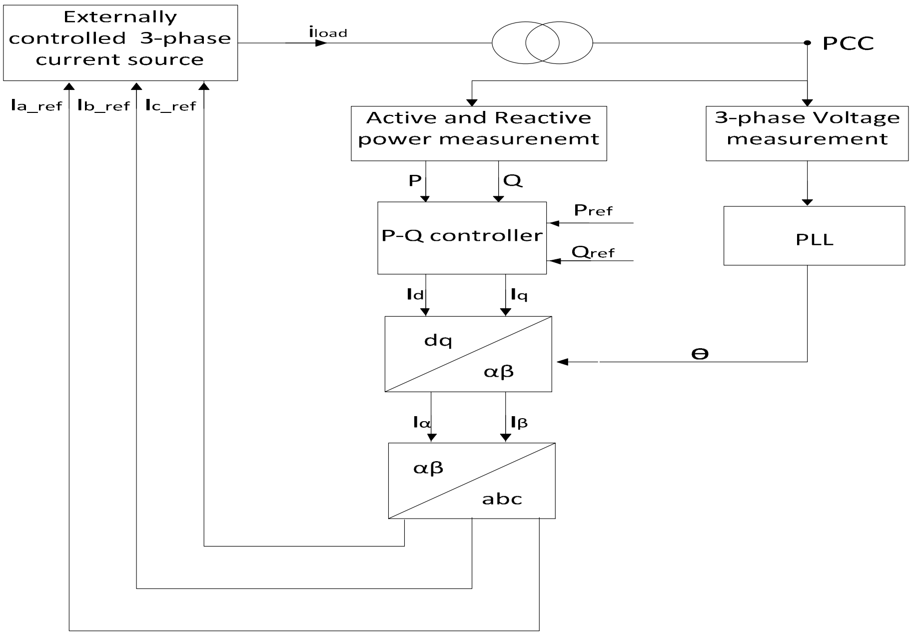


Figure 5.6 Design of test object

## 5.4.2. abc to dq Transformation

It is the transformation of coordinates from three phase stationary coordinate system "abc" to "dq" two phase rotating coordinate system. It is done in two steps,

(i) Transformation from three phase stationary coordinate system to two phase stationary coordinate system known as"αβ", called Clark's transformation.

(ii) Transformation from "αβ" to "dq" rotating coordinate system, called Park's transformation.

This transformation is done because in dq system the quantities are in dc form, so it is easy to compare the dc quantity rather than ac. In dc system where frequency w=0,so integrator limit goes towards infinite and it can make steady state error zero while in case of ac quantity the integrator is limited to some value so it can reduce the steady state error to some value but cannot make it to zero. So, it is easier to do analysis and control design tasks in "dq" coordinate system [5].

Mathematically Clark's transformation is expressed as,

Neglecting zero sequence $v_a(t) + v_b(t) + v_c(t) = 0$

Where $v_a(t), v_b(t), v_c(t)$ are the three phase voltages,

$$v_s(t) = \frac{2}{3}K\left[v_a(t) + v_b(t)e^{j\frac{2\pi}{3}} + v_c\,(t)e^{j\frac{4\pi}{3}}\right] = v_\alpha\,(t) + jv_\beta(t)$$

$$v_s(t) = K\frac{2}{3}\left[v_a(t) + v_b(t)e^{j\frac{2\pi}{3}} + v_c\,(t)e^{j\frac{4\pi}{3}}\right] =$$

$$K\frac{2}{3}\left[v_a(t) + v_b(t)\cos\frac{2\pi}{3} + jv_b(t)\sin\frac{2\pi}{3} + v_c\,(t)\cos\frac{4\pi}{3} + jv_c\,(t)\sin\frac{4\pi}{3}\right] =$$

$$K\frac{2}{3}\left[v_a(t) - \frac{1}{2}v_b(t) - \frac{1}{2}v_c(t) + j\frac{\sqrt{3}}{2}\left(v_b(t) - v_c(t)\right)\right] =$$

$$K\left[\frac{2}{3}v_a(t) - \frac{1}{3}v_b(t) - \frac{1}{3}v_c(t) + j\frac{1}{\sqrt{3}}\left(v_b(t) - v_c(t)\right)\right] = v_\alpha\,(t) + jv_\beta(t) \qquad (5.2)$$

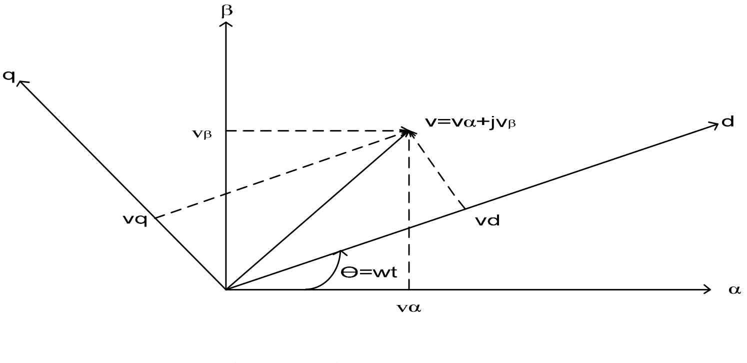
$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = K\begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

And from αβ to abc ,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{K}\begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

K is the scaling constant and its value can be chosen arbitrarily. For amplitude invariant scaling, K= 1 and for RMS value scaling, K=$\frac{1}{\sqrt{2}}$ and for power invariant scaling, K= $\sqrt{\frac{3}{2}}$. In this project, the power invariant system has used.

Park's transformation can be expressed as,



$$v_{\alpha\beta} = v_{dq}e^{j\theta} = \left(v_d + jv_q\right)(\cos\theta + j\sin\theta)$$

$$= \left(v_d\cos\theta - v_q\sin\theta\right) + j\left(v_q\cos\theta + v_d\sin\theta\right) = v_\alpha + jv_\beta \qquad (5.3)$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

## 5.4.3. Phase locked loop:

Phase locked loop (PLL) is used to track angle of PCC voltage. PLL take the phase angle from the PCC voltage and synchronizes the controller with that point. There are two types of PLL used like voltage oriented PLL and flux oriented PLL. In voltage oriented PLL the voltage vector is aligned with the d-axis that means the q-component of the voltage vector is equal to zero. On the other hand, in flux oriented control the voltage vector is align with the q-axis that means the d-component of the voltage vector is zero. For the case of drive's control the flux oriented PLL is used and for transmission and distribution of power the voltage oriented PLL is used. As it is needed to sense the voltage at grid point, so the voltage oriented PLL is selected. The figure 5.8 shows the block diagram and figure 5.9 shows the vector diagram of voltage oriented PLL. The controller is voltage oriented, so PLL makes Vq=0, during steady state operation it locks the controller phase voltage with the phase voltage of PCC.

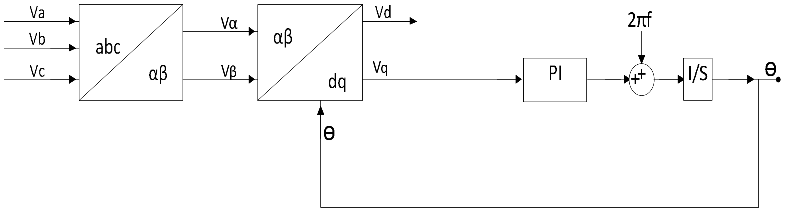


Figure 5.7 Design of PLL block

The transfer function of the PI controller is,

$$F_{c,PLL} = k_{p,PLL} + \frac{k_{i,PLL}}{s} \tag{5.4}$$

The proportional gain $k_{p,PLL}=2\alpha$ and the integrator gain $k_{i,PLL}=\alpha^2$ taken from[17]. Where the bandwidth $\alpha = 2\pi f_{PLL}$ and $f_{PLL}$ is chosen as 5 Hz, as we are using slow PLL.

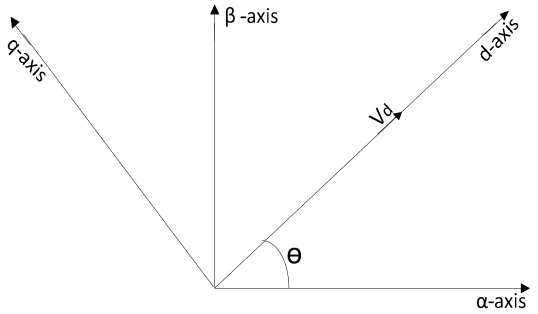


Figure 5.8 Voltage oriented PLL vector diagram

### 5.4.4. P-Q controller

To design the controller, the PI controller based system has selected. Because it is simple and the voltage and current ratings are not the concerned here where in other types of controllers the voltage needed to be scaled for a small value. As it is mentioned that the PLL is using here is voltage oriented and the system is in power invariant, so the equations for active power and reactive power in d-q frame are

$$P = v_d i_d + v_q i_q \tag{5.5}$$

$$Q = v_q i_d - v_d i_q \tag{5.6}$$

So if the d-component of the voltage is zero then the equations become

$$P = v_d i_d \tag{5.7}$$

$$Q = -v_d i_q \tag{5.8}$$

Now from equation (5.7) and (5.8), if it is needed to make the voltage stagnant at PCC then only by controlling the current, the active and reactive power can be controlled. The reference value of the active power and reactive power are chosen and the actual value of the active and reactive power can be measured from the PCC. Then these reference values and actual values of the active power and reactive power are compared in separate comparators block to generate the error signals. So when this error signal passes through PI controller it gives the current as output. In figure 5.9 the voltage V<sub>d</sub> is the D-component of PCC voltage that is measured and for steady state operation this voltage is desired to be 1 p.u.

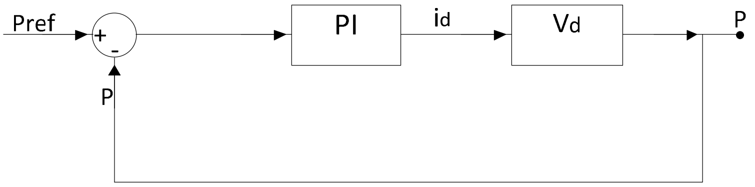


Figure 5.9 Block diagram of active power controller

For the active power controller the current,

$$i_d = (P_{ref} - P)F_c \tag{5.9}$$

Where Fc is the transfer function of the PI controller. It can be written as,

$$\begin{aligned} F_c &= \left(k_p + \frac{k_i}{s}\right) \\ &= k_p\left(1 + \frac{1}{ST_s}\right) \end{aligned} \tag{5.10}$$

So from the equation 5.10, if the value of the proportional gain kp and the time constant of the integrator Ts are known , then one can calculate the value of Fc.

In this case the value of the kp=0.97 is selected through hit and trial method .The value of time constant Ts has chosen is 200ms.

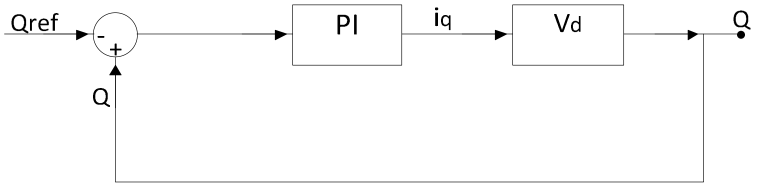


Figure 5.10 Block diagram of reactive power controller

Same parameters are also used for the reactive power controller. In this case the current equation is,

$$i_q = -(Q_{ref} - Q)F_c \tag{5.11}$$

## 5.4.5. Tuning of controller for the test object

Initially the reference values for active and reactive power were set to zero then when a step to the active power to 1 p.u is applied and the reactive power remains at zero, the actual value of the active power try to reach its reference value and it takes 1.8 sec to settle with the reference value. The rise time in this case is, trr= 500 ms.

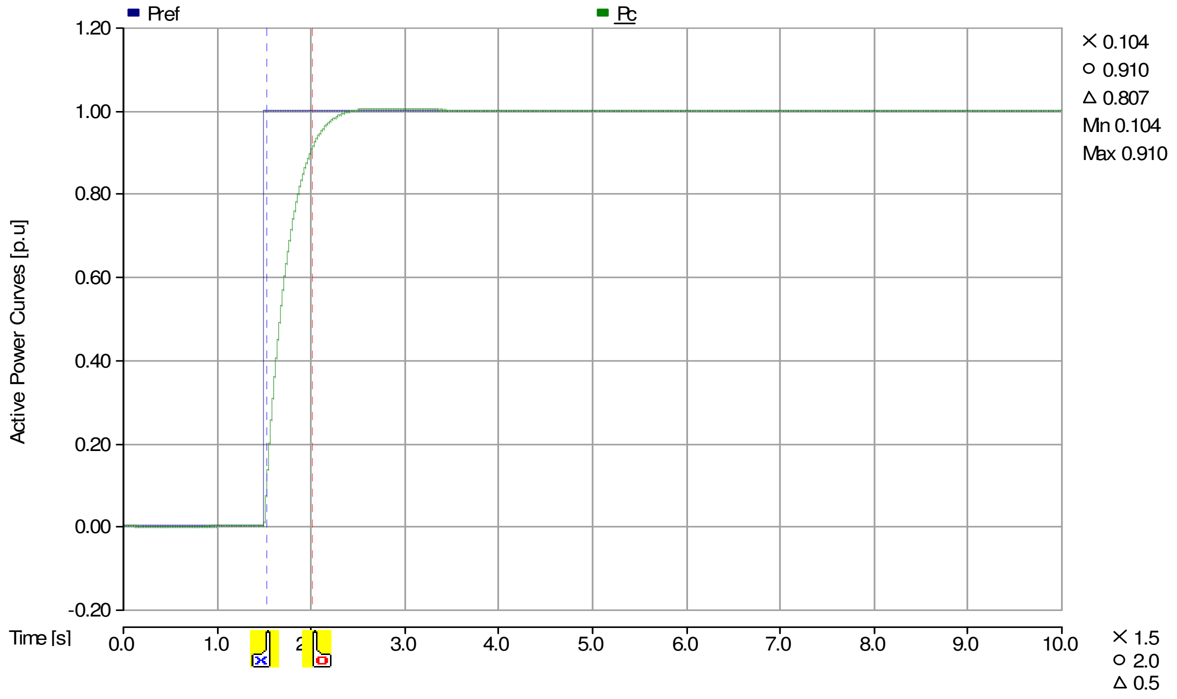


Figure 5.11 Active power response

## 5.4.6. Externally control current source

It is a current source that consists of an external control and with high internal shunt impedance chosen from PSCAD library. The outputs of the PI controller are converted from d-q quantity to abc quantity and given it as the reference value of the current source.

## 5.5 Control strategy for different Grid code profiles

As it is mentioned earlier that the goal of this thesis project is to implement grid code test through VSC, so VSC is modelled in such a way as shown in figure 5.15 that, it can satisfy the requirements. It is know that by varying the amplitude of the control signal of PWM, the magnitude of output voltage from the VSI will change. Similarly by varying the frequency of the control signal the variation in the fundamental frequency of the output signal from the VSC can be seen. In this project the similar technique has chosen. Grid code profiles for voltage magnitude and frequency are created in p.u and multiplied them with the amplitude and frequency of the control signals respectively. This provides the desired output from the VSC that is applied to the test object.

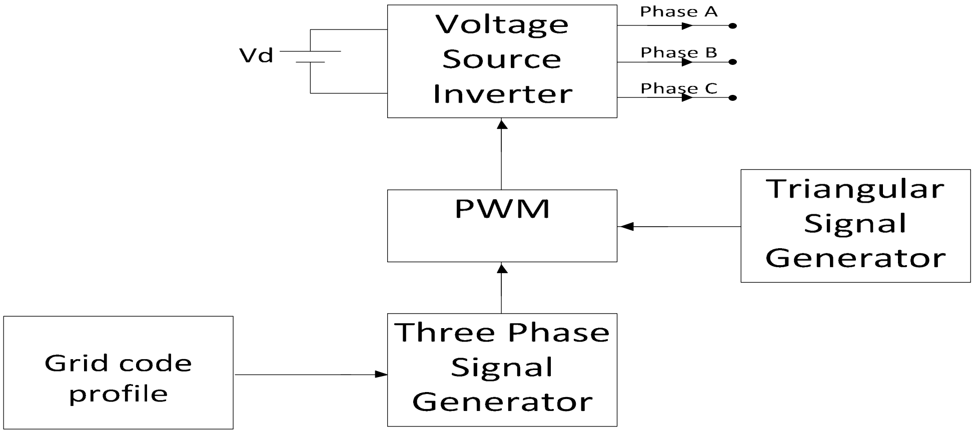


Figure 5.12 Control strategy for different Grid code profiles

### 5.5.1. Complete representation of the system

Figure 5.13 represents the block diagram of complete model while figure 5.14 represents the designed network in PSCAD with the components and its ratings.

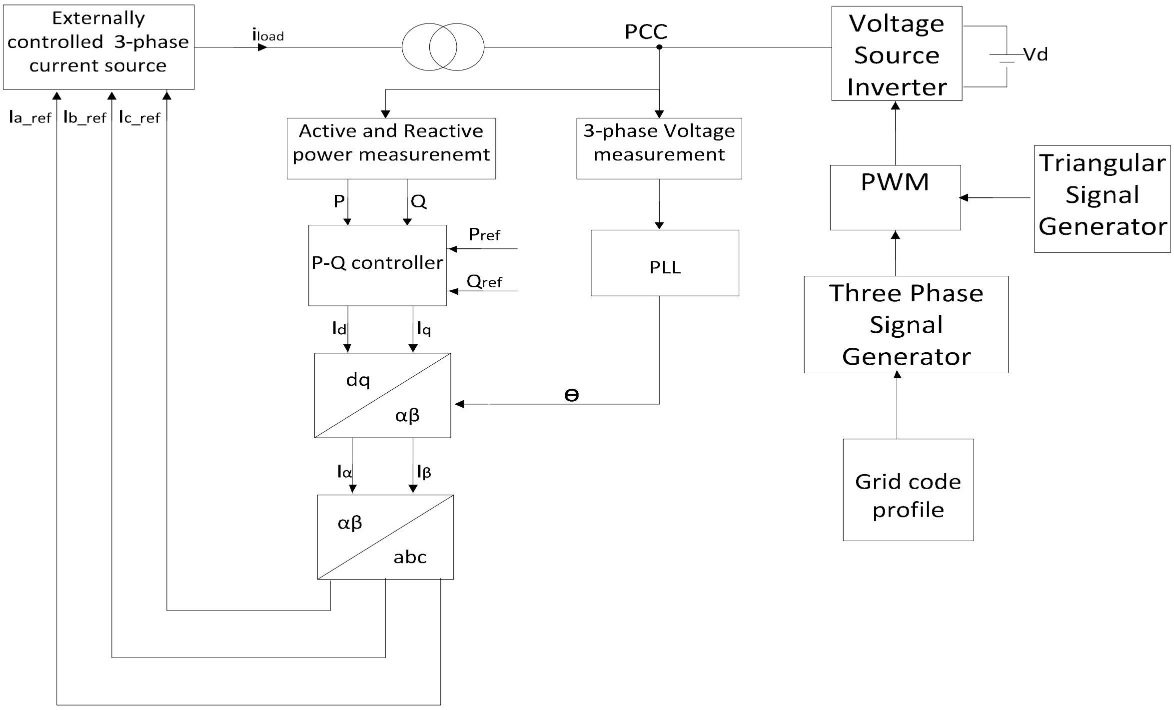


Figure 5.13 Complete block Representation of the system

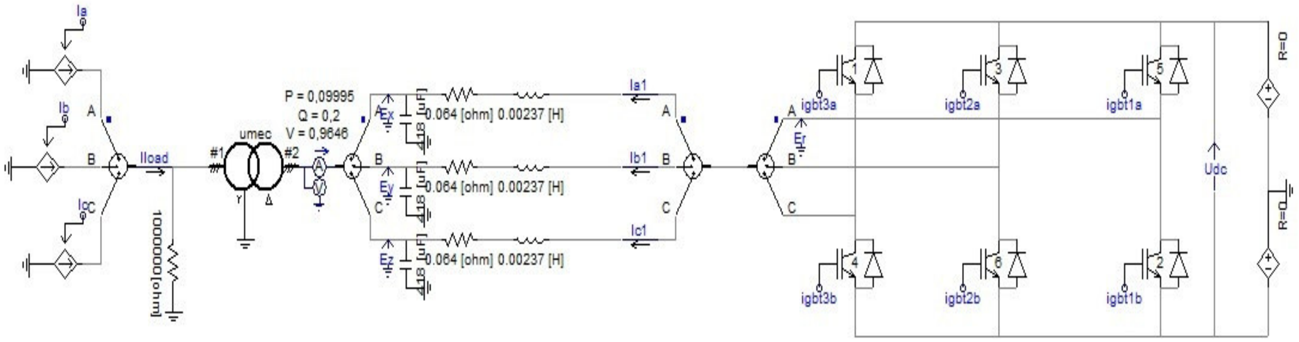


Figure 5.14 Complete design of the system in PSCAD

# Chapter 6

# Results and Analysis

In this chapter different simulation results are analysed by creating different voltage and frequency profiles according to grid codes in order to see the response of the load in these situations and to check the performance of designed test equipment in PSCAD. Project considers different cases here and in each case voltage from converter is 1p.u and frequency is set to 50 Hz.

## Case 1: Applying Active power and Reactive power steps in the P-Q controller respectively.

The simulation is carried out in the following steps:

(i) Start with the initial condition and wait for some time until the system reaches steady state.
(ii) At t=1.57 sec, set Pref= 1 p.u and Qref=0 p.u and wait to make the response stable.
(iii) At t=6.2sec, hold Pref to 1 p.u and set Qref to 1p.u and wait until response stabilized.
(iv) At t=9.1 sec, set Pref= 0 p.u and remain Qref to 1p.u and wait until the condition stabilized.
(v) Finally at t= 12sec, hold Pref to 0 p.u and set Qref to 0 p.u.

The curves of the active and reactive power are seen form the figure 6.1(a) and (b) respectively. The blue curves represent the reference value and the green curves represent the measured at PCC. As both active and reactive power both are interrelated quantity, the step changes in one gives the deviation in the value of other quantity. The measured values of both active power and reactive power need some time to achieve the reference value.

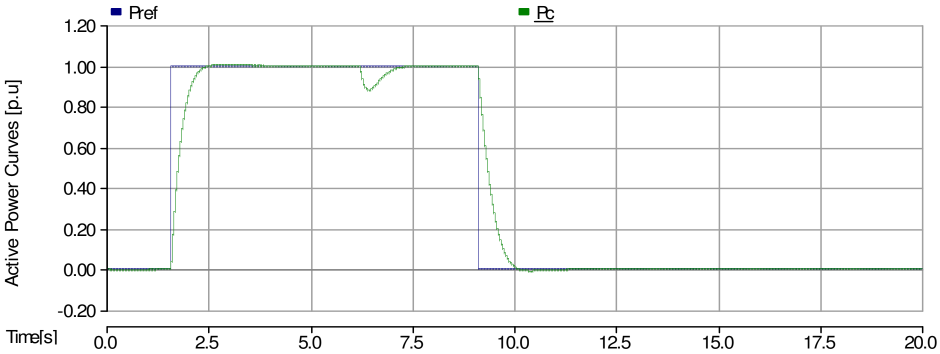


Figure 6.1(a) Active Power Curves of the P-Q controller.

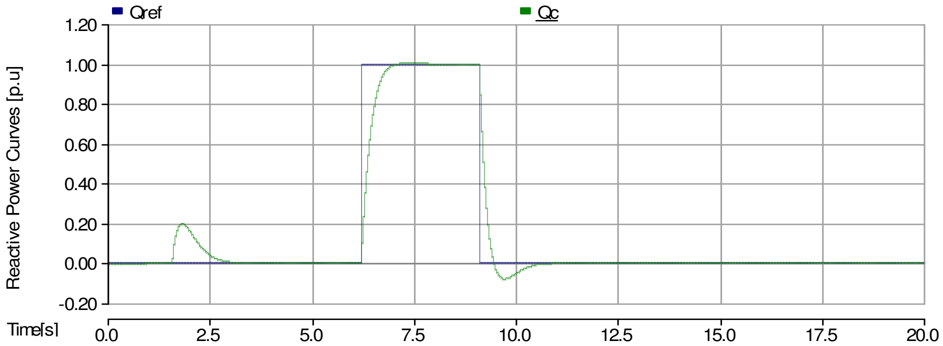


Figure 6.1(b) Reactive power curves of the P-Q controller

The current through the filter of the converter can be seen by the figure 6.2(a) and figure 6.2(b) represents the 3-phase current output from the P-Q controller. Current from the controller will increase when the active power step is applied, because at that time the voltage is fixed and the active power depends only on the current injection from the current source. When P and Q reference both are set to 1 p.u, the active and reactive current output from the P-Q controller will increase. It is also noticeable that the current from the converter filter is also increased.

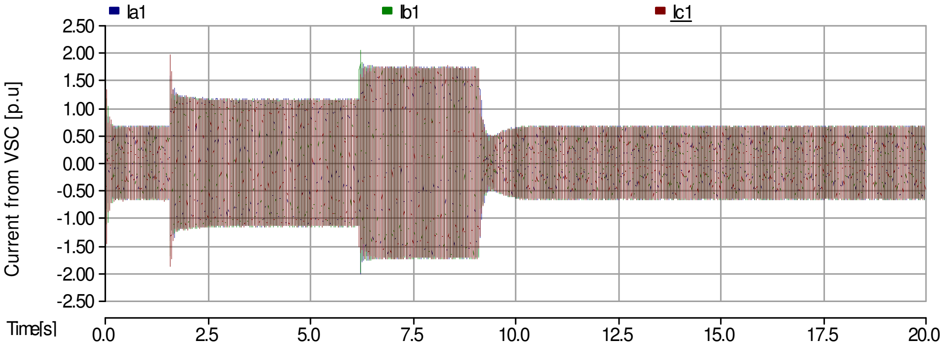


Figure 6.2 (a) 3-phase currents from the converter.

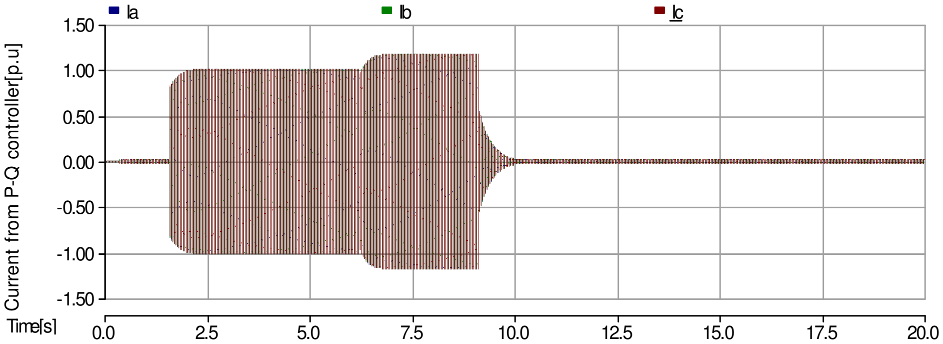


Figure 6.2 (b) 3-phase current from the P-Q controller.

Figure 6.3(a) represents the control 3-Phase voltage given at the PWM of the converter. This is considered as the reference voltage. The voltage measured at the point of common coupling (PCC) can be seen from the figure 6.3(b). The PCC voltage is increased significantly when the reactive power step is applied with the active power step.

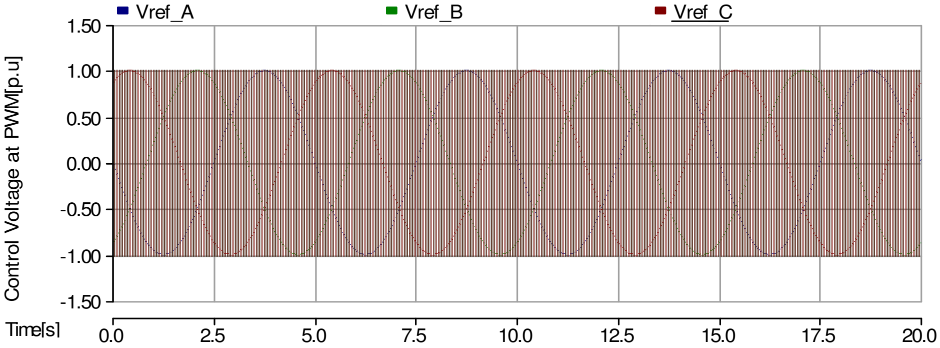


Figure 6.3(a) 3-phase reference voltage

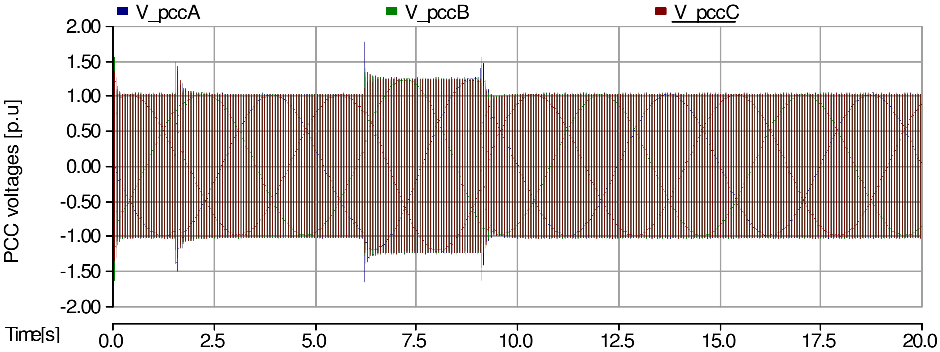


Figure 6.3(b) Voltage Measured at PCC

## Case 2: Applying 0.7 p.u voltage dip from the Converter

The simulation is carried out in following steps:

(i) Start with the initial condition and wait for some time until the system reaches steady state. At t=1.65 sec, set Pref to 1 p.u and Qref remains to 0 p.u. Wait until the situation reaches steady stare.

(ii) At t=3sec, holding the value of Pref and Qref, reduce the control signal magnitude to 30%, gives 0.7 p.u output from the converter. Wait for some time until the situation gets stable.

(iii) At t=6 sec, apply a step on Qref to 0.5 p.u and wait for some time to see the response.

(iv) At t=9 sec, apply another step on Qref to 1p.u and wait until the situation get stable.

(v) Finally at t= 12 sec, bring back Qref to 0 p.u and voltage to 1 p.u values and wait for some time until the system stabilized.

The active and reactive power curves are seen from figure 6.4(a) and 6.4(b) respectively, which gives the similar kind of behaviour as in the previous case.

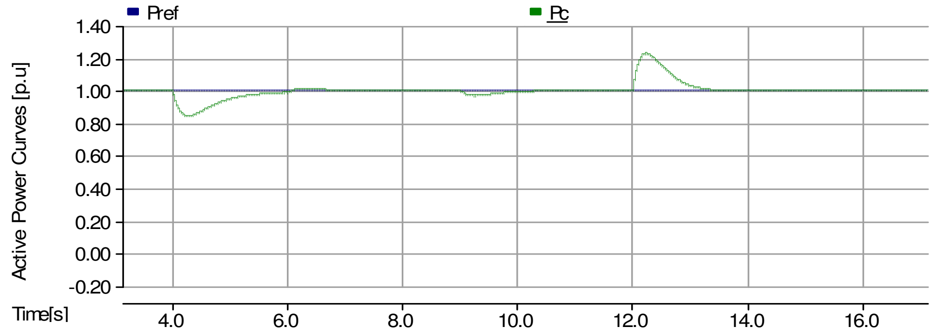


Figure 6.4 (a) Active power for 0.7p.u voltage dip.

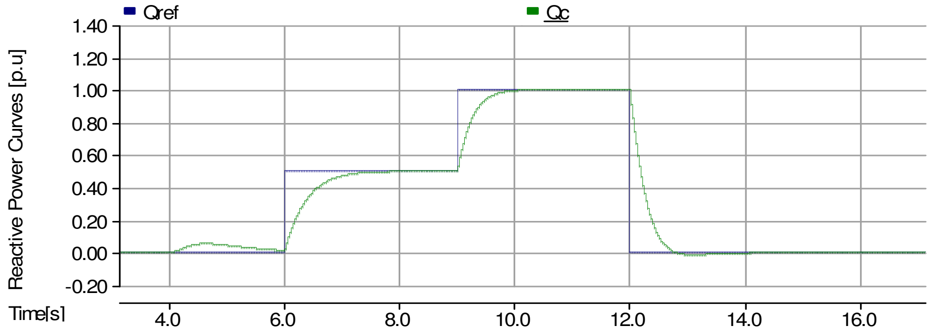


Figure 6.4(b) Reactive power for 0.7p.u voltage dip.

The Control voltage for PWM, 3-phase Voltage for PCC and D-Q voltage for PCC at 0.7p.u voltage dip are shown in figure 6.5 (a),(b) and (c) respectively. Form the effect of voltage dip is seen clearly. As the reactive power steps are applied also in the simulation, it can be clearly seen from the voltage curve at PCC. When the Qref is 1 p.u the voltage at PCC is maintained approximately to 1 p.u. It means that if the reactive power support is applied, it is possible to boost the voltage at PCC.

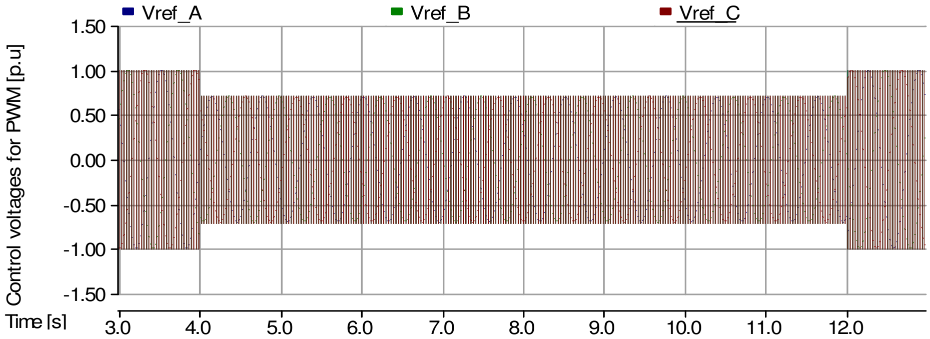


Figure 6.5 (a) Control voltage for PWM for 0.7p.u voltage dip

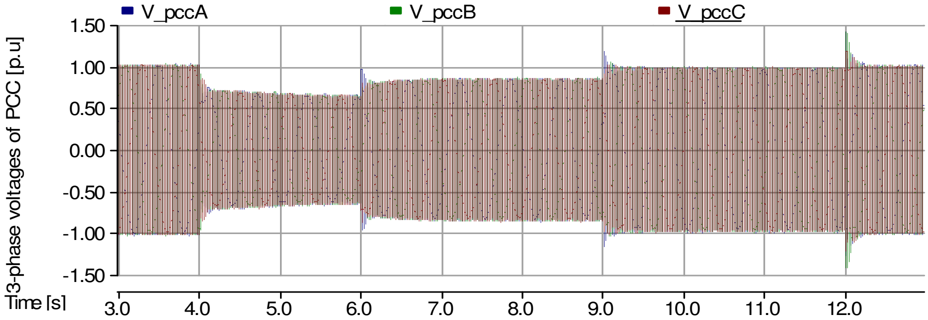


Figure 6.5(b) 3-phase Voltage for PCC for 0.7p.u voltage dip.

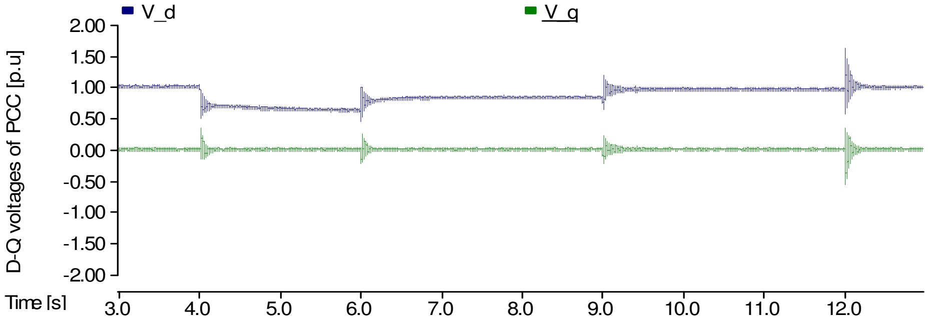


Figure 6.5(c) D-Q voltage of PCC for 0.7p.u voltage dip.

3-phase current from controller and from converter at 0.7p.u voltage dip are shown in figure 6.6 (a) and (b) respectively. Current is increased as the voltage is dropping down.

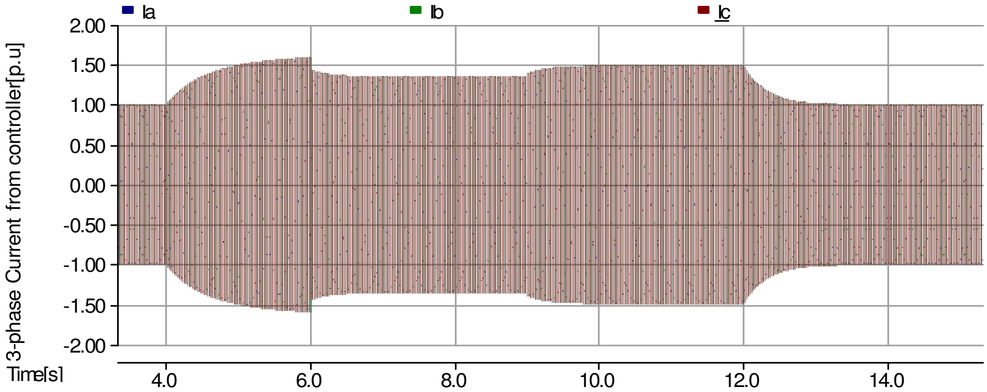


Figure 6.6(a) 3-phase current from controller for 0.7p.u voltage dip.

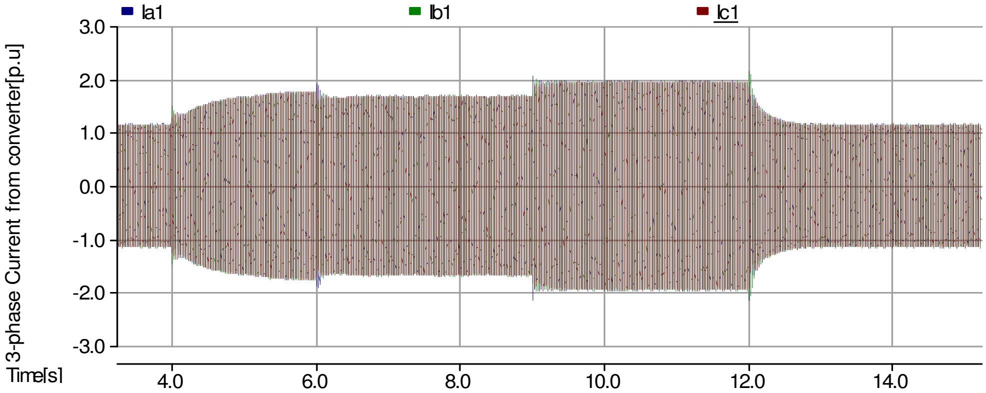


Figure 6.6(b) 3-phase current from converter at 0.7p.u voltage dip.

## Case 3: Voltage Control at the PCC

To simulate this case, the grid codes compliance of Svenska Kraftnat is considered, which is explained in section 4.1. For this simulation set the reactive power reference Qref to 0 p.u and voltage from the converter is set to 1 p.u initially. Then change the voltage magnitude in to some stapes like 1.05 p.u, 1p.u, 0.95 p.u and again to 1 p.u . On the other side vary the active power reference Pref to 0.2 p.u, 0.4 p.u, 0.6 p.u, 0.8 p.u and 1 p.u at 2 sec, 6 sec, 10 sec, 14 sec and 18 sec respectively. The active power steps are shown in figure 6.7 (a)Active power.

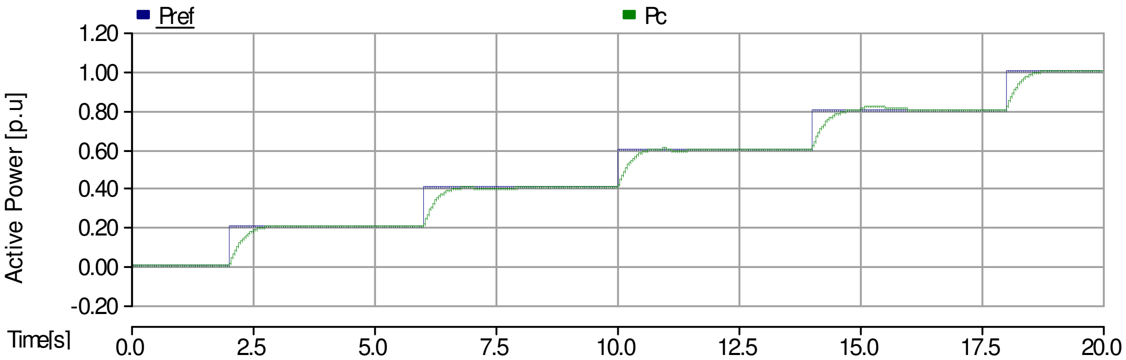


Figure 6.7(a) Active power for case 3.

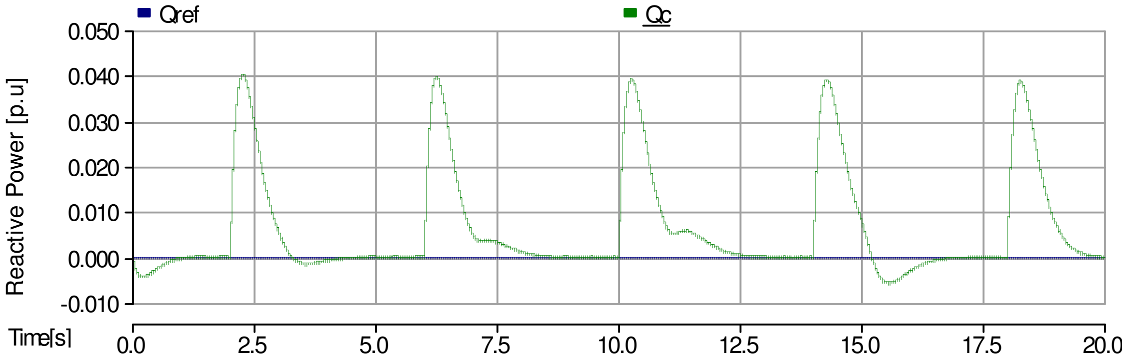


Figure 6.7(b) Reactive power curves for case 3.

During the time of simulation it is noticed that the voltage variation from the converter is given to ±5% and the voltage at PCC gives the similar types of variation. This can be seen from figure 6.8(a) and (b) respectively.

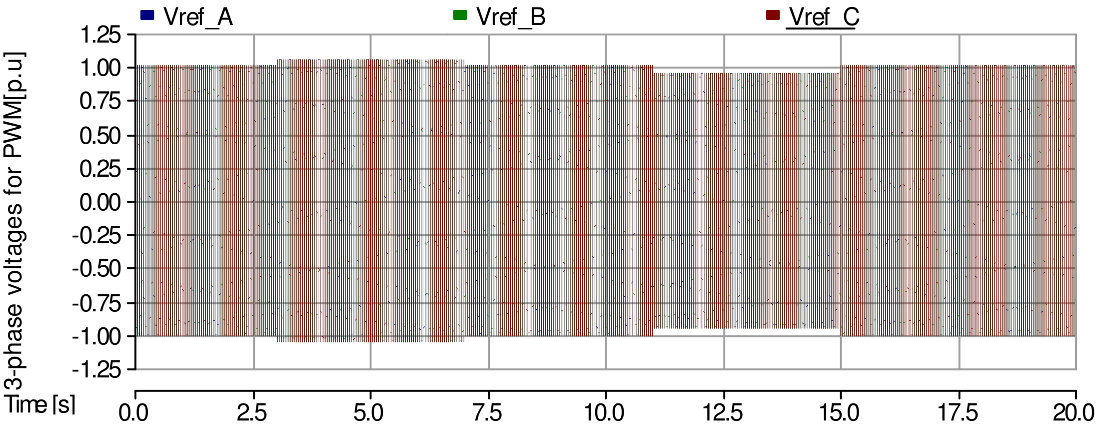


Figure 6.8(a) 3-phase voltage for PWM in Case 3.

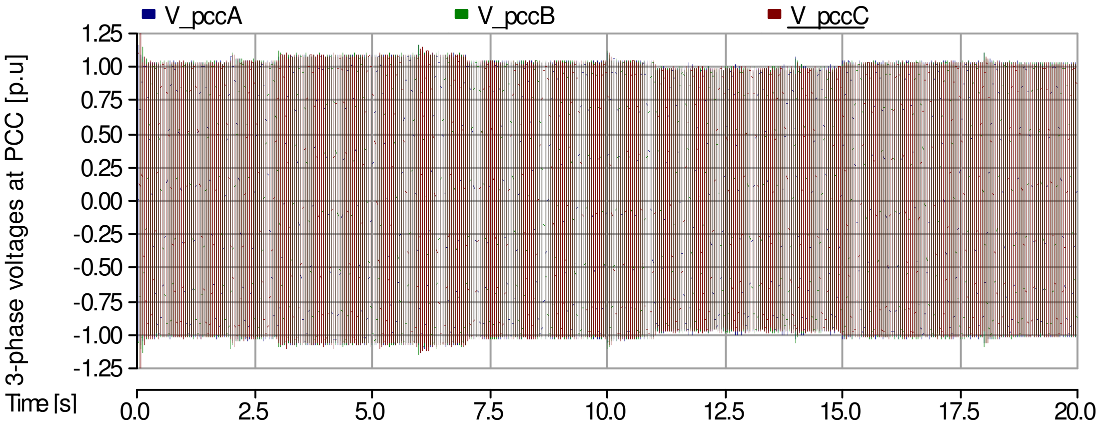


Figure 6.8(b) 3-phase Voltage at PCC for Case 3

As the active power is varied only and voltage variation very low, the current is increasing significantly which can be seen from the figure 6.9.

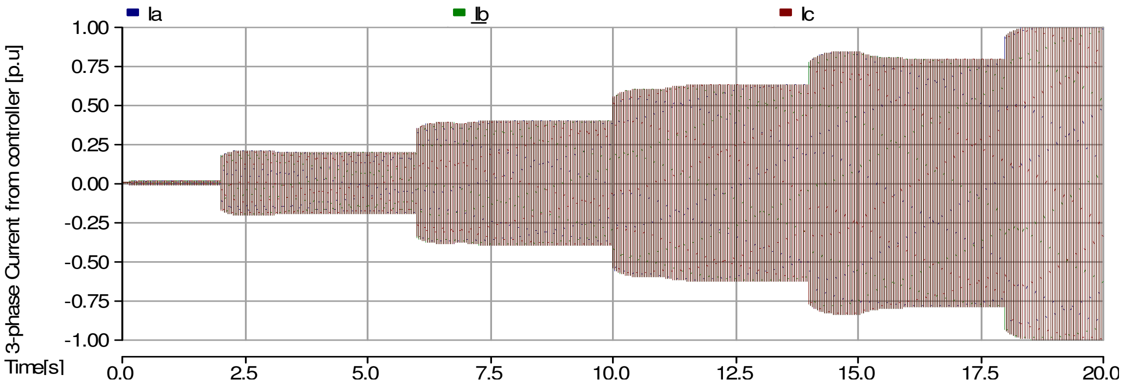


Figure 6.9 (a)3-phase current from controller for case 3.

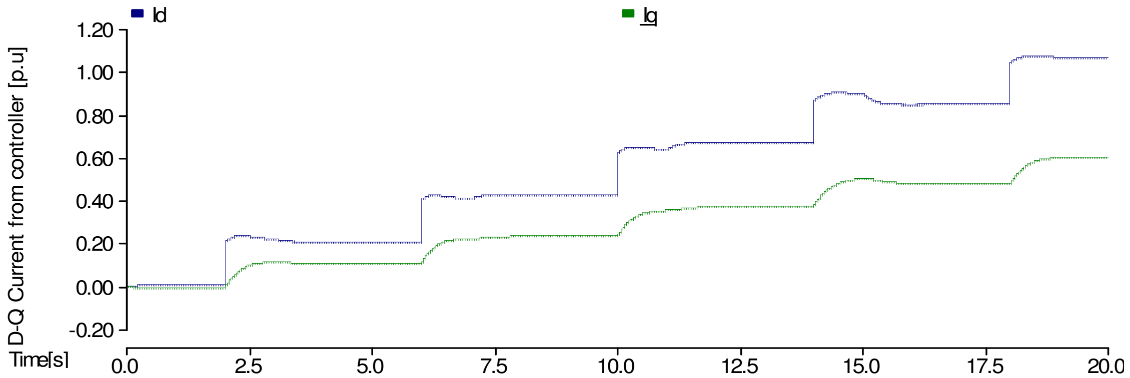


Figure 6.9(b) D-Q current from controller for case 3

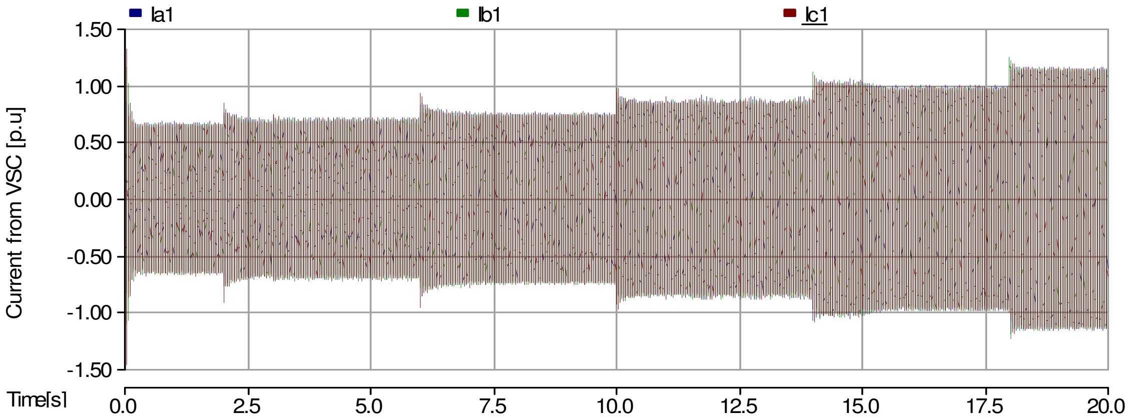


Figure 6.9(c) 3-phase current from VSC for case 3.

## Case 4: Low voltage Ride through Simulation

### Three phase fault

Low voltage ride through requirements are described in section 4.4.To simulate the three phase fault the E.ON grid code profile is prepared in the simulation block as shown in figure 6.10. The simulation is done in the following way:

(i) Start the simulation with Pref to 1 p.u and Qref to 0 p.u always.
(ii) 2. At t=0.2 set Pref=0.5 p.u and implement the E.ON grid code profile at that time.

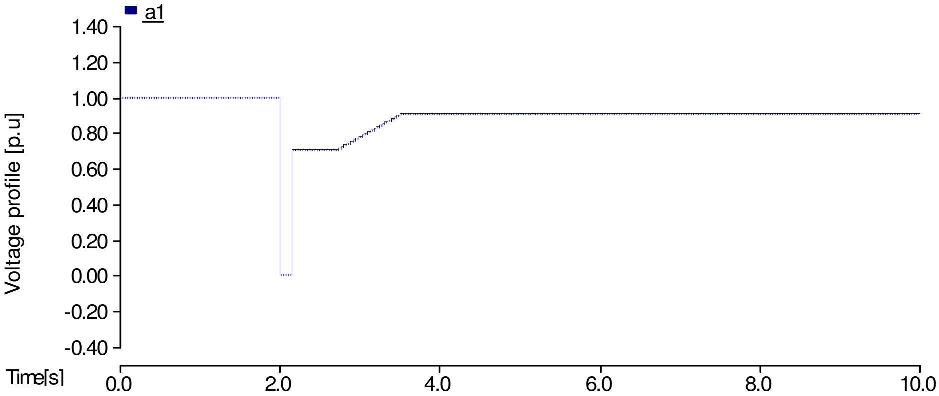


Figure 6.10 E.ON's Low voltage ride through profile applied in the converter

The Active Power and Reactive Power curves are shown in figure 6.11(a) and (b) respectively. Before applying the profile the active power is reduced to 0.5 p.u, which is shown in figure.

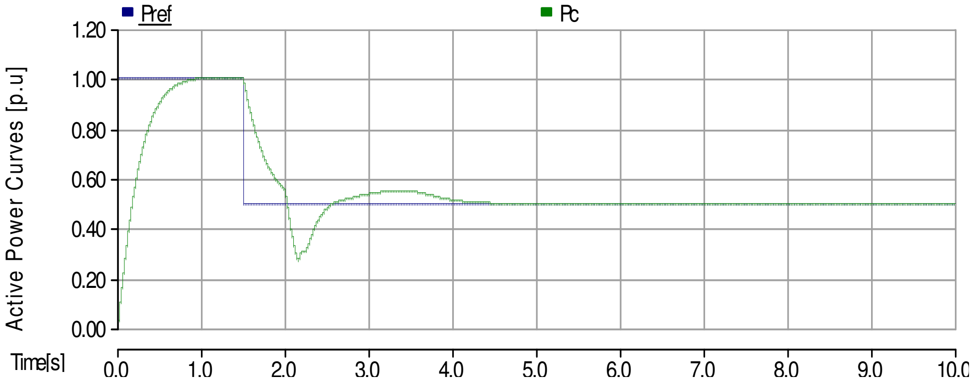


Figure 6.11(a) Active Power for three phase fault.

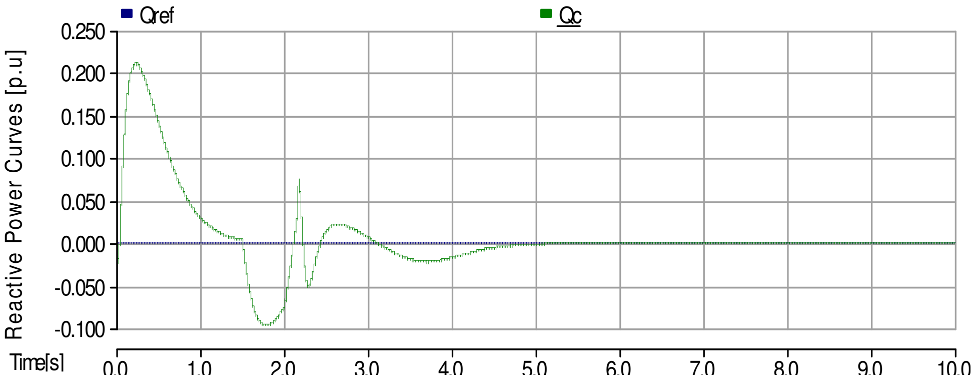


Figure 6.11(b) Reactive Power curves for three phase fault.

The fault is applied from the converter side which is shown in figure 6.12(a). The effect of this situation at the point of common coupling (PCC) can be seen from the voltage at PCC 6.12(b). The d-component of the PCC voltage of figure 6.12(c) is quite similar to the profile of figure 6.10.

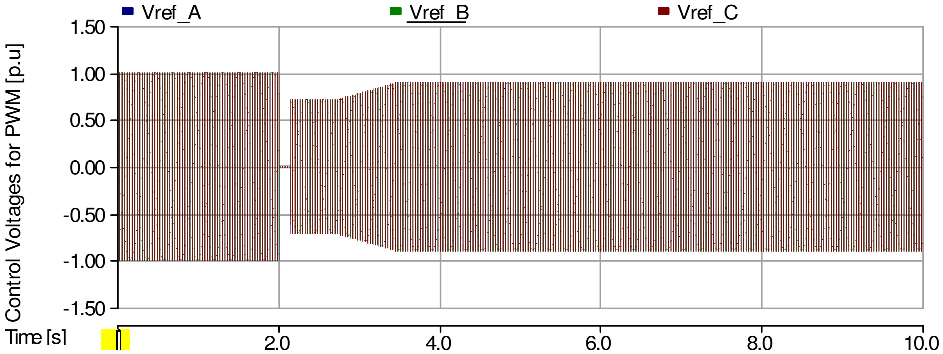


Figure 6.12(a) Control voltage for PWM for three phase fault.

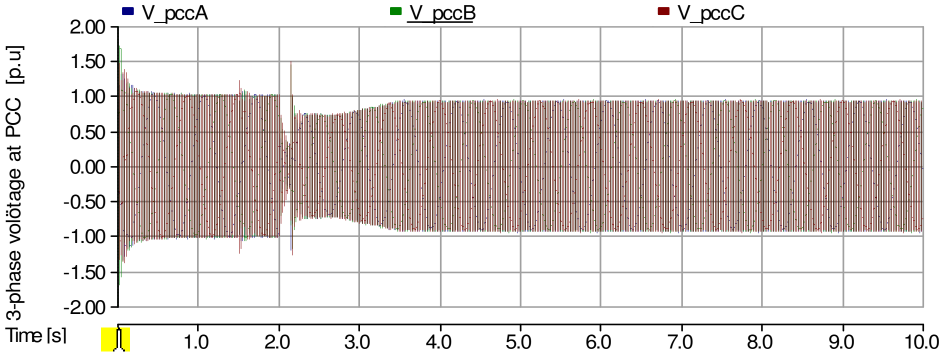


Figure 6.12(b) 3-phase Voltage at PCC for three phase fault.

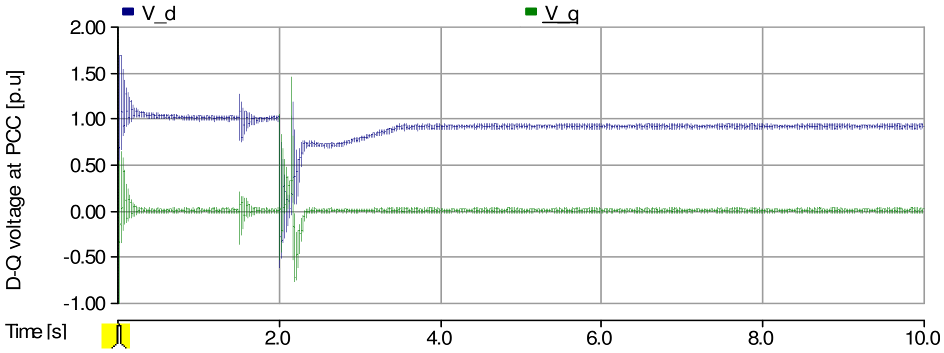


Figure 6.12(c) D-Q voltage at PCC for three phase fault.

During the fault the voltage at PCC is decreasing and the current is increased very high as shown in figure 6.13(a) 3-phase current from VSC,(b) 3-phase current from controller and (c)D-Q current from controller.

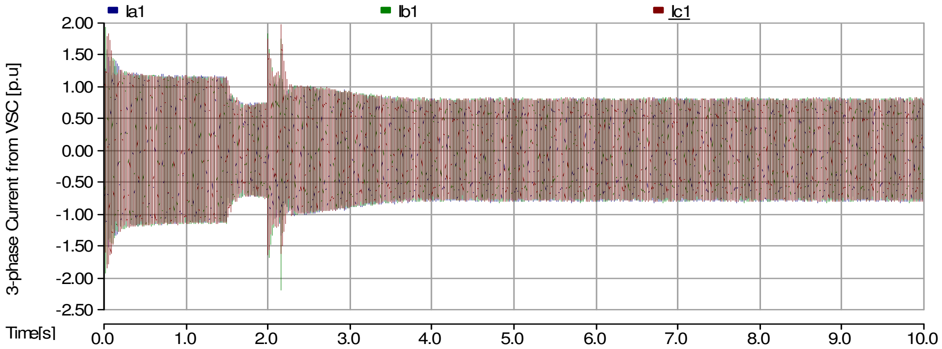


Figure 6.13(a) 3-phase current from VSC for three phase fault.

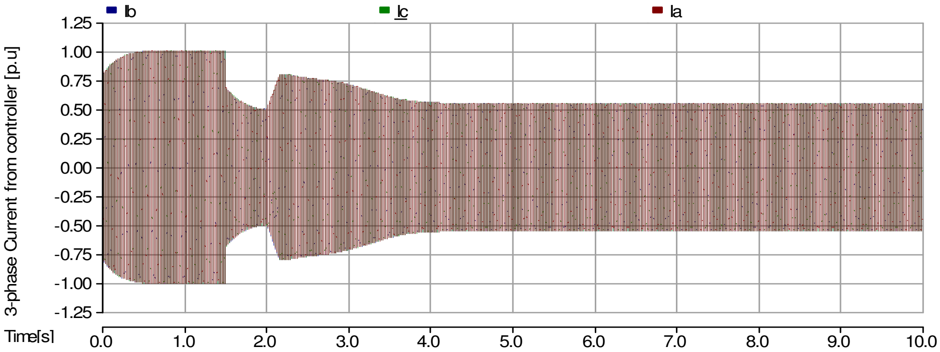


Figure 6.13(b) 3-phase current from controller for three phase fault.

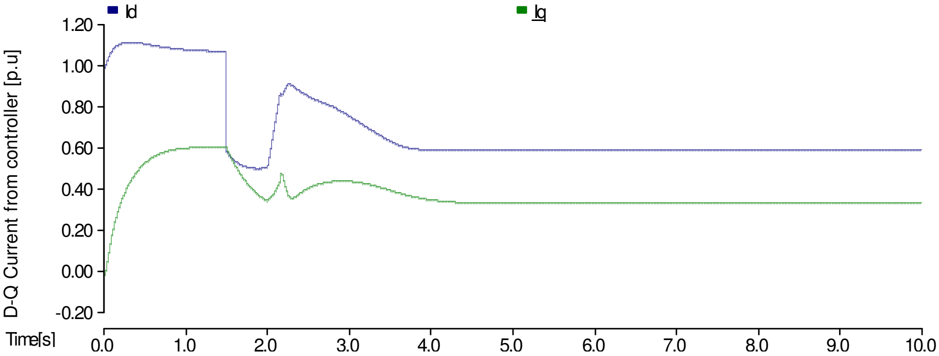


Figure 6.13(c) D-Q current from controller for three phase fault.

## Two phase fault

The two phase fault and single phase fault is described in section 4.5 according to Danish grid code. For two phase fault the grid code profile is prepared for simulation. The simulation is done in the following way:

(i) Start the simulation with Pref=1 p.u and Qref to 0 p.u.
(ii) At t=0.2 sec apply Danish grid code profile for two phase fault.

The voltage of the corresponding phases goes to zero when the fault occurs on that phase. This can be seen from the figure 6.14.

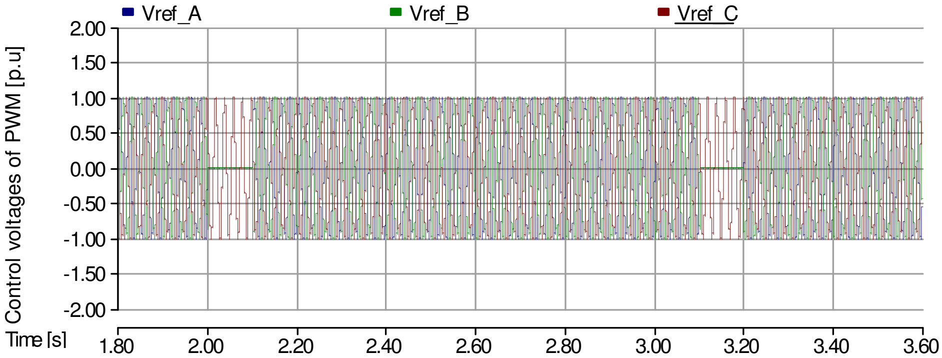


Figure 6.14(a) Control voltage for PWM for two phase fault.

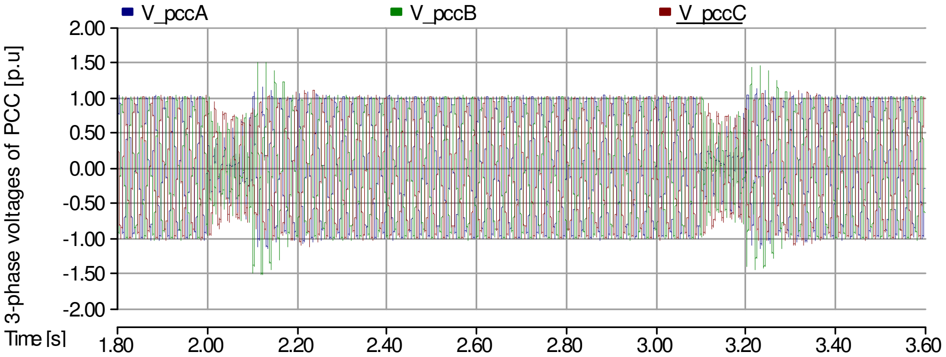


Figure 6.14(b) 3-phase Voltage at PCC for two phase fault.

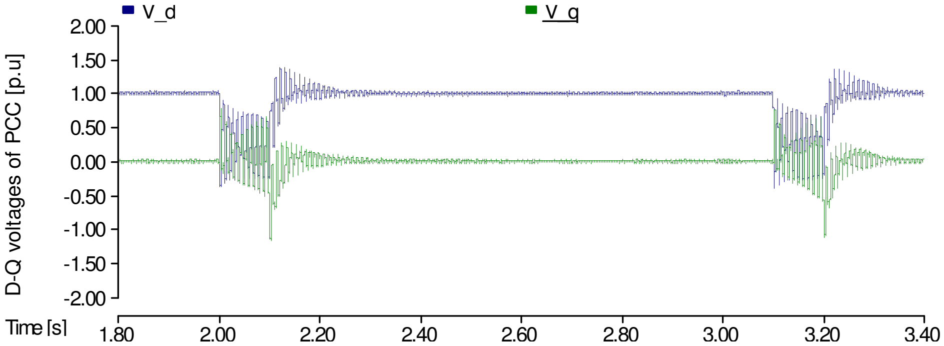


Figure 6.14(c) D-Q voltage at PCC  for two phase fault.

The current is increased when the fault is applied which is seen from the figure 6.15.

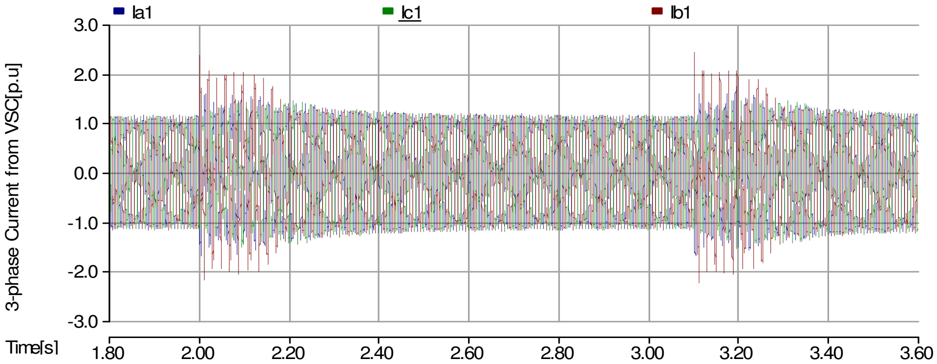


Figure 6.15(a) 3-phase current from VSC for two phase fault.

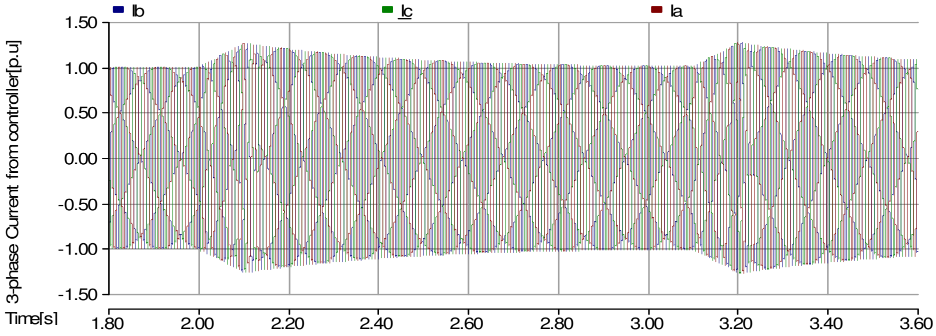


Figure 6.15(b) 3-phase current from controller current  for two phase fault.

When the fault is applied the active power goes down and the reactive power goes up at the same time. This can be seen from figure 6.16(a) and (b) respectively.

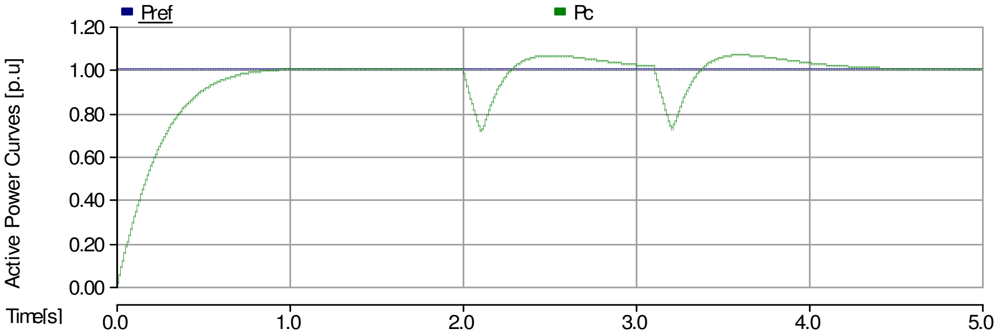


Figure 6.16(a)  Active power for two phase fault

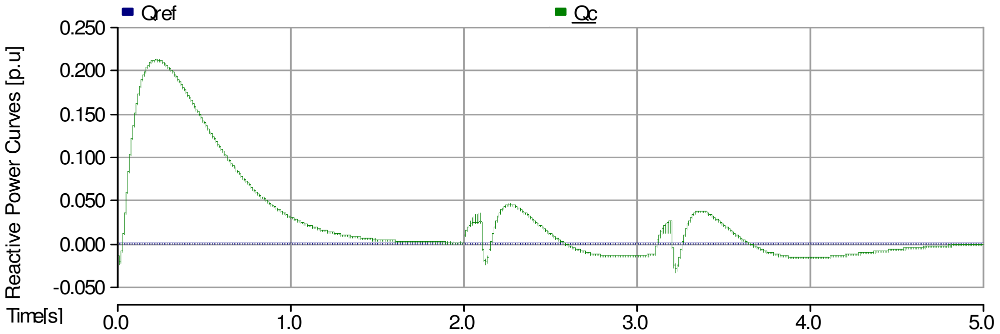


Figure 6.16(b)Reactive power curves for two phase fault.

### Single phase fault

As mentioned in the previous simulation, this simulation is also performed by Danish grid code profile for single phase fault, which is described in section 4.5. The simulation is carried out in the following way:

(i) Start the simulation with Pref=1 p.u and Qref to 0 p.u.
(ii) At t=0.2 sec, apply the grid code profile .

The voltage of the phase A is goes to zero when the fault is applied in this phase, which is shown in the figure 6.17(a).

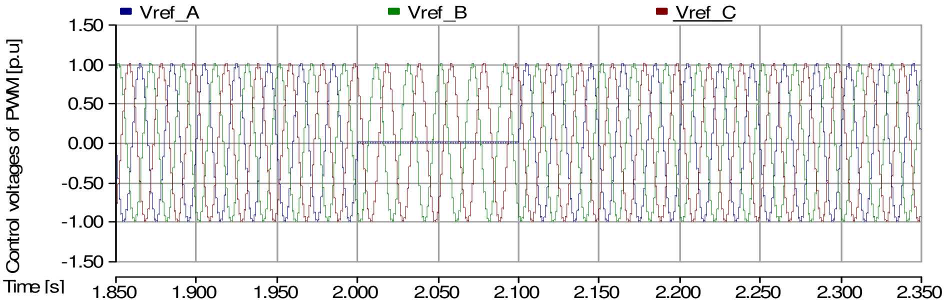


Figure 6.17(a) Control voltage for PWM for single phase fault.

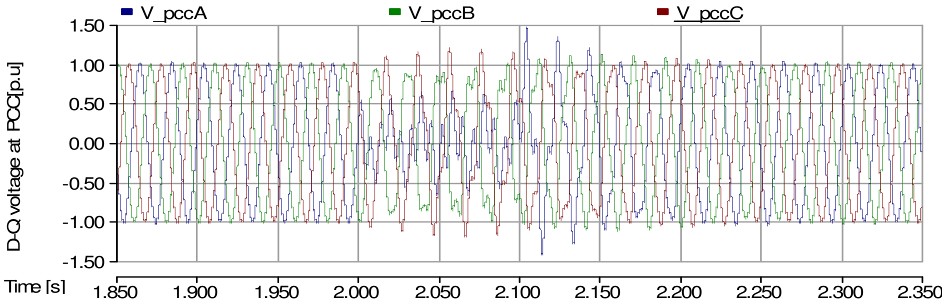


Figure 6.17(b) 3-phase Voltage at PCC for single phase fault.

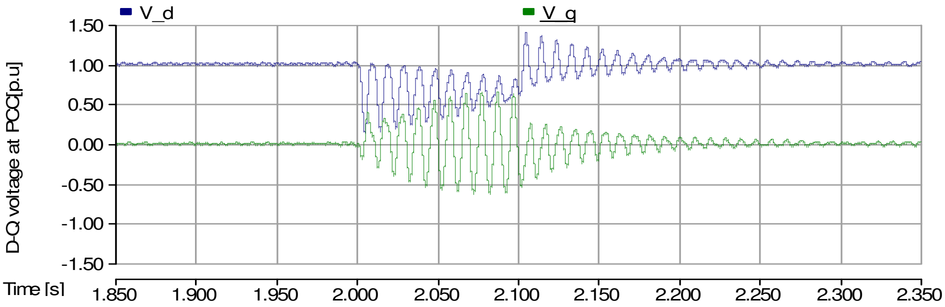


Figure 6.17(c) D-Q voltage at PCC for single phase fault.

The current from VSC and controller are shown in figure 6.18 (a) and (b) respectively. The current is increased as fault occurs in the system.

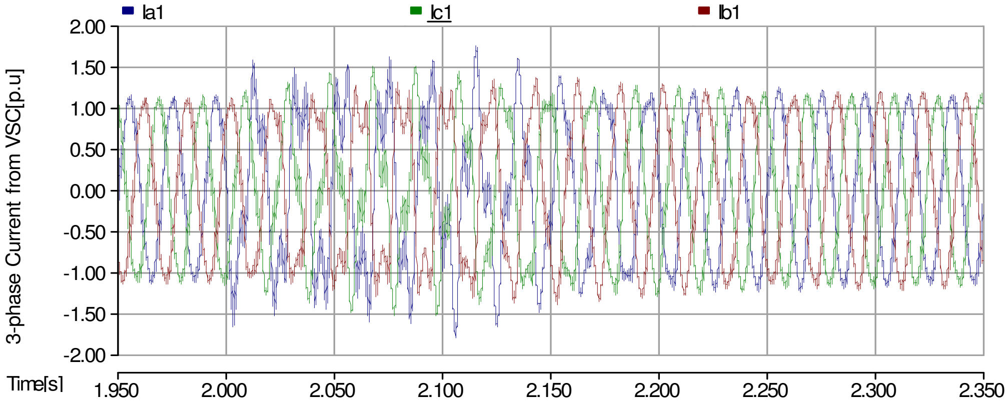


Figure 6.18 (a) 3-phase current from VSC for single phase fault.

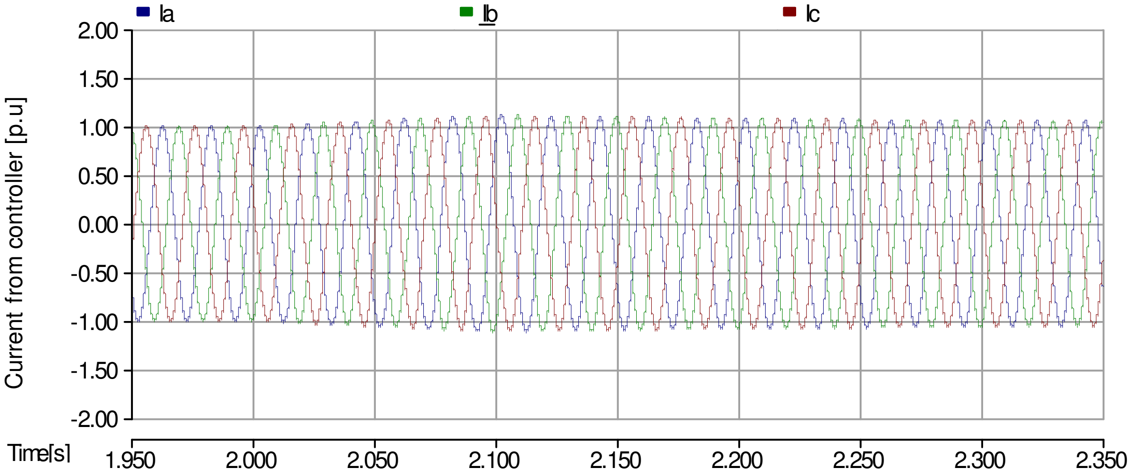


Figure 6.18(b) 3-phase current from controller current for single phase fault.

From the figure 6.19 of active and reactive power curve, shows clearly where the fault occurs. Because during that time the active power at PCC is going down and the reactive power is increased correspondingly.

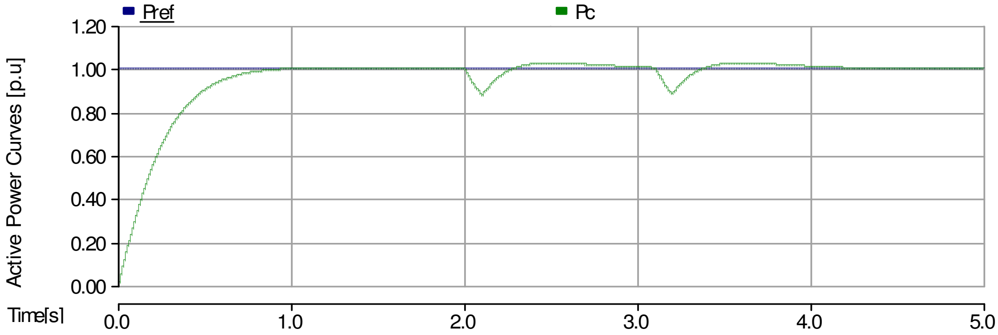


Figure 6.19(a) Active power for single phase fault.

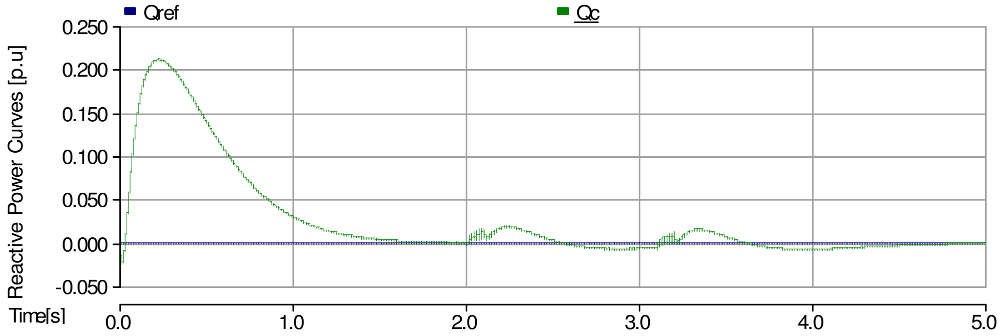


Figure 6.19(b) Reactive power curves for single phase fault.

## Case 5: Features of voltage and frequency change

In this case a frequency profile and a voltage as shown in figure 6.20(a) and (b) are prepared according to the grid code described in section 4.3.This case only deal with the continuous region A of the rectangle of figure 4.3 .The prepared profiles are implemented in the converter three phase signal generator block, where the voltage profile is multiplied with the magnitude of three phase signal and the frequency profile is multiply with the frequency of that signal to provide the variation on voltage and frequency of the converter output respectively.

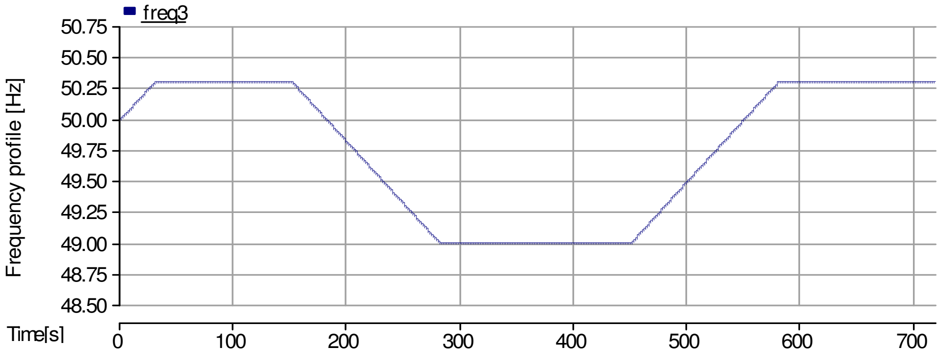


Figure 6.20 (a) Frequency profile .

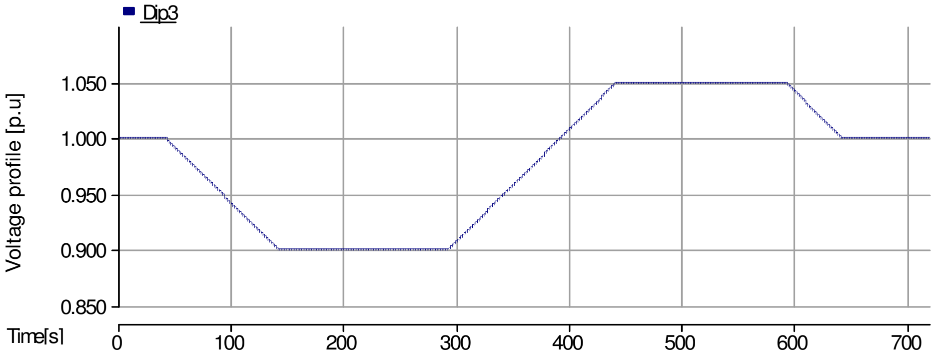


Figure 6.20(b) Voltage profile.

The figure 6.21(a) 3-phase Voltages at PCC and (b) D-Q Voltage at PCC .The effect of voltage variations can be seen from the figure. When the voltage from the converter side decreases or vice-verse, similar types of response can be seen from the voltage at PCC.

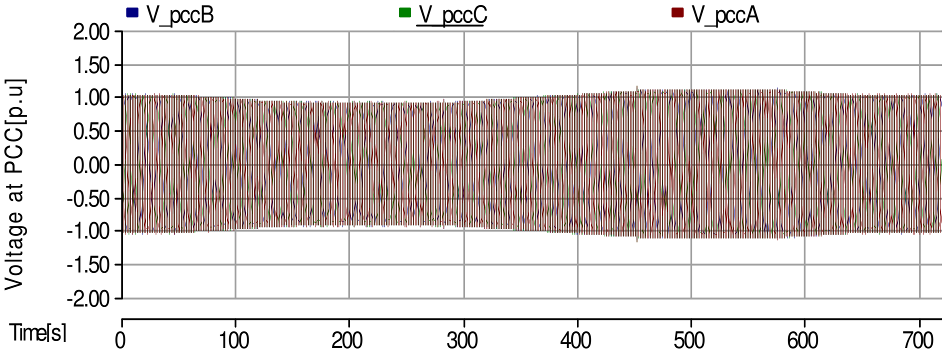


Figure 6.21 (a) 3-phase Voltages at PCC .

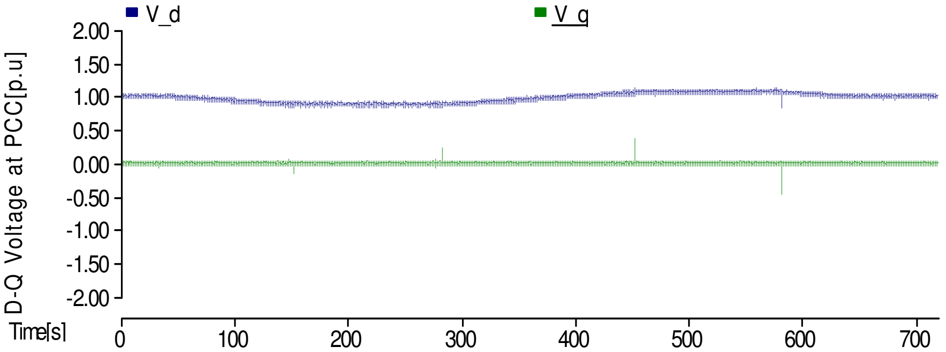


Figure 6.21(b) D-Q Voltage at PCC.

The figure 6.22 (a) represents the 3-phase output Current from controller and 6.22(b) represents the D-Q current through PCC. Observing the current curves it can be clearly seen that it behave opposite to the voltage curves of figure 6.20.This is because to maintain constant power flow at the PCC.

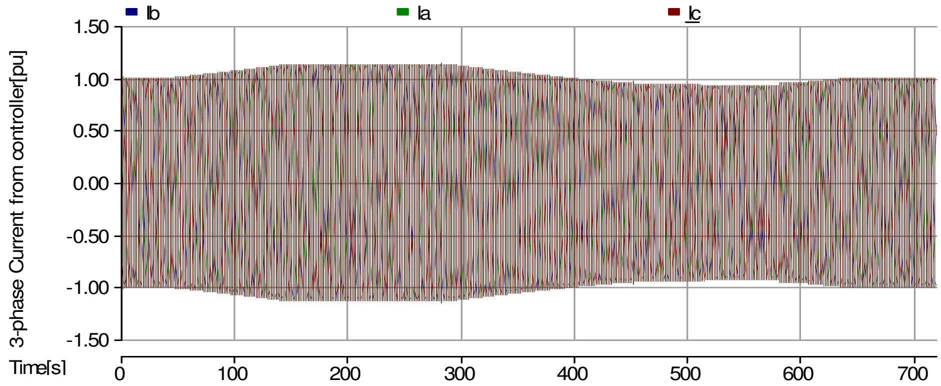


Figure 6.22 (a) 3-phase output Current from controller.

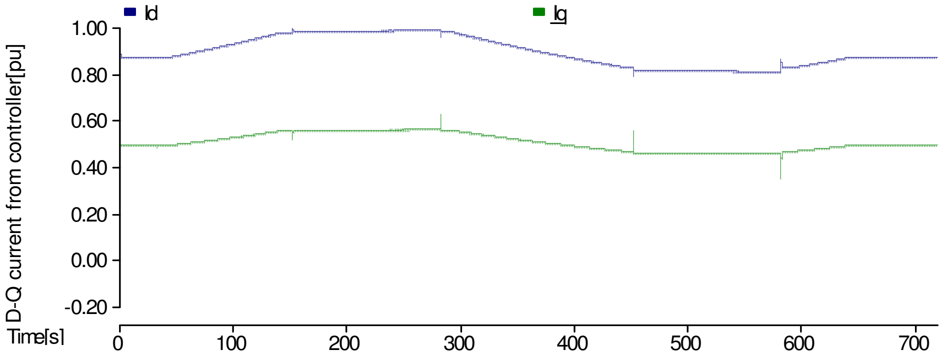


Figure 6.22(b)D-Q current through PCC.

From figure 6.23 the frequency variation and the respond from the test object can be observed. The frequency is measured when the system is running with the frequency of 51.5Hz.At that time the frequency of converter voltage and PCC voltage is measured and the result is found approximately 51.5Hz.So the converter and the load is running with the same frequency which is desired for stable operation of the system. It means that the PLL of the test object tracking the converter frequency and the test object working at the same frequency as the converter.

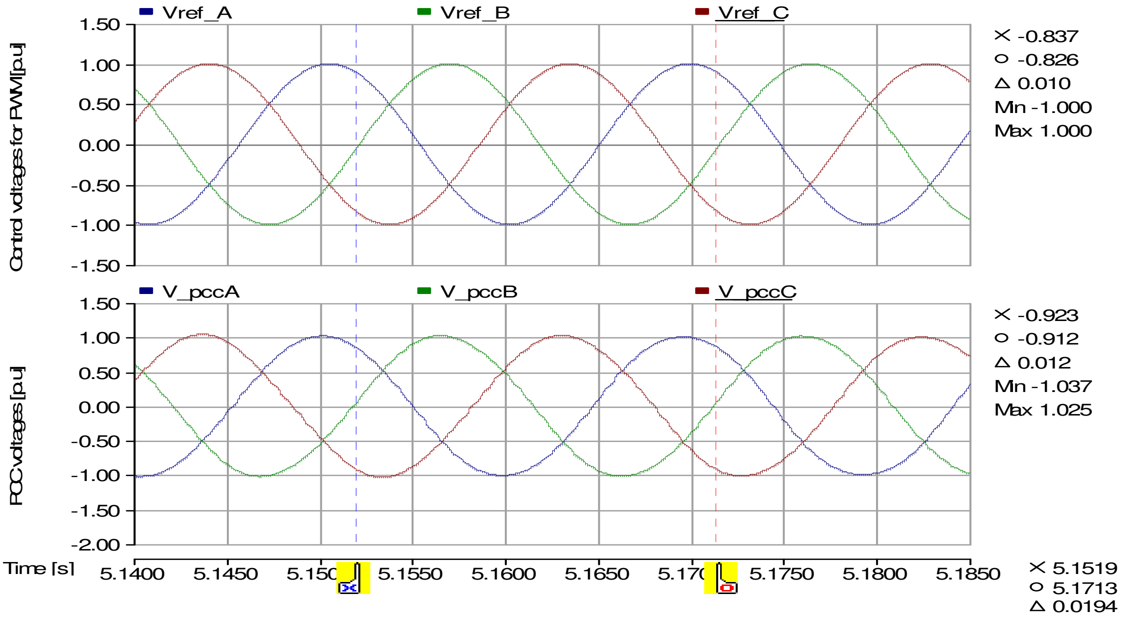


Figure 6.23 Frequency measurements of the converter voltage and the PCC voltage.

# Conclusion

In this project, a testing method is developed which will be feasible for a single wind turbine to test grid codes compliance  by using voltage source converter based test equipment, so that the wind turbines would become more efficient in normal and fault conditions in the grid. The test equipment consists of a voltage source converter that exhibits the characteristics of a grid. In practical case the test object will be a wind turbine connected to the grid through transformer and transmission line. For the simplicity of modelling and analysis a P-Q controlled test object is designed instead of the wind turbine. This kind of test object has the similar type of behaviour like a wind turbine in active and reactive power exchange with the grid. From the simulation results, it can be seen that different voltage and frequency variations can be applied to the test equipment according to grid codes by the voltage source converter. Moreover voltage source converter based test equipment can also provide the effect of fault on the grid side and from the behaviour of test object, the behaviour of wind turbine can be estimated connected to the grid during the faulty condition.

# Future Work

In this project, the whole system is implemented in PSCAD so one can realise the necessity to perform a laboratory test/ a real time simulation test in order to verify the obtained results and for different wind turbine topologies and wind conditions. This testing method is designed to test a single wind turbine but as the current system consists of wind farms/parks so a testing method can be designed to test a wind farm/park.

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