GRID SIDE CONVERTER CONTROL OF DFIG AND MITIGATION OF VOLTAGE SAG

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
In
Electrical Engineering
By
Satish Kumar Patnaik
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DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA-769008,

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Dedicated

To

My Parents

Sarat Kumar Patnaik

&

Sudharani Patnaik

CERTIFICATE

This is to certify that the thesis entitled, **“GRID SIDE CONVERTER CONTROL OF DFIG AND MITIGATION OF VOLTAGE SAG”** submitted by **Mr. Satish Kumar Patnaik** in partial fulfilment of the requirements for the award of Degree of Master of Technology in **ELECTRICAL ENGINEERING** with specialization in **“INDUSTRIAL ELECTRONICS”** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

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Abstract

Now days wind power energy is playing a major role in power industry. With the increase in application of wind power variety of new topologies are coming into picture. Among the different form of variable speed fixed frequency topologies DFIG is most popular form due to its efficiency and ability to allow wide range of speed variation at reduced converter size.

Doubly Fed Induction Generator (DFIG) is basically a wound rotor induction generator which is used to fed power from both stator and rotor circuit. Stator feeds power directly to grid which is unidirectional. Rotor circuit is connected to a bidirectional ac/dc/ac converter having a common dc link bus. In rotor, power flow is bidirectional i.e. depending on the mode of operation the power flow is either from rotor side to grid or it may be from grid side to rotor. The rotor side converter also fed reactive power to DFIG so as it can run at a near unity power factor. The function of the grid voltage converter is to maintain the DC link voltage constant, which ultimately fed a constant amplitude ac voltage to rotor side for maintaining the flux constant.

But when grid voltage variation occurs, the dc link voltage also varies, ultimately rotor input voltage varies. This causes abnormal input of reactive power to rotor circuit. So to maintain the reactive power demand of machine, it draw reactive power from grid' Which may lead to a condition of voltage fluctuation at PCC. One solution to this problem may be compensation of grid voltage variation before grid converter circuit. This compensation of voltage sag is done by a custom power device, known as Dynamic Voltage Restorer (DVR).

The current Topic discusses about the application of DVR to DFIG to compensate voltage sag of grid so that the voltage of DC link will remain constant.

LIST OF FIGURES

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LIST OF SYMBOLS

P_o	Power contained in wind
P_m	Power output of the wind turbine
ρ	Air density in Kg/m3= 1.225 Kg/m
A	Effective swept area created by the rotor revolution
V_o	Wind speed in m/sec
C_p	Power co-efficient
P_s	Stator circuit active power
Q_s	Stator circuit reactive power
P_r	Rotor circuit active power
Q_r	Rotor Circuit reactive power
f_{STATOR}	Frequency of stator
f_{ROTOR}	Frequency of rotor.
P_m	Mechanical Power input to DFIG
P_{ag}	Power available to rotor i.e. air gap power
s	Slip of rotor
ϕ_{ds}	d-axis stator flux component
ϕ_{qs}	q-axis stator flux component
ϕ_{dr}	d-axis rotor flux component
ϕ_{qr}	q-axis rotor flux component

$\mathbf{L_{ss}}$	Stator inductance
$\mathbf{L_{rr}}$	Rotor inductance
$\mathbf{L_m}$	Magnetisation inductance
$\mathbf{R_s}$	Stator effective resistance
$\mathbf{R_r}$	Rotor Effective resistance
$\mathbf{V_{ds}}$	d-axis stator voltage component
$\mathbf{V_{qs}}$	q-axis stator voltage component
$\mathbf{V_{dr}}$	d-axis rotor voltage component
$\mathbf{V_{qr}}$	q-axis rotor voltage component
$\mathbf{V_{dg}}$	d-axis grid voltage component
$\mathbf{V_{qg}}$	q-axis grid voltage component
$\mathbf{I_{dg}}$	d-axis component of grid current
$\mathbf{I_{qg}}$	q-axis component of grid current
$\mathbf{L_g}$	Grid filter Inductance
$\mathbf{R_g}$	Grid filter resistance
$\mathbf{P_g}$	GSC input active power from grid side
$\mathbf{Q_g}$	GSC input reactive power form grid side
$\mathbf{V_{dc}}$	DC link voltage
C	DC link capacitor
$\mathbf{V_{inj}}$	Injected voltage by DVR during sag
VSI	Voltage source inverter

$\mathbf{V_{sc}}$	Voltage across super capacitor
$\mathbf{L_{smes}}$	Inductance Rating of SMES
$\mathbf{I_{smes}}$	Current through SMES
$\mathbf{J}$	Moment of inertia of Flywheel
$\boldsymbol{\omega_{fw}}$	angular velocity of Flywheel

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Few decades before, most of the research in power system was going on the development of conventional energy based power generation. But the issues like international oil crisis, limited availability of conventional sources and environmental pollution effect forced the researcher to think about an alternative source of energy that can be the solution for the above issues. The renewable energy sources like wind energy, solar energy, tidal energy etc. can be a possible solution to this. Renewable energy is derived from natural processes that are replenished constantly. All these sources are plentifully available in nature, are recyclable and almost available free of cost.

Wind power, as an alternative to fossil fuels (such as coal, natural gas etc.), is available plentifully, renewable, widely distributed, clean, produces zero greenhouse gas during operation and uses little land for its installation. This technology is not new to the human beings. Wind power has been used as long as humans have put sails into the wind. For more than two millennia wind-powered machines have ground grain and pumped water. It was the year 1887 when wind power was first time used for producing electricity. After that wind energy was used to produce power at small scale. It was the year 1973, when the oil price crisis accelerated the investigation of non-petroleum energy and researchers started doing research on wind based power generation for bulk use.

According to the report of “ENERGY STATISTICS 2013”, the total installed capacity of wind power generation in India as on 31.03.2012 is estimated to be 49130MW which is around 54.73% of the total installed renewable energy capacity.

Wind power generation technology faces many challenges like selection of topologies for wind power generation, mode of operation, control, power quality issues etc. Wind based power station can be work in both in isolated mode as well as grid connected mode. This current project is based on the wind power generation in grid connected mode. There are basically four type of wind generator topology such as fixed speed, semi-variable speed, fully variable speed with partial rated frequency converter and fully variable speed with full rated frequency converter. The focus of this project is on the application of doubly fed induction generator (DFIG) in wind power generation, which is basically a fully variable speed generator having a partial rated frequency converter.

1.2 MOTIVATION BEHIND THIS PROJECT

When a DFIG is connected to the grid and supplying power, many issues come into picture which may affect the working of this generator. The measure issues are sudden wind gust, grid abnormalities such as voltage sags, swells, frequency variation etc.

The effect of wind gust could be probably seen as the stator frequency and voltage fluctuation. But DFIG is quite able to handle this problem by adjusting frequency of rotor injected source. Along with the DFIG convThe turbine control schemes like pitch control scheme, Yaw control etc. are used to compensate these fluctuation up to some extent.

But what about grid abnormalities? Grid abnormalities can lead to serious problems like torque pulsation, reactive power pulsation, abnormal current and mechanical stress on generator, gear box and sometime also on wind turbine. So the major question is how to control DFIG based wind generation during grid abnormalities. This problem encourages me to choose this issue as my research objective.

1.3 OBJECTIVE OF THIS PROJECT

The main objectives of this project are listed as follows:

- Study the basic DFIG scheme
- Study and analysis of Grid converter control scheme
- Study and analysis of effect of voltage disturbances on grid converter
- Study of Voltage Sag mitigation scheme
- Study of energy storage device for wind power application

1.4 LITERATURE REVIEW

- From [1] studied the overview of DFIG. Particularly this paper shows, how with the change of rotor voltage the DFIG operation can change from super sysnchronous to sub synchronous mode.
- From [2] we have studied the basics of DFIG. This paper first dicusses about the various topologies of adjusted speed generators. Then it discussed about the DFIG in detail
- From [3] & [4] gives the basic modelling concept of DFIG . Then a brief discussion on simple vector control scheme is discussed.
- From [5]: This paper works on a DFIG of 2MW rating. We have use this paper as the reference for our DFIG parameters
- From [7] & [11] this paper gives a introduction to DFIG control scheme. We have followed this paper as a reference for analysing grid converter control scheme.

- From [8] & [10] We have studied the concept of Dynamic Voltage Regulation control.
- From[9] We got the fundamental concept of various energy storage devices available commercially. This paper also shows a comparison of various energy storage device.
- From[12] and [13] , mechanical aspect of wind turbines and various wind firsm topology has been studied.
- From [14] and [15] concepts like SVPWM switching, Vector axis orientation are studied.

1.5 THESIS OUTLINE

The thesis is organised as follows:

- Chapter 2 discussed about the basic wind power principle. It also discuss about various wind generator topologies and wind turbine control schemes.
- Chapter 3 focuses on the principle of DFIG. It also discusses about rotor converter control scheme and a brief discussion on grid converter control scheme.
- Chapter 4 discusses about the detail discussion on grid converter control. It also highlights the issue of voltage sag on grid converter.
- Chapter 5 is about the sag mitigation technique using DVR. This chapter show, how DVR is used to compensate the deficit voltage during SAG.
- Chapter 6 shows the simulation results of this project. It also draw a conclusion of the project and the scope for future work.

CHAPTER 2

WIND POWER PRINCIPLE

WIND POWER PRINCIPLE

2.1 INTRODUCTION:

Wind power is a good renewable, clean and free source of energy for power production. The air flow on earth is created due to the atmospheric air mass as a result of variation of air pressure. This difference in air pressure results due to difference in solar heating of different parts of the earth's surface.

The kinetic energy of air in motion is known as wind. This wind energy when comes in contact with wind turbine blades, it exert force on the blades which makes the turbine to rotate. This means wind turbine converts the kinetic energy of air into mechanical energy which is further used to convert it into electrical energy by means of a generator coupled to it. Generally wind turbines have much lower operating speed than the rated speed of electric generator. To compensate this mismatch gear box is used in between turbine and generator i.e. generator is coupled to turbine through this gear box.

The whole arrangement of gear box, power generator and other auxiliary devices like drive train and brake assembly are kept in a housing called Nacelle. Nacelle along with turbine hub connected with turbine blades is kept at certain height from the ground by the help of tower to maintain certain ground clearance for safe operation. In general for medium and large turbine the height of the tower is generally chosen such that it will slightly greater than the rotor diameter. But for the smaller turbines, towers are much taller as compared to their rotor diameter.

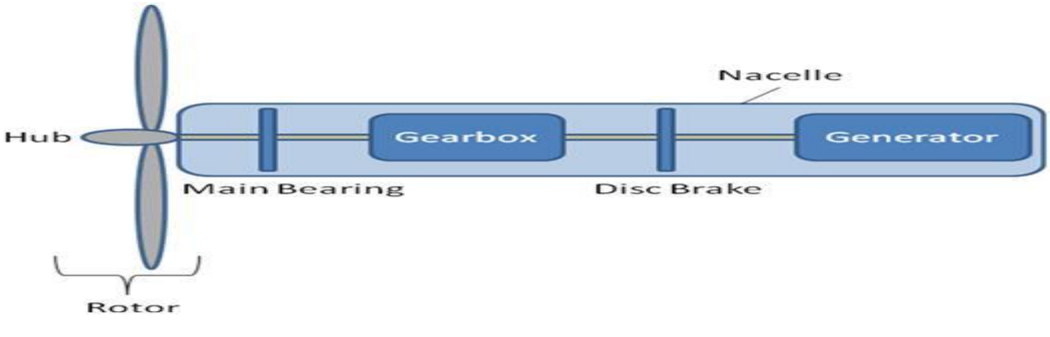


Fig 2.1 Components Present Within Nacelle

2.2 WIND POWER TOPOLOGY:

Many types of wind turbines are available commercially. These are classified as shown in the figure below.

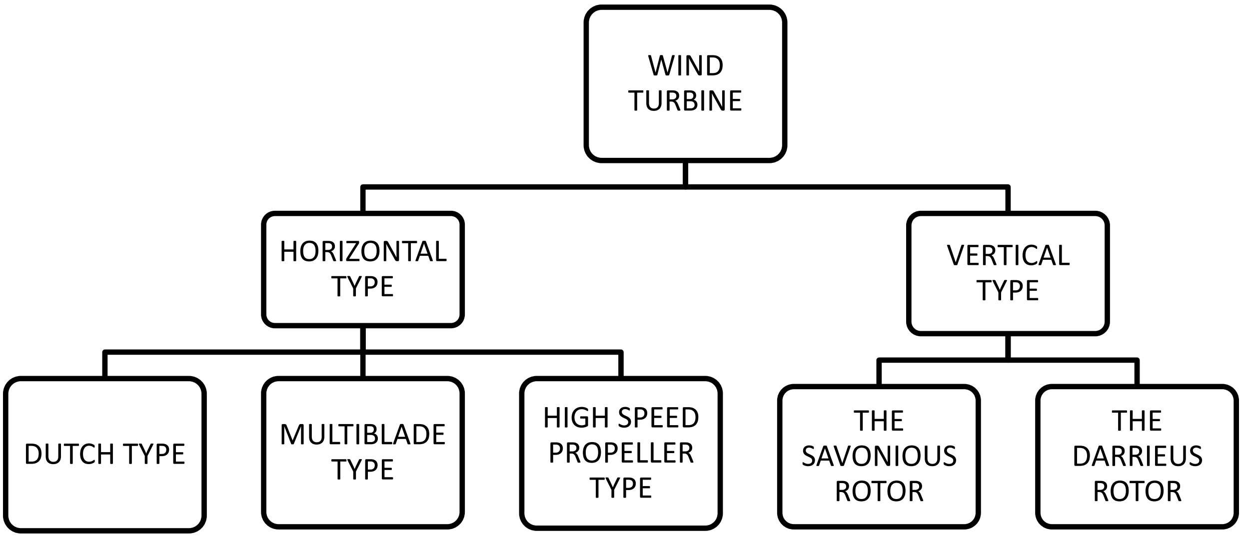


Fig 2.2 Wind Turbine Classification

The turbines can also be classified as (I) Thrust Operated Turbine and (II) Aerodynamics operated Turbine. Dutch type, Multi blade type and the Savonious type turbines came under former category while high speed propeller type and the Darrieus type turbines are categorised under the latter one. Thrust operated type turbines produce more torque, hence used for water pumping process. But for generation of electricity we need turbines which produce high speed. Turbines which are having aerofoil type blades produce very high speed due to aerodynamic principle. Among these all high speed aerodynamic type turbines propeller type turbines are most efficient ones. Hence these are generally used for wind power generation purpose.

Wind power generation can be operated in two types of modes:

1. Fixed Speed Mode
2. Variable speed mode.

In fixed speed mode, the rotor is bound to run at one fixed speed to to get the desired output frequency. Any change in wind speed will reflect as a change in frequency of output. They are designed to give maximum efficiency at one particular speed. The main disadvantages of this type operation are that it consumes reactive power in uncontrolled manner, it exerts mechanical stress and it has limited power quality control.

In variable speed operation, maximum efficiency can be achieved at wind range of wind speeds. These are used to give constant out frequency operation even if the input wind speed changes. But in these topology uses complicated electrical circuits to feed power to the grid.

Base on the above two modes of operation, the electrical generator are connected in four ways, which are classified as Type-A, Type- B, Type- C and Type- D system.

2.2.1 Type-A: Fixed Speed System

Type- A topology is a fixed speed topology. It generally employees squirrel cage induction generator (SCIG) or synchronous generators for its operation. The stator circuit, in this type of topology is directly connected to grid (Sometimes through a soft starter to minimize inrush current). When SCIG is used, an additional capacitor bank is required to feed its reactive power demand. But when fluctuation in wind speed occurred (application of sudden wind gust), this fluctuation, changes the speed of the rotor and hence the fluctuation in output frequency and voltage fluctuation can be seen, which is highly undesirable for electrical loads. This will also draw uneven amount of reactive power from grid, which increases voltage fluctuation in grid. So this topology required a stiff grid for its operation.

2.2.2 Type-B: Limited Variable Speed System

This type of topology uses a wound rotor induction generator (WRIG) whose rotor circuit is connected to a variable resistor bank. The generator is also directly connected to grid through a soft starter and also use capacitor bank for its reactive power demand. Whenever wind speed changes, by adjusting the rotor resistance value the output frequency can be maintained fixed. The range of the speed control depends on the value of this resistor bank. The main disadvantage of this type topology is that, it dumps the extra power to the resistor which dissipated as heat loss. The speed range for this topology is 0 to 10% above the synchronous speed.

2.2.3 Type-C: Variable Speed with Partial Scale Frequency Converter System

This configuration is also known as doubly fed induction generator topology, which use a WRIG for its operation. In this topology, stator side is directly connected to grid whereas rotor circuit is connected to grid through a bidirectional frequency converter. Typical rating of this converter is 20 to 30% of the actual machine rating. The speed range for this topology is -40% to +30% around the synchronous speed, that means it can generated power in both super synchronous and sub synchronous mode. Its main disadvantage is that it uses slip rings which may lead to sparking problem as the machine rating increases.

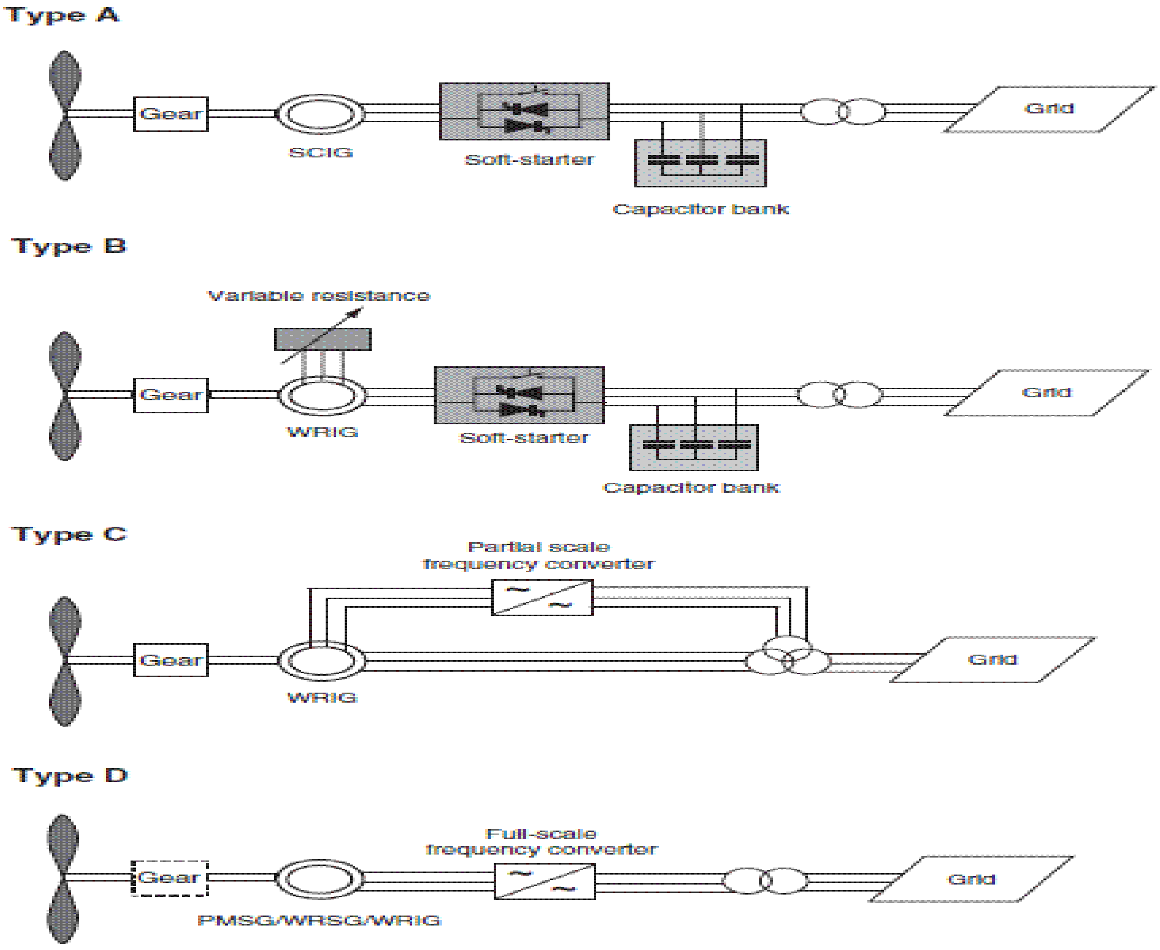


FIG 2.3 Wind Generator Integration Topologies

2.2.4 Type-D: Variable Speed with Full Scale Frequency Converter System

This topology uses SCIG, Synchronous Generator or Permanent magnet synchronous generator (PMSG) for this operation. In this topology the stator of the generator is connected to grid through a full scale frequency generator. The frequency converter also performs the task of reactive power compensation.

2.3 MECHANICAL ASPECT OF WIND ENERGY

The power contained in wind is defined as the kinetic energy exerted in wind per unit time.

This can be formulated as

$$\mathbf{P_o = \frac{1}{2}\rho A V_o{}^3}$$

But the power that can be converter for useful work is limited by a factor called “Betz Limit” which is 0.5925 or 59.25%. That means maximum efficiency that can be achieved is 59.25% .

Maximum power available at the turbine output is given by

$$\mathbf{P_m = \frac{1}{2}\rho C_p A V_o{}^3}$$

Where C_p is called power coefficient which depends on the pitch angle and tip speed ratio (TSR). We can achieve maximum power by operating the turbine at $C_{p,opt}$. For different values of pitch angle, when we draw curves between Cp vs TSR it will be as shown in the figure below.

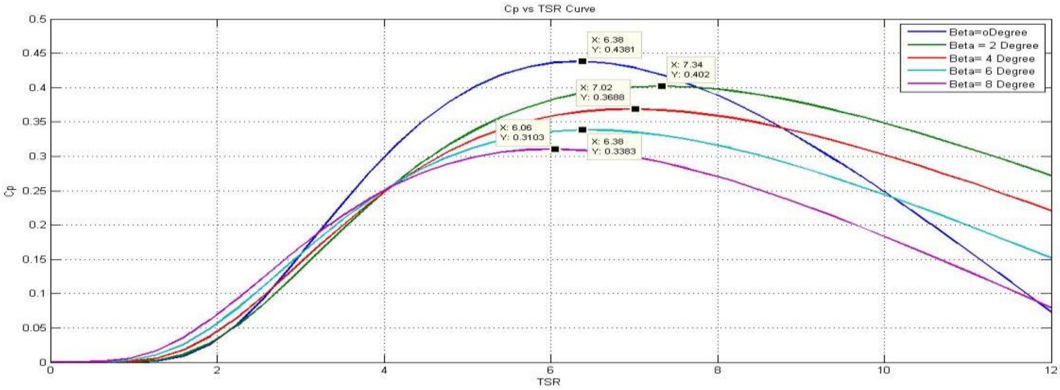


Fig 2.4 Cp vs TSR Characteristic Curve

In the above figure, it can be seen that with increase in the value of pitch angle the optimum value of Cp is decreasing. So in other words we can say with increase in the value of pitch angle, the turbine power decreases and beyond certain value of pitch angle the power output becomes zero. This is the principle of stall control, which is utilized to cut-off power generation of generator when wind speed goes beyond the furling wind speed or cut-off wind speed.

The turbine has also has a lower limit of wind speed requirement, below which it cannot produce any power. This speed of wind is called cut in speed. Beyond this speed up to the rated speed the power of the turbine varies with the cube of wind speed. In fixed speed device after the rated speed till the cut-off speed the power output remains constant. Here pitch control method is employed to make the output power constant by adjusting the $C_{p,opt}$ and TSR value. But for certain variable speed wind turbine schemes power can be generated beyond the rated speed, however power generation will be stopped when speed reaches cut-off speed.

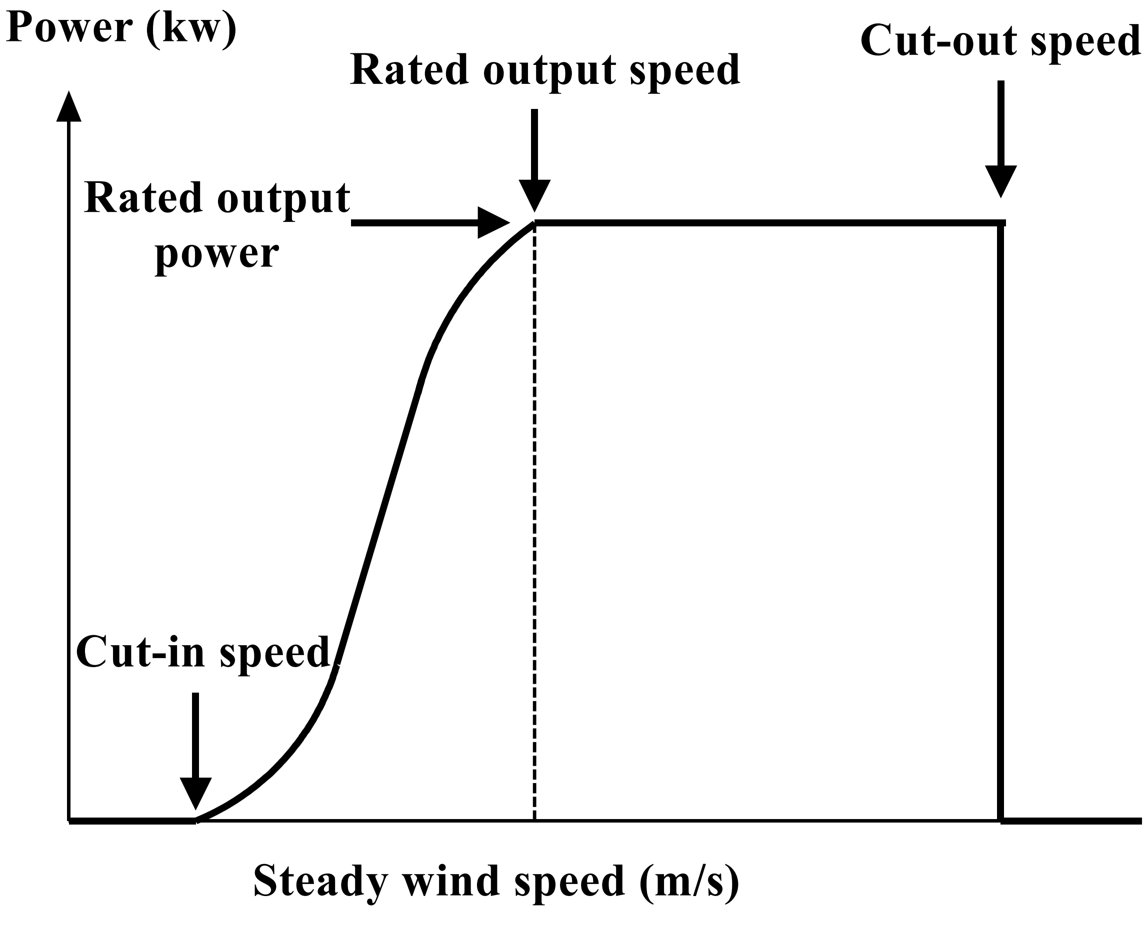


Fig 2.5 Wind Turbine Characteristic- Power Vs Wind Speed Characteristic

2.4 WIND TURBINE CONTROL SYSTEM

Due to changing environmental effect, wind speed always varies. Also wind direction is not same in all time. To extract optimum power from wind generation system with changing wind condition various control schemes are used. This control scheme may include the control of turbine and control of electrical generator scheme.

Various control schemes are used for wind turbines. These schemes are

1. Pitch Angle Control
2. Stall Control
3. Power Electronic Control
4. Yaw Control

2.4.1 PITCH ANGLE CONTROL

In pitch angle control scheme, the pitch angle of the blades of the wind turbine changes with the variation of wind speed to achieve of maximum efficiency. This is done by adjusting the rotor position of the pitch angle actuator which is connected with the rotor blade. The block diagram of pitch angle control system is as shown in the figure below.

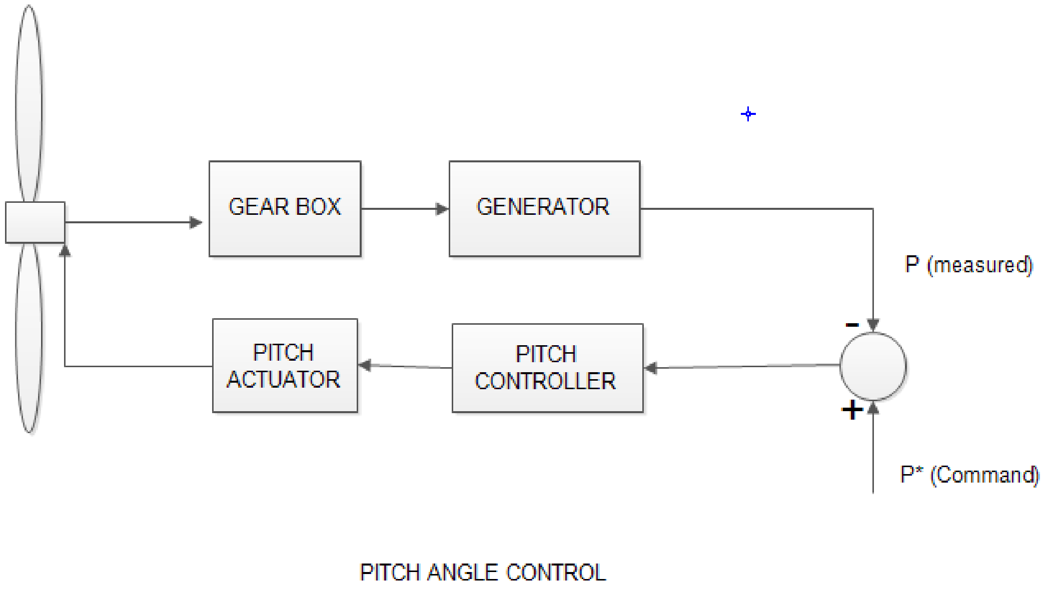


Fig 2.6 Pitch Angle Control

2.4.2 STALL MODE CONTROL

In this type of control scheme, at high wind speeds, turbine blade is rotated by a few degrees in opposite direction to that in a pitch control scheme. This is done to achieve constant rated power at a high wind speed ranging from speed above its rated speed up to the furling speed.

2.4.3 POWER ELECTRONIC CONTROL

In this control scheme the electrical load of the system is dynamically controlled without doing any adjustment in mechanical power. This instantaneous change in power lead to change in speed and by this we can achieve the desired speed without the implementation of any mechanical control scheme.

2.4.4 YAW CONTROL

In this control scheme, with the change in direction of wind flow the turbine is oriented to get maximum power. In small turbines, tail-vane is used to achieve this yaw control scheme while in large turbines special yaw motors are used. This yaw motor is connected to the nacelle and it used to move the whole turbine hub and nacelle in the direction of wind flow.

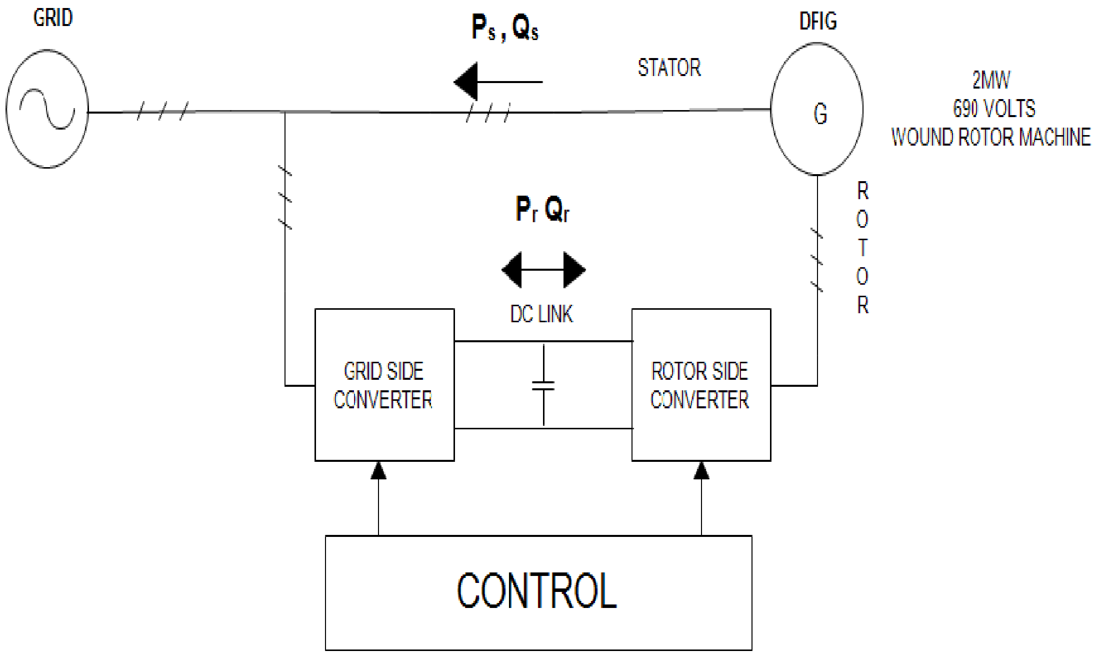
CHAPTER 3

DOUBLY FED INDUCTION GENERATOR

DOUBLY FED INDUCTION GENERATOR

3.1 INTRODUCTION

When a wound rotor induction machine (WRIM) works as a generator and fed power from both stator and rotor side, it is termed as Doubly Fed Induction Generator (DFIG). DFIG scheme is used as a variable speed fixed frequency topology. In this scheme, stator is directly connected to the grid while the rotor circuit is connected to grid through an AC/DC/AC back to back frequency converter. The rating of this converter is typically 25-30% of the total power rating of the generator. This is the main advantage of DFIG over other variable speed topologies as it provides same features at lesser cost and provides good efficiency. The following figure shows a typical DFIG configuration.



BASIC CONFIGURATION OF DOUBLY FED INDUCTION GENERATOR (DFIG)

Fig 3.1 DFIG Configuration

P_r and Q_r are the rotor active and reactive power and P_s and Q_s are the stator active and reactive power respectively. In the above figure we can see that the power flow in stator side is unidirectional i.e. from stator to grid. But the power flow in rotor circuit is bidirectional i.e. either from grid to rotor or rotor to grid. Usually the deviation in power due to wind fluctuation is managed through this rotor circuit. So the power rating of this circuit along with the converters is less compared to the main machine rating (Usually 20-30% of the machine rating).

3.2 WORKING PRINCIPLE

Whenever a fixed speed squirrel cage induction generator is subjected to variable wind speed, its rotor speed changes with the change in wind speed. As it cannot be compensated by any means (there is no provision for power to flow from rotor side), so this change in rotor speed reflects as a change in frequency of output (i.e. Stator frequency). It can be expressed by the following formula:

$$f_{\text{STATOR}} = \frac{\text{ROTOR SPEED X NUMBER OF POLES}}{120}$$

It can be seen that, with variation of rotor speed stator frequency varies, which is undesirable. The solution to the problem is the use of variable speed fixed frequency generators. DFIG is a popular form of variable speed generator whose stator frequency is given by the following formula:

$$f_{\text{STATOR}} = \frac{\text{ROTOR SPEED X NUMBER OF POLES}}{120} \pm f_{\text{ROTOR}}$$

From the above equation it can be seen that, even if the rotor speed varies, by the adjustment of rotor frequency properly we can get a constant stator frequency. This is the principle of DFIG.

When the generator is in super synchronous mode i.e. when it is running above synchronous speed, then to maintain the rotor frequency at constant value, we have to add a negative frequency component ($-f_{\text{rotor}}$). Here negative components means, power is delivered by the rotor to grid. Similarly when the generator is running at a speed less than the synchronous speed we have to add a positive rotor frequency ($+f_{\text{rotor}}$), so as to maintain the stator frequency at a constant value. During synchronous speed the rotor frequency will be zero that is a pure dc is fed to rotor. Hence we can say that in synchronous speed, DFIG will act as a synchronous generator.

In other words we can say that, when turbine speed goes beyond the synchronous speed, energy content of rotor increases, which tries to speed up the rotor. But by help of a proper control scheme in DFIG this extra power in rotor is extracted and fed to grid, hence the rotor speed as well as the output frequency remains constant. This operational mode is called super synchronous mode in which power flow in rotor circuit is from rotor side to grid side. Similarly during sub synchronous mode, when rotor tries to slow down, power is fed to it and it exerts motoring action to maintain its speed at synchronous speed and hence in this mode the power flow is from grid side to rotor side. The power flow direction of DFIG in both super synchronous and sub synchronous mode is as shown in the figure below.

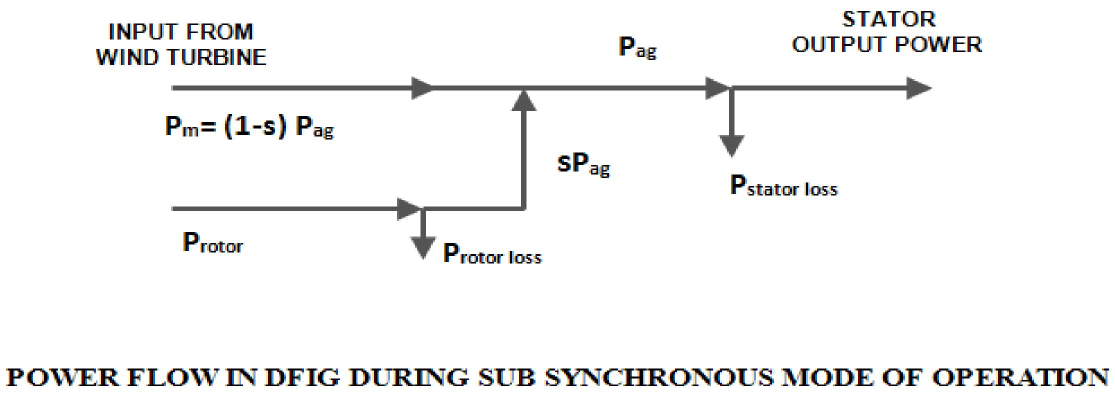


Fig 3.2 Sub Synchronous Power Flow in DFIG

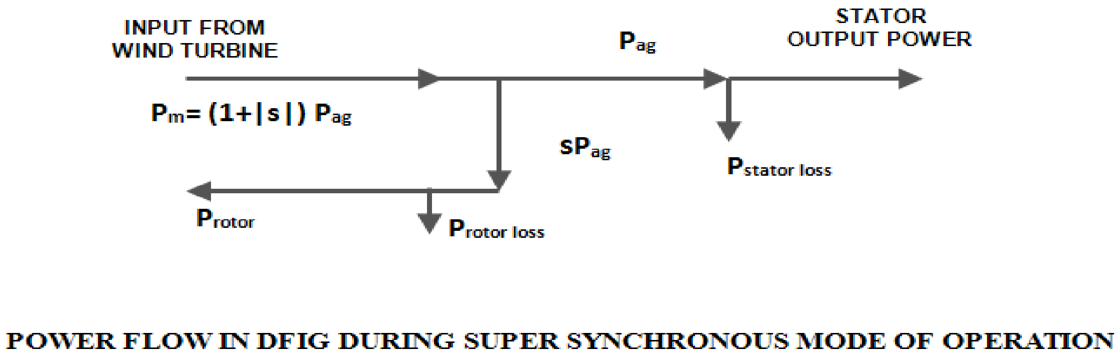


Fig 3.3 Super Synchronous Power Flow in DFIG

3.3 MODELLING OF DFIG

DFIG is basically a WRIG which has a stator and rotor circuit. Stator circuit of the DFIG consist of stator frame, laminated stator core having stator slots embedded in it and a balanced 3 phase windings placed 120 degree electrically apart from each other. The winding distributed in nature, are insulated and are housed in the stator slots. Stator windings may be connected in delta or star manner.

Rotor circuit consist of rotor, rotor slots and a 3 phase insulated winding. These 3 phase winding is uniformly distributed .These windings are connected to one end to form star connection and on the other side connected to slip rings.

The stator circuit is connected directly to grid (or sometimes through a soft stator to minimize the high inrush current). Rotor circuit is connected to grid through a bidirectional AC/DC/AC bidirectional converter.

The bidirectional AC/DC/AC converter is consists of two, 2 level full bridge converters connected in cascade by means of a DC bus. The converter which is connected to rotor side of machine is called rotor side converter (RSC) and converter which is connected to grid side is called grid side converter (GSC). This converter depending on the mode of operation (Sub synchronous or synchronous mode) may act as rectifier or inverter. When one converter behaves as rectifier then other one behaves as inverter and vice versa. The switches used in these converters require high speed operation. So typically IGBT switches are used for this purpose. The following figure shows a typical IGBT based converter circuit.

The main purpose of RSC is to supply voltage to rotor circuit and to control rotor current such that the rotor flux will optimally oriented towards the stator flux in order to produce the desired torque.

The main purpose of GSC is to regulate the DC link voltage. Apart from that, it is sometimes help to improve the power quality of grid at the point of common connection (PCC) by feeding reactive power during reactive power fluctuation in grid.

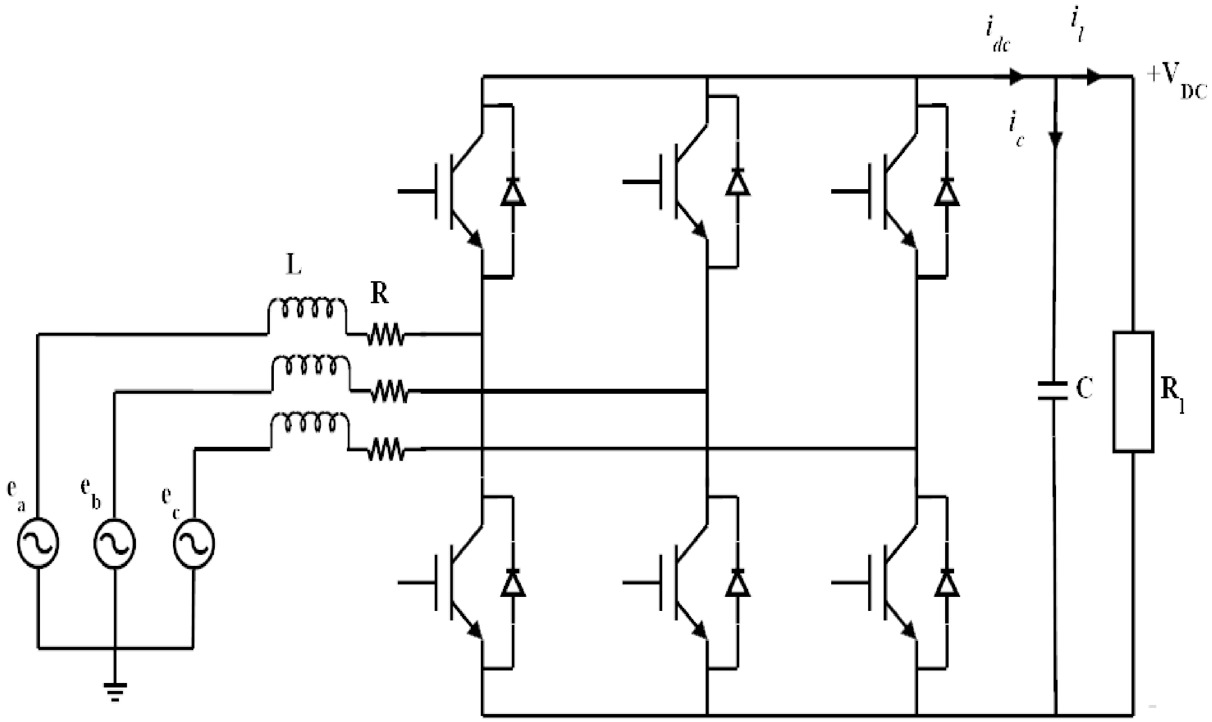


Fig 3.4 Igbt Based 2 Level Full Bridge Converter Circuit

When the DFIG is connected to a 3 phase balanced supply, a rotating magnetic field will be created in stator circuit. Also due to the power fed to rotor side a magnetic field will be also established in rotor side. The two magnetic fields represented by rotating reference frame are given below.

$$\phi_{ds} = L_{ss}\, i_{ds} + L_m\, i_{dr}$$

$$\phi_{qs} = L_{ss}\, i_{qs} + L_m\, i_{qr}$$

$$\phi_{dr} = L_{ss}\, i_{dr} + L_m\, i_{ds}$$

$$\phi_{qr} = L_{ss}\, i_{qr} + L_m\, i_{q}$$

Similarly the stator and rotor voltages in rotating reference frame are given by the following equations.

$$V_{ds} = R_s\, i_{ds} + (d\, \phi_{ds}/dt) - \omega_s\, \phi_{qs}$$

$$V_{qs} = R_s\, i_{qs} + (d\, \phi_{qs}/dt) + \omega_s\, \phi_{ds}$$

$$V_{dr} = R_r\, i_{dr} + (d\, \phi_{dr}/dt) - (\omega_s - \omega_r)\phi_{qr}$$

$$V_{qr} = R_r\, i_{qr} + (d\, \phi_{qr}/dt) + (\omega_s - \omega_r)\, \phi_{dr}$$

The last term is the rotational emf which occur due to the rotation of axis. In stator circuit the speed of the magnetic field is equal to the synchronous speed (ω_{s}). But in rotor circuit the speed of the rotating axis will be the relative speed between stator rotating magnetic field and the rotor. So it is represented by $\omega_s - \omega_r$.

Similarly the active and reactive power of the stator is given by

$Ps = 3/2 (Vds *ids + Vqs*iqs)$; $Qs = 3/2 (V_{qs} *i_{ds} - Vds*i_{qs})$;

3.4 DFIG CONTROL SCHEMES

Control of DFIG can be achieved by controlling the rotor side power flow. Hence controlling the power converter of rotor side (i.e RSC and GSC) we can control the DFIG completely. To achieve a smooth operation generally vector control method is adopted on both sides. In vector control scheme first the 3 phase quantities are transformed into 2 mutually orthogonal frames of reference and then by controlling this 2 components independently, decoupled control is achieved. The main advantage of this type control is that, the response will be first and we can control both active and reactive power independently.

3.4.1 ROTOR SIDE CONVERTER CONTROL

The main purpose of controlling rotor side converter is to control stator side active and reactive power independently. In order to implement the decoupled control method of active and reactive power, stator flux oriented vector control scheme is adopted.

To achieve this stator field oriented scheme, some assumption has to be made which are given as follows.

I. Stator voltage drop across resistance has been neglected as the stator resistance value are quite low in value.
II. The DFIG is connected to stiff grid i.e. the frequency and amplitude of stator and grid voltage is assumed to be constant
III. The q- axis is rotating 90^o ahead of d-axis at synchronous speed in the direction of rotation.
IV. The stator flux vector is aligned with the d-axis of the stator.

The above assumption in mathematical form will be as follows.

$V_{ds} = 0; \qquad V_{qs} = V_s;$

$\phi_{ds} = \phi_s; \qquad \phi_{qs} = 0$

This will reduce the active and reactive power to the following form.

$Ps = 3/2\ (V_{qs} * i_{qs})\ ; \qquad Qs = 3/2\ (\ V_{qs} * i_{ds});$

So we can say that by controlling the d- and q-axis component independently of current we can control the stator active and reactive power in decoupled manner.

3.4.2 GRID SIDE CONVERTER CONTROL

Grid side converter control is used to regulate the voltage across the DC link and sometime also to compensate harmonics. This is a two stage controller scheme which is achieved by grid voltage oriented vector control scheme i.e. by aligning the dq- axis in the direction of grid voltage. The detailed discussion on this grid converter control scheme is proposed in the next chapter.

3.5 SALIENT FEATURES OF DFIG

i. It can produce constant amplitude and frequency at stator even if the wind speed is varying i.e. variable speed constant frequency operation
ii. It can generate even at lower wind speed.
iii. It allows a speed range of ± 30% around the synchronous speed.
iv. It use a reduced rated AC/DC/AC bidirectional converter (25-30% of total rating), hence are cheaper than other variable speed generator.
v. It can control the power factor so as to run it as a unity power factor device.

CHAPTER 4

GRID SIDE CONVERTER CONTROL

GRID SIDE CONVERTER CONTROL

4.1 INTRODUCTION

Grid converter is typically a three phase, two level voltage source converter which uses IGBT as a switching device. As we have discussed earlier, the main purpose of grid side converter control is done to regulate the DC link voltage. This is done by implementing grid voltage oriented control scheme.

4.2 MODELLING OF GRID SIDE CONVERTER

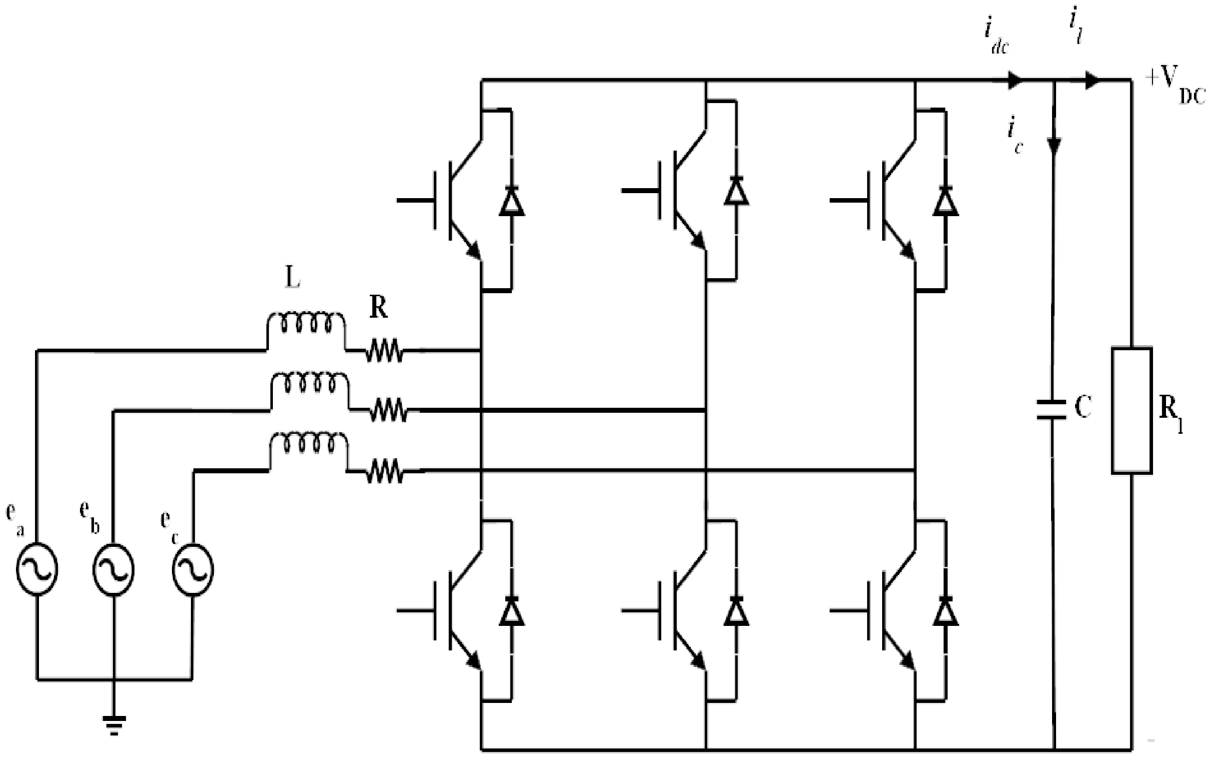


Fig 4.1 Grid Converter Configuration

The above figure shows a grid side converter circuit getting its supply from a balanced 3 phase circuit. Here the converter is a Voltage source converter which using a IGBT switch. In the figure we can see that the dc link consist of a filter capacitor C feeding to a load resistance R. The main aim of GSC is to maintain a constant DC link voltage, and if desired it can also feed limited reactive power.

The dynamic model of converter in dq-reference frame is given by:

$$L_g \frac{didg}{dt} = V_{dg} - R_g i_{dg} - V_{dc} + \omega_g L_g i_{qg}$$

$$\text{and,} \quad L_g \frac{diqg}{dt} = V_{qg} - R_g i_{qg} - V_{dc} - \omega_g L_g i_{dg}$$

Similarly, the active and reactive power associated with GSC are given as follows,

$$P_g = 3/2\ (V_{dg} * i_{dg} + V_{qg} * i_{qg})\ ; \qquad Q_g = 3/2\ (V_{qg} * i_{dg} - V_{dg} * i_{qg});$$

4.3 CONTROL OF GSC

To control the grid side converter we adopt the grid side voltage oriented vector control scheme. In this scheme. The rotating reference frame dq-axis will be rotated along the grid voltage. So V_{dg} will be equal to full grid voltage ($V_{dg} = V_g$) and V_{qg} will become 0. This will reduce the power equation into the following form.

$$P_g = 3/2\ (V_{dg} * i_{dg})\ ; \quad Q_g = -3/2\ (V_{dg} * i_{qg});$$

The grid converter control has 2 control loops. The control scheme of GSC is as described below.

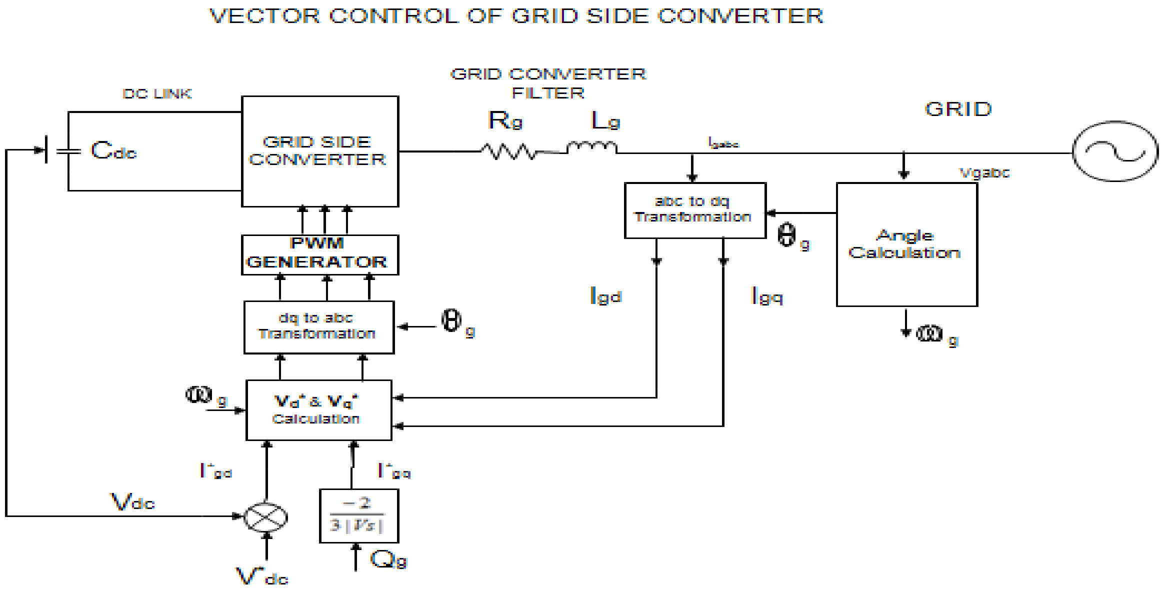


Fig 4.2 Grid Converter Control Scheme

Dc link voltage control loop is developed on the principle of power balance on both side of GSC i.e. DC-link side and grid side. So in mathematical from it can be written as:

$$V_{dc}\, i_{dc} = V_{dg}\, i_{dg} + V_{qg}\, i_{qg}$$

As the d-axis of the reference frame is oriented towards the grid voltage, so V_{qg} component will be zero. Hence the above equation will reduce to

$$V_{dc}\, i_{dc} = V_{dg}\, i_{dg}$$

But $$i_{dc} = i_c + i_1 = C\frac{dVdc}{dt} + i_1$$

So this equation will be reduced to the form as:

$$\frac{dVdc}{dt} = \frac{Vdg\ i\ dg}{C\mathrm{Vdc}} - \frac{i1}{C}$$

If we take i1 as disturbance, then we can see that, V_{dc} can be controlled by controlling i_{dg} alone. In the above figure we can see that, Dc link voltage is compared with a reference DC link voltage . This reference value of DC link voltage can be calculated from the following formula:

$$V_{dc,min} \geq \sqrt{3}\, V_{gm} \text{ (For SVPWM switching)}$$

The difference of the two voltages then fed to a PI controller to obtain the reference value i_{gd}^{*}. Similarly from reactive power Q_g we can get the reference value of i_{gq}^{*}. These two values are compared with the original dq-value of grid current i.e. i_{gd} and i_{gq} . Resultant signal is again fed to PI controllers to obtain V_{gd}^{*} and V_{gq}^{*}. These signals are then converted to αβ-reference frame and fed to SVPWM generator to generate control pulses. Value of Q_g can be calculated using the formula discussed earlier.

4.4 EFFECT OF VOLTAGE SAG

One of the main assumptions of grid converter control is that the grid should be stiff. Here grid stiffness necessarily implies, there will not be any abnormalities in grid voltage. But in practical cases 100% stiffness is not possible. This fluctuation in grid will lead to the fluctuation in the DC link voltage. When this DC link voltage is feeding to a DFIG rotor through another converter circuit, this change in voltage will feed reduced voltage to rotor. In other words we can say that DFIG rotor will fed insufficient reactive power. So to maintain the reactive power demand of machine, DFIG will draw reactive power from grid. As the reactive power input from rotor side is varying in nature, so stator will also draw uneven amount of reactive power. This will reflect as a voltage variation at point of common coupling. So to avoid this problem we have to take necessary remedies. This compensation technique is described in next chapter.

CHAPTER 5

MITIGATION OF VOLTAGE SAG

MITIGATION OF VOLTAGE SAG

5.1 INTRODUCTION

As discussed earlier, the fluctuation in input voltage to the GSC will lead to problem like uneven reactive power consumption by the machine. So it is advisable to adopt some technique to mitigate this problem. One of such mitigation technique is the topic of discussion of this chapter.

5.2 VOLTAGE SAG

Voltage sag is a term given to that voltage abnormality condition in which the voltage will decrease to a value 0.1 p.u. to 0.9 p.u. and may exist for a time of 5 cycles to 1 minute. The most common reason for voltage sag is the faults in grid. These faults may be of symmetric type 3phase faults or asymmetric type line to line, line to line to ground or line to ground fault. Another reason of voltage sag is sudden loading on power system. Sag can also occur due to energization of heavy load or due to the starting of large industrial motors. When a heavy load is connected to the grid suddenly, it draws reactive power from grid. As the synchronous generator excitation system will take some time to compensate this increased reactive power demand, the reactive power contain in grid goes down. This will result in the voltage sag.

5.3 MITIGATION OF VOLTAGE SAG

Mitigation of voltage fluctuation can be done in 2 ways. One solution of power quality can be done at load side and in second approach we can mitigate this voltage loss at grid side itself. First method is called load conditioning and later one is called line conditioning. Unified power quality conditioner and Dynamic voltage restorer (DVR), Static Transfer Switch(STS) are few examples of conditioning devices used for voltage SAG compensation.

5.4 DYNAMIC VOLTAGE RESTORER

Static series compensator or popularly known as Dynamic voltage Restorer (DVR) is a custom power device which is used for mitigation of problems like voltage sag and swell. It is a series connected device which inject a dynamically controlled voltage to correct the voltage disturbance in grid.

It consists of an energy storage device, a voltage source inverter, ac filter and a coupling transformer. The below figure shows a typical block diagram of DVR.

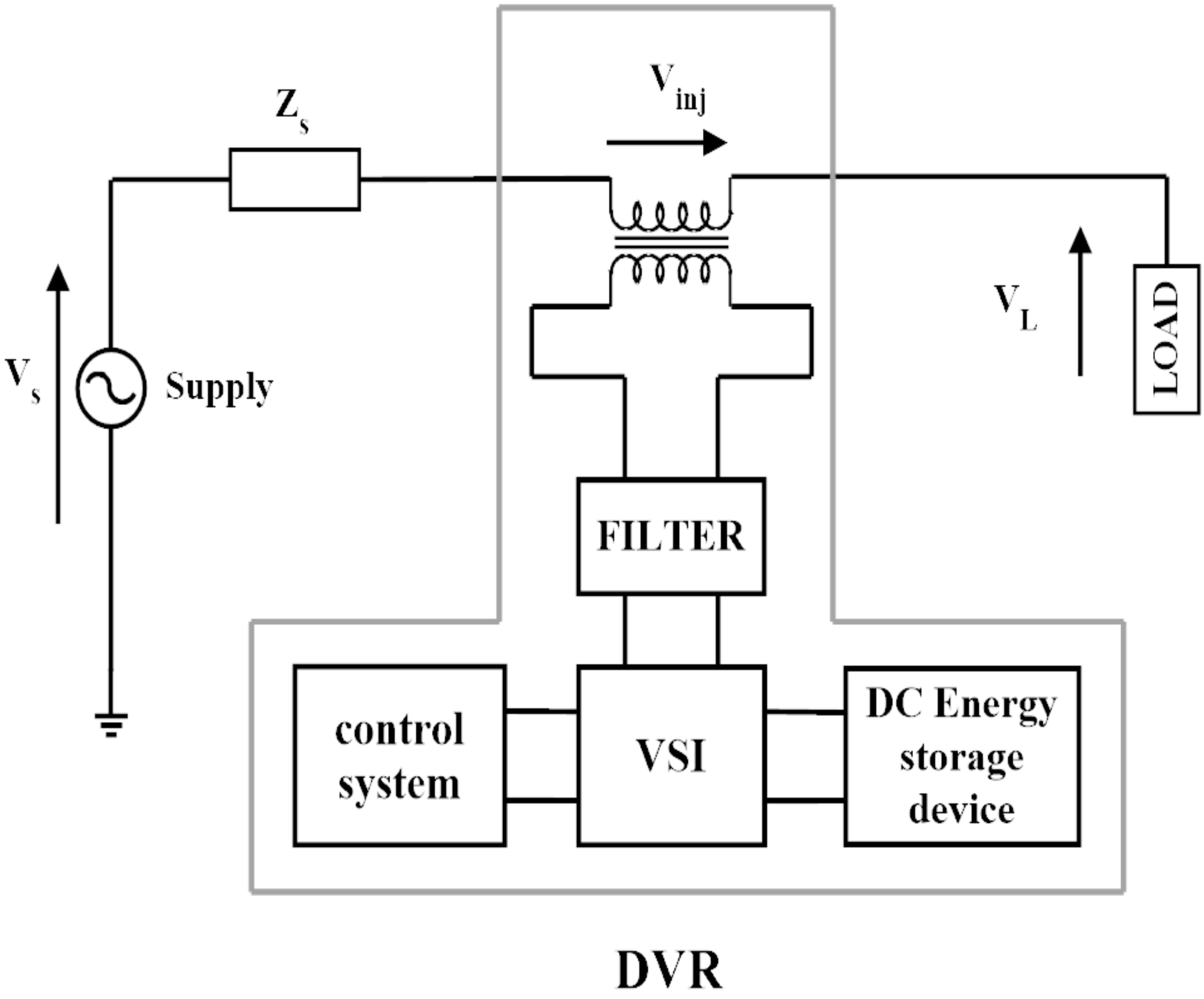


Fig 5.1 Block Diagram Representation of DVR

The energy storage device supplies the required power to overcome this voltage sag. Typically the voltage rating of the energy storage devices are quite low. So to interface it with VSI, boost converter is used between energy storage device and dc storage device. Output of the boost converter is connected to a dc link capacitor which is a common voltage source for inverter. The inverter produces a compensation voltage which is fed to the grid through a series transformer. The description of various equipment is discussed as follows.

5.5 ENERGY STORAGE DEVICE

Many types of energy storage devices are available commercially such as battery energy storage device (BES), super capacitor energy storage device (SCES) , Superconducting magnetic energy storage device (SMES) etc. Each device has some advantages over others and has some limitations too.

5.5.1 Battery Energy Storage Device (BESS): Batteries are the electrochemical devices, which converts chemical energy into electrical energy and vice versa. In general, for renewable energy application secondary cells or rechargeable batteries are used. Typically, the voltage and current rating of individual cell is very low. So to obtain the desired voltage and current level, we connect these cells in parallel-series manner. Many types of batteries are available commercially. Lead acid type, Lithium Ion type, Valve regulated (VRLA) type, Metal air, Sodium sulphur (NaS) are some typical examples of batteries.Energy function of a typical battery is given by:

$$E(t)= E_o +\int v(t).i(t)$$

Where, E_o represents the initial battery voltage level.

The main advantage of BESS over other energy devices is its high energy density. But

5.5.2 Super Capacitor Energy Storage (SCES): Super capacitors are those devices, which has high energy and power density than that of conventional electrolytic type capacitors. It provides a high value of capacitance (Typically in the range of 1500 F). Unlike the conventional capacitors, super capacitor does not use dielectric. It use activated carbon to create a physical barrier between plates of the capacitor. When electric field is applied to this device, then a double electric field is generated which will act like a virtual dielectric. The surface area created by the activate carbon is very high. So it absorb large amount of ions. Energy function of SCES is given by:

$$E(t)= \frac{1}{2} C V_{sc}^2$$

5.5.3 Superconducting Magnet Energy Storage (SMES): Superconducting magnet energy storage devices stores energy in the form of magnetic field, which is created when a dc current passes through a superconducting coil. This superconducting coil is kept at a very low temperature (Below its super conducting critical temperature) inside a cryogenically cooled refrigerator. Energy function of SMES is given by:

$$E(t)= ½ L_{smes} I_{smes}^2$$

5.5.4 Flywheel Energy Storage: Flywheel energy storage devices are the mechanical energy storage devices which store energy in the form of rotational energy. This device is constantly revolving in nature. When energy is stored in the device its speed increase and similarly when energy is extracted from it , its speed decreases. Energy function of typical flywheel is given by:

$$E(t)= ½J \omega_{fw}^2$$

The following table shows comparison between various energy storage devices.

TYPES OF ENERGY STORAGE	***POWER RANGE***	***ENERGY RANGE***	***CHARGE TIME***	***POWER DENISTY***
BESS	5 KW-10MW	0.1-600MJ	Hours	10-300
SCES	5-100KW	1KJ-10MJ	Seconds to Minute	2000-10000
SMES	1-50 MW	1-100MJ	Minutes	300-1000
Flywheel	1KW-10MW	1-15MJ	Minutes	1000-10000

TABLE. 5.1 COMPARISION BETWEEN VARIOUS ENERGY STORAGE DEVICE

Each of the devices has some advantage and disadvantages when compared with others. BESS has a very high energy density as compared to other, but its disadvantage is its charging and discharging time which is high. Similarly SCES has high power density and lower charging time, but its energy density is low as compared to BESS. SMES lies in between SCES and BESS. It has good power range and its power and energy density both are good. But the main disadvantage in SMES is the requirement of cryogenics filter, which make the system bulky and costlier. Flywheel has good power density but moderate energy density. However selection of devices totally depends on the type of operation. For high power application, flywheels are commonly used. For DFIG application, BESS or SCES are generally used.

5.6 CONTROL OF DVR

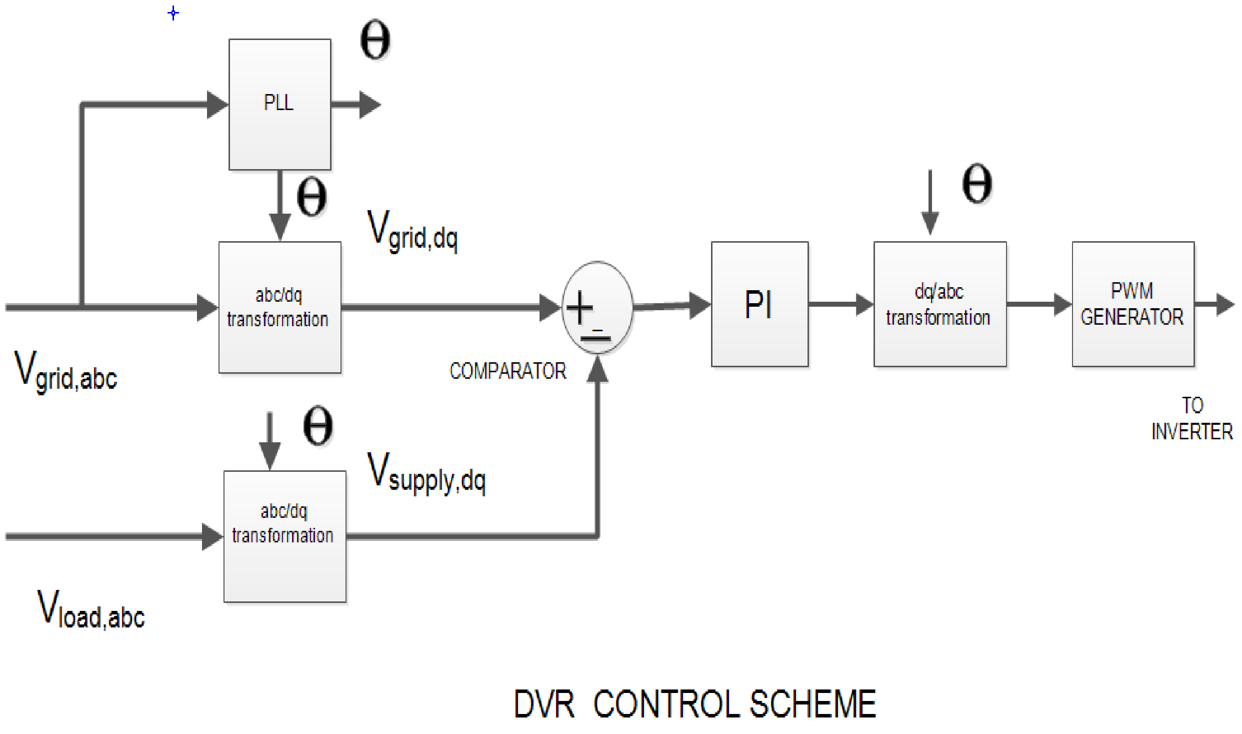


Fig 5.2 DVR Control Scheme

The above control scheme is used to control the inverter circuit of DVR. Voltage is sensed from both grid and load side and converted into rotating dq-axis. Then both d & q components of each signals compared and error signal generated is fed to PI controller. Then the dq component is converted into abc- reference frame and fed to PWM generator for generating inverter pulse signal.

DVR uses various techniques to compensate voltage sag. Some of the methods are pre-sag compensation method, in phase compensation method etc.

In pre-sag method, continuously voltage is detected and if any disturbance will occur then it will be compensated immediately by DVR. In this method compensation for both load angle and magnitude occur. Figure a. of the following diagram shows a compensation method of pre-sag Technique.

In-phase compensation method is the simplest compensation method for voltage sag compensation. In this method only amplitude compensation is done i.e. injection voltage and supply voltage are in same phase. Figure b. shows the phasor representation of in-phase voltage compensation technique.

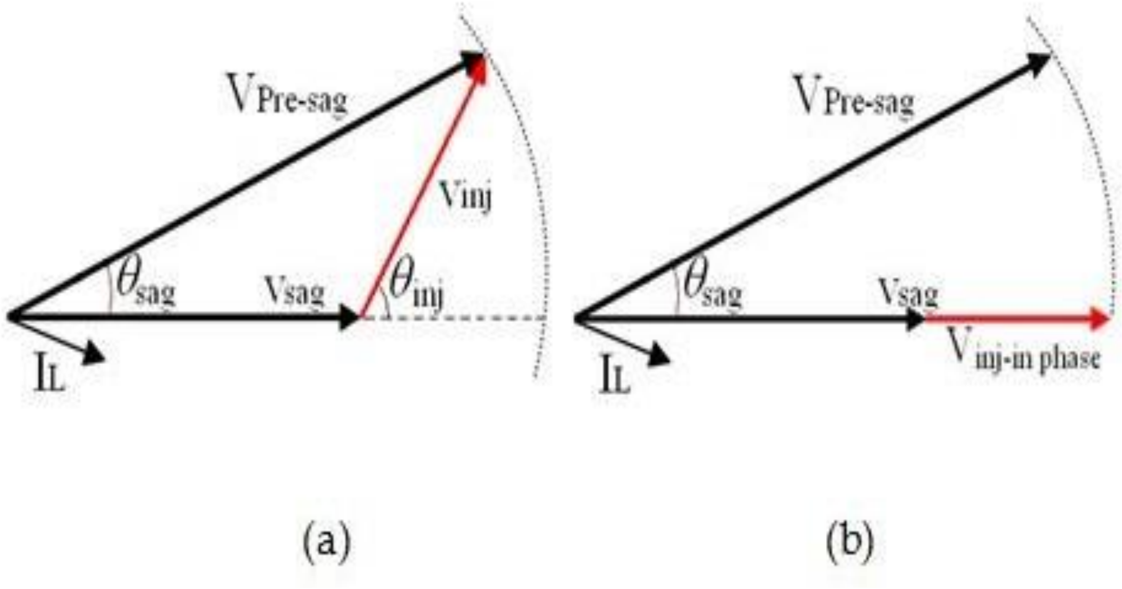


Fig 5.3 Sag compensation Techniques (a) Pre-Sag Control Scheme (b) In-Phase Control Scheme

CHAPTER 6

SIMULATION RESULT AND CONCLUSION

SIMULATION RESULTS & CONCLUSION

6.1 SIMULATION

6.1.1 GRID CONVERTER CONTROL

Fig 6.1 shows an open loop control output of a VSI converter. This shows that in open loop system, dc link voltage fluctuation is very large. To achieve minimum fluctuation, we have to increase the DC link capacitor size, which will be difficult to implement in practical case. So we adopt an advance control scheme for GSC such as vector control scheme.

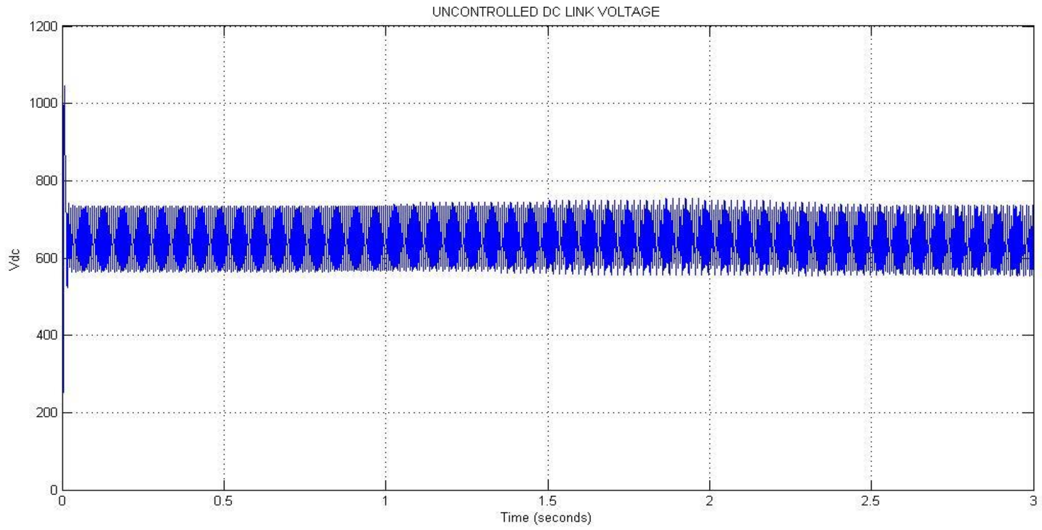


Fig. 6.1 DC Link Voltage without Grid Converter Control

The second figure (Fig. 6.2) shows the DC link voltage after implementing the grid voltage oriented vector control scheme. Here the by proper control of converter the fluctuation became very less. Here the DC link voltage is around 975 Volts .

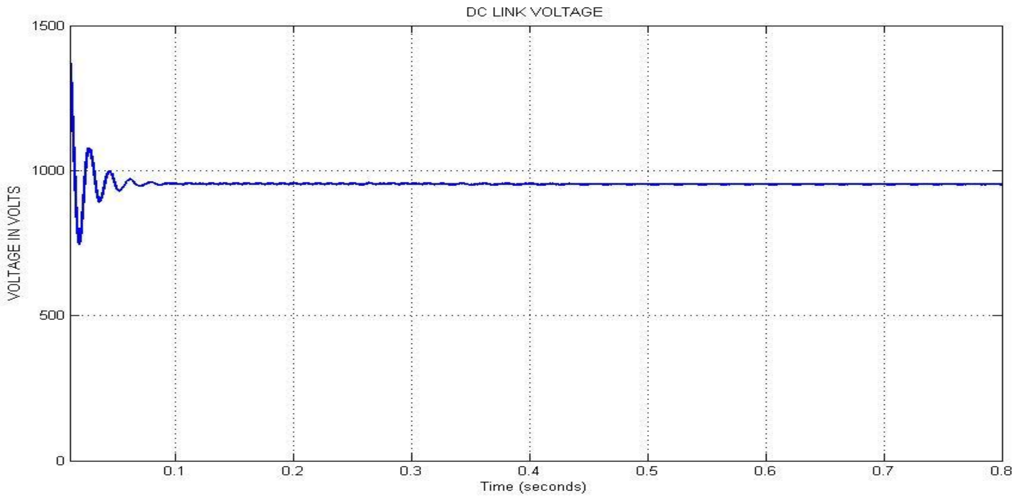


Fig 6.2 DC Link With Grid Voltage Oriented Vector Control

6.1.2 EEFECT OF SAG

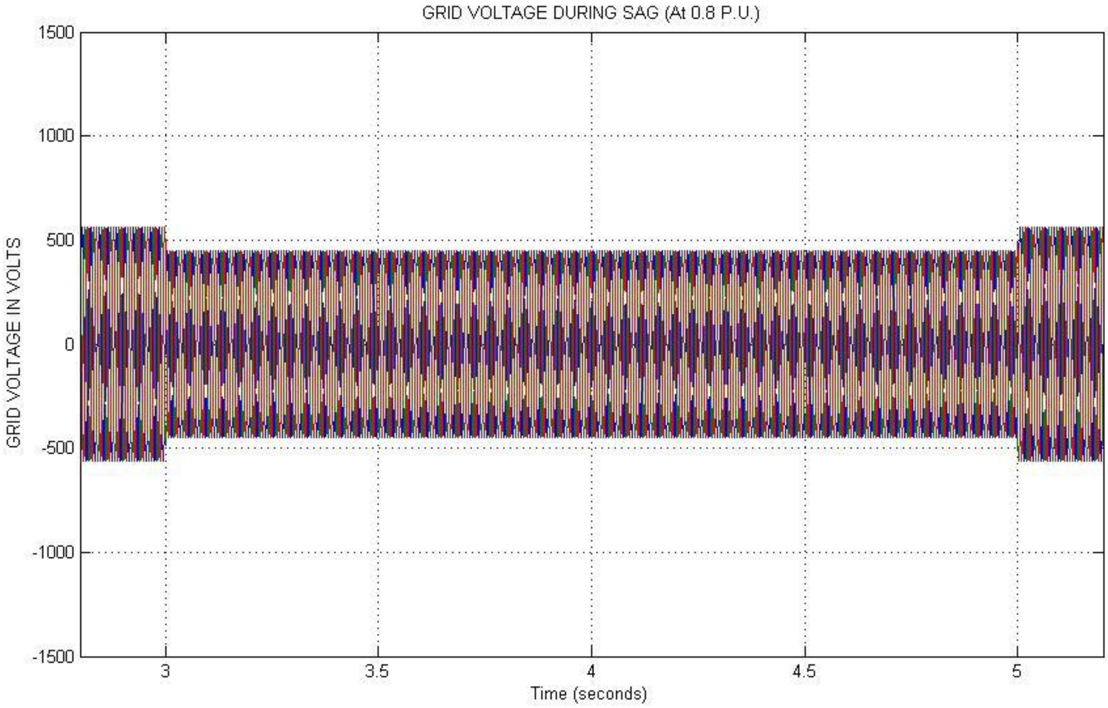


Fig 6.3 Grid Voltage During Sag of 0.8 P.U.

The above figure (Fig 6.3) shows the input voltage to GSC during voltage SAG. Effect of voltage sag on DC link is shown in below figure (Fig. 6.4) (Taking 0.8 p.u. value).

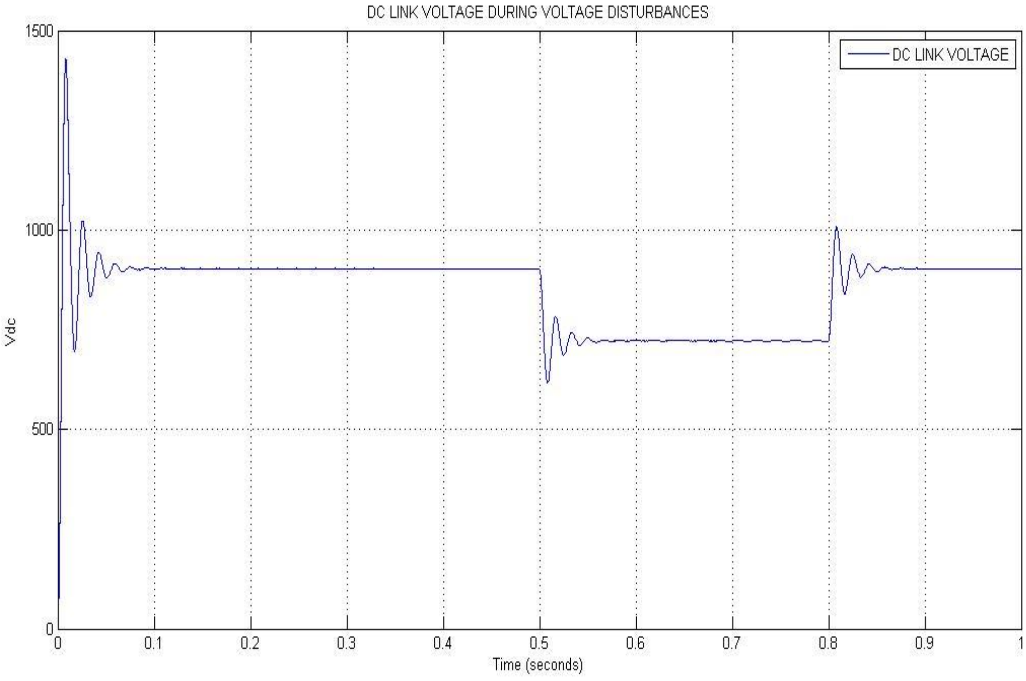


Fig 6.4 DC Link Voltage During Sag

6.1.3 SAG MITIGATION USING DVR

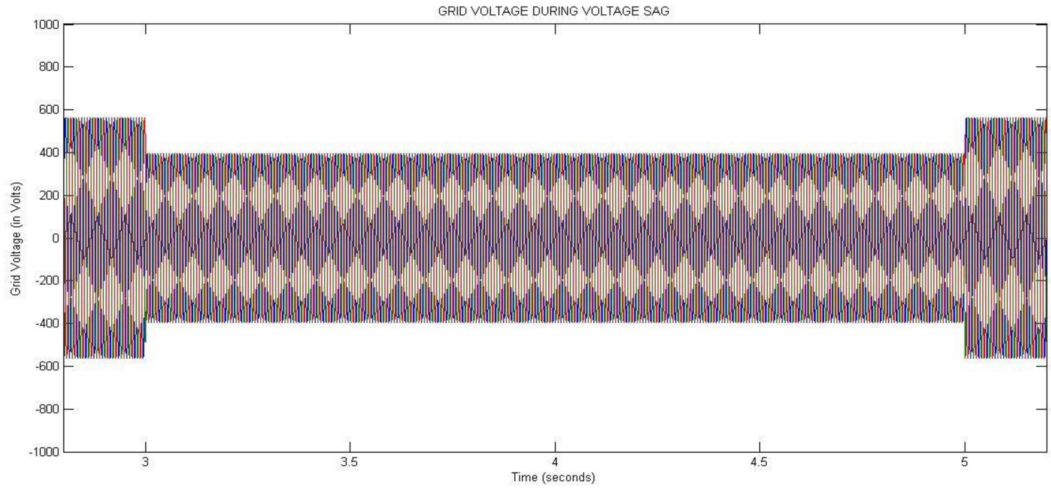


Fig 6.5 Grid Voltage During Sag

Fig 6.5 shows the grid voltage during voltage sag of 0.7 p.u. which remain in the grid for 2 seconds.

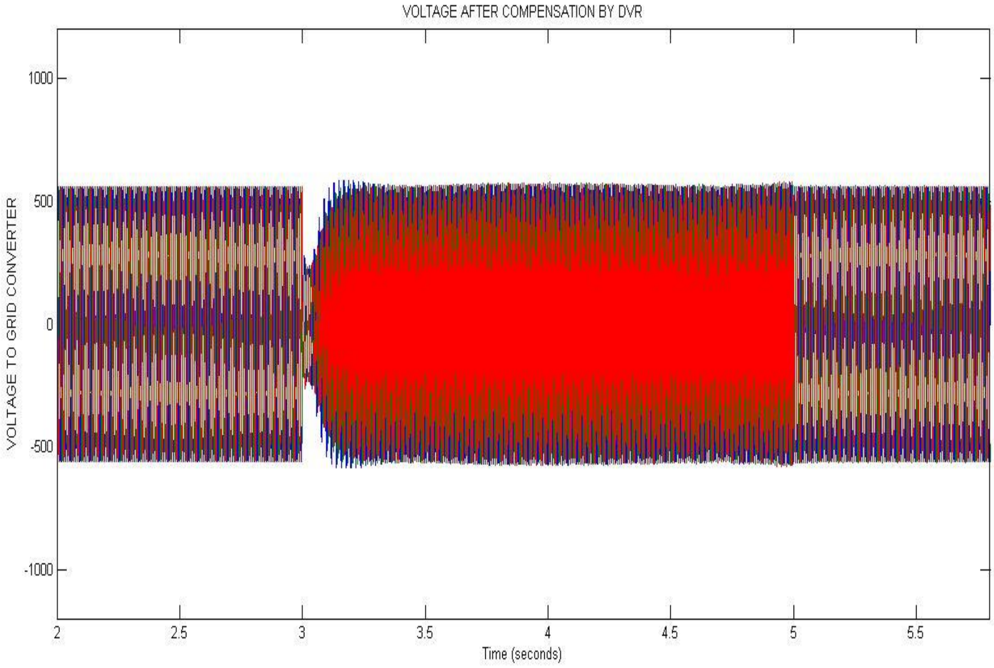


Fig. 6.6 Compensated Input Voltage to GSC

Fig 6.6 shows the DVR compensated three phase voltage at load end. The series transformer, which was connected in between grid and grid converter will feed the deficit voltage , whenever voltage sag occurs.

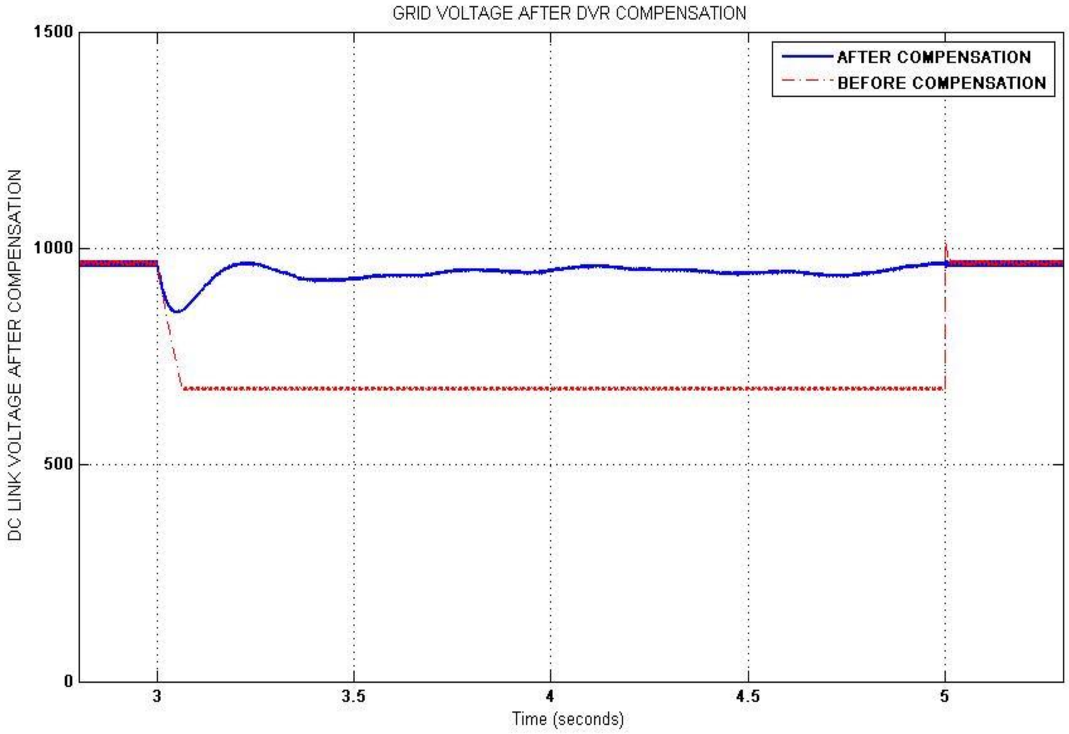


Fig 6.7 Compensated DC Link Voltage

Finally Figure 6.7 shows a comparison between DC link voltages before and after the compensation of voltage by DVR.

6.2 CONCLUSION

In this project work, we have studied about the concept of DFIG and studied the working principle of grid side converter. We have implemented the grid voltage oriented vector control scheme to regulate the DC link voltage. However we have seen that, when input voltage to the voltage source inverter changes, it could not maintain the voltage at constant value.

So to get a constant value of DC link voltage, we have tried to maintain the input voltage of the VSC constant even if the grid voltage was varying. For this we have adopted the dynamic voltage restoration technique.

6.3 FUTURE WORK:

Like the DVR, unified power quality condenser (UPQC) can also be applied to the sag compensation. Currently in this project we have used battery as the energy storage device. This research work can also extend to other form of energy storage application like SMES, Super capacitor Energy Storage devices etc.

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REFERENCE

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APPENDIX A

A.1 DFIG PARAMETERS

SL NO	***PARAMETER NAME***	***RATING***
1.	Rated Power	***2.00 MVA***
2.	Rated Voltage	***690 V***
3.	Rated Current	***2.00 KA***
4.	Rated Frequency	***50 Hz***
5.	Pole Numbers	***4no***
6.	Stator Resistance	***0.34 p.u.***
7.	Rotor Resistance	***0.009p.u.***
8.	Stator Leakage Inductance	***0.105 p.u.***
9.	Rotor Leakage Inductance	***0.111 p.u.***
10.	Magnetic Inductance	***3.34 p.u.***
11.	Magnetic Resistance	***47.61 p.u.***
12.	Angular Moment Of Inertia	***3.825 p.u.***
13	Mechanical Damping	***0.01 p.u.***

Table. A.1

A.2 WIND TURBINE PARAMETERS

SL NO	***PARAMETER NAME***	***RATING***
1.	Turbine Rotor Speed Range	***9-19 RPM***
2.	Rated Rotor Speed	***1500 RPM***
3.	Rated Wind Speed	***13 m/s***
4.	Turbine Tower Height	***80 m***
5.	Rotor Diameter	***80 m***
7.	Gear Box Ratio	***1:100***

Table. A.2

A.3 CALCULATION OF DC LINK VOLTAGE

RMS value of grid line voltage V_g= 690 V

Grid phase voltage RMS value is = $690/\sqrt{3} = 398.37$

Peak value of grid phase voltage $V_{gm}= \sqrt{2} * 398.37 = 563.392$

For SVPWM technique, $Vdc = \sqrt{3} * V_{gm}$

Hence DC link voltage $Vdc = \sqrt{3} * V_{gm}= 975.8$

So reference value of V_{dc} i.e. Vdc* must be greater than calculated Vdc so 1000 V can be selected as a reference value.