FAULT ANALYSIS AND PROTECTION OF DOUBLY FED INDUCTION GENERATOR-BASED WIND FARMS

By

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CHAPTER I

INTRODUCTION

1.1 Global Energy Scenario

Energy supply plays an important role in the social and economic development of nations. With increases in energy consumption, scarcity and cost of basic energy resources have become a worldwide challenge. While coal remains apparently an abundant resource, oil and natural gas supply have concerns of declining in the long run [1]. Further, using conventional carbon-based energy resources will have harmful environmental impacts including global warming and climate change. As a result, to develop an ecologically sustainable energy supply, much attention is focused on utilizing renewable energy resources such as wind, photovoltaic, small hydro, wave, tidal, biomass and geothermal. In addition to the traditional use of hydro power, there is an immense potential for solar energy in its various manifestations such as wind, biomass, etc. However, they are subjected to the vagaries of nature. Conversion systems required to exploit these energy sources are still in various stages of development for large scale technical application. As of now, wind power is the most advanced and least expensive renewable resource for grid integrated electrical power generation [2].

1.2 Development of Wind Energy Utilization

Wind power has been used for pumping water and grinding grain for more than thousand years. Water pumping wind mills were used widely in the rural areas of the United States in the mid 1800s, and this stimulated investigations on using wind for generating electricity. With the oil crisis triggered by the Arab oil embargo in 1973, wind energy research and development programs were initiated and tax and other financial incentives were put in place to support the growth of the wind industry [3]. Initially various designs including vertical axis wind turbines were considered, and over the time a three bladed, stall regulated, nearly constant speed wind turbine became popular under the name 'Danish' concept. These wind turbines were rated from about a few kilowatts to about 1000 kW over the next 15 years. However, during mid 1990s, advantages of newer concepts such as variable speed operation, pitch regulation and advanced materials were coming into vogue and they were investigated in the earlier government funded research programs [4]. Development of wind turbine technology in United States from 1980 to 2015 is given in Figure 1.

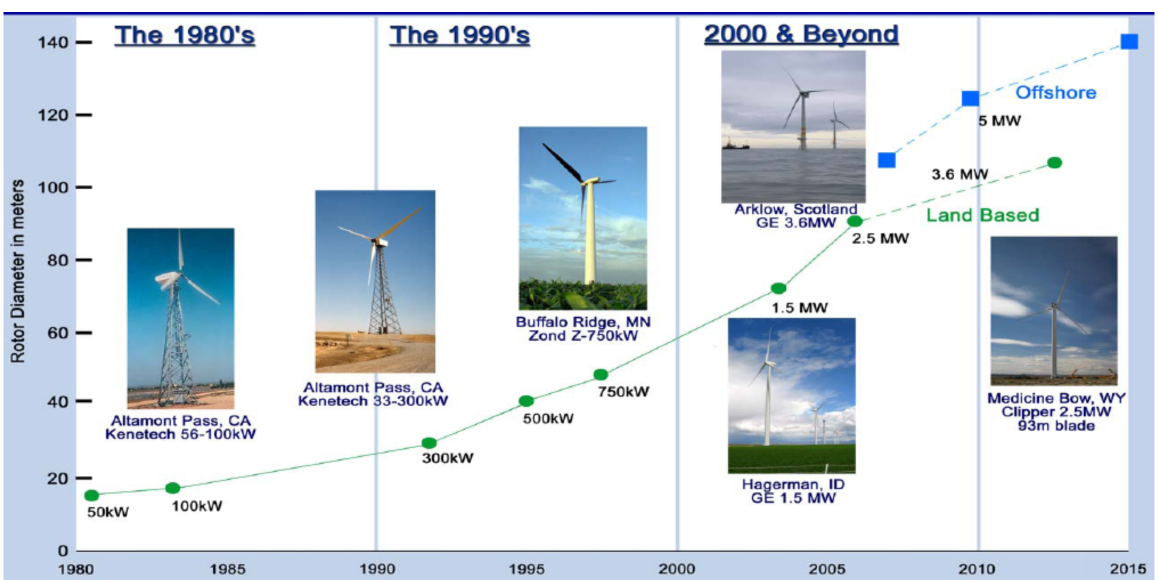

Figure 1: Evolution of Commercial Wind Technology in United States [5]

Wind electric power generation dramatically grew with the employment of these newer concepts. Worldwide installed wind capacity doubled approximately every three years and as of January 2008, total world-wide installed wind capacity exceeds 90 GWs as shown in Figure 2.

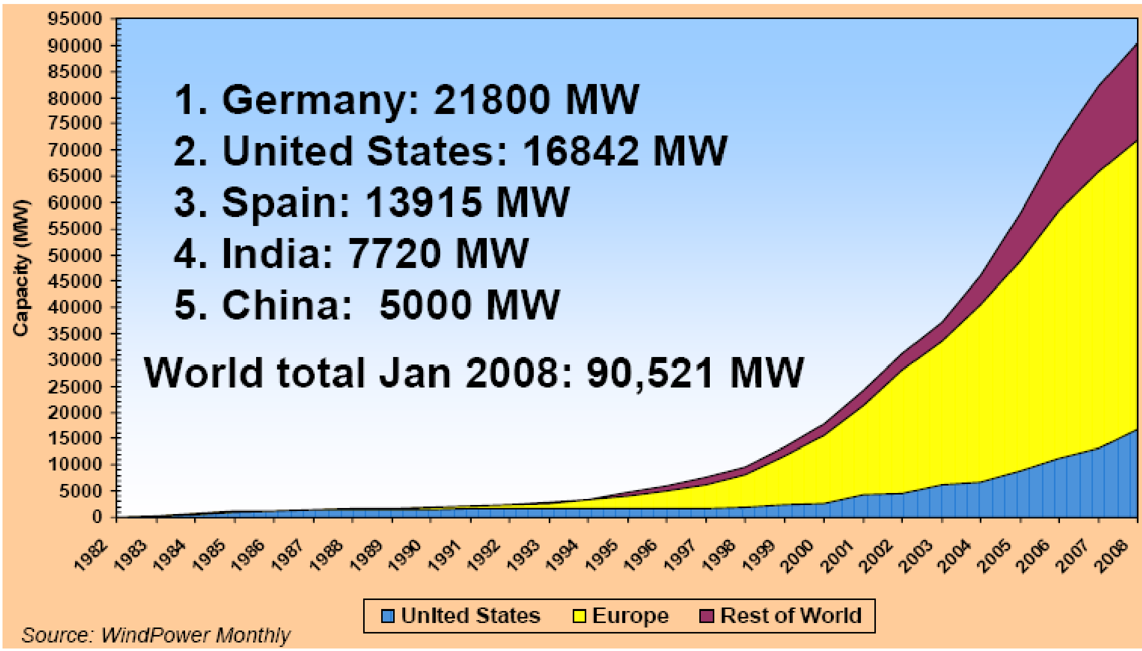

Figure 2: Worldwide Total Installed Wind Capacity [5]

According to Figure 2, as of January 2008, United States is the second largest with a cumulative installed wind capacity of nearly 17 GW. However, during the year 2007 and onwards United States added more wind capacity than any other country. Table 1 presents the capacity additions during the year 2007. The latest information puts the United States as the world leader in cumulative installed wind capacity [6]. With these growing trends, the US Department of Energy envisages 20% of electric installed capacity to be obtained from wind power by 2030 [7].

Cumulative Capacity (end of 2007)	
Germany	21,800
United States	16,842
Spain	13,915
India	7,720
China	5,000
Denmark	3,132
France	2,624
Rest of the World	19,488
Total	**90,521**

Incremental Capacity (2007, MW)	
United States	5,144
China	2,406
Spain	2,300
India	1,450
Germany	1,178
France	1,155
Portugal	494
Rest of the World	5248
Total	**19,375**

Table 1: International Ranking of Wind Power Capacity [5]

Over the years different types of wind turbine generators have been used ranging from nearly constant speed operation to variable speed operation. Detail description of different types of wind turbine generators are given in Chapter 2.

1.3 Power System Concerns

Traditionally, power systems were designed with large centrally dispatched power plants delivering power to consumers through transmission and distribution networks. With high penetration of wind power into power distribution and transmission networks, technical concerns such as fault current contribution, protection coordination, voltage control and stability, power quality, reliability and control issues will affect the performance of the overall power system [8].

1.4 Modeling of Wind Farms

Modeling wind farms will facilitate the understanding of their operation and impacts on the overall power system. Various approaches have been used to model the wind turbine, generator, transformers and control and protection systems. Detailed modeling aspects of induction generators are discussed in Chapter 3. There are many software tools which have the capability to model wind farms in detail [9]. In this thesis Matlab/Simulink/SimPowerSystems is used for the modeling and simulation studies.

1.5 Fault Analysis and Protection

Understanding the behavior of wind farms under faulted conditions is very important for designing the system from interconnection point to the generator. Further, selecting switchgear, control gear and protective gear is done based on the prospective fault levels [10]. Probable fault locations and factors which determine the fault current contribution are discussed in Chapter 4. Different types of faults from balanced to unbalanced and the use of symmetrical components in analyzing unbalanced faults are also included in the discussion.

1.6 Outline of the Thesis

The purpose of this thesis is to study the fault current dynamics of wind farms (employing Doubly Fed Induction Generators, DFIG) and identify the potential impacts of fault currents on the protection of wind farms. In order to analyze the DFIG performance during transient conditions, control and modeling of DFIG are important and they are discussed in this thesis. Outline of the various chapters are as follows:

In Chapter 2, descriptions of different types of wind energy conversion systems and the associated speed and power regulation methods are summarized.

In Chapter 3, Induction machine modeling fundamentals are presented and DFIG modeling for short circuit analysis is discussed.

In Chapter 4, description of fault current contributing factors, possible locations of faults, grounding methods together with theoretical background of fault calculations are considered.

Chapter 5 presents and discusses the simulation results.

In Chapter 6, protection aspects of wind farms used at present are discussed and additional protection functions are recommended.

Finally in Chapter 7, concluding remarks and scope for future work are documented.

1.7 List of Publications

Some of the results presented in this thesis have been disseminated in the following publications:

1. V.P. Mahadanaarachchi and R. Ramakumar, "Simulation of Faults in DFIG-Based Wind Farms," accepted for to the IEEE Power & Energy Society General Meeting Conference, Calgary, Alberta, July 2009.
2. V.P. Mahadanaarachchi and R. Ramakumar, "Analysis of Capacitive Voltage Transformer Transients with Wind Farm Integration," accepted for the Power Systems Conference, Clemson University, Clemson, SC, March 2009
3. V.P. Mahadanaarachchi and R. Ramakumar, "Security Aspects of Electric Energy Systems-An Overview," presented in the International Conference on Sensors, Security, Software and Intelligent Systems (ISSSIS 2009), Coimbatore Institute of Technology, Coimbatore, India, January 2009.

4. V.P. Mahadanaarachchi and R. Ramakumar, “Modeling considerations for Wind Turbine Generators,” in Proceedings of the 41st Annual Frontiers of Power Conference, Oklahoma State University, Stillwater, October 2008.pp IV-1 to IV-8
5. V.P. Mahadanaarachchi and R. Ramakumar, "Impact of Distributed Generation on Distance Protection Performance-A Review,” in Proceedings of the IEEE Power & Energy Society General Meeting Conference, Pittsburgh, PA, July 2008. Paper no. 08GM1276
6. V.P. Mahadanaarachchi, "Protection of Doubly Fed Induction Generator (DFIG) based Wind Farms,” IEEE Power & Energy Society General Meeting Student Poster, Pittsburgh, PA, July 2008.
7. V.P. Mahadanaarachchi and R. Ramakumar, "Challenges and Issues Involved in Wind Farm Protection," in Proceedings of the 40^{th} Annual Frontiers of Power Conference, Oklahoma State University, Stillwater, October 2007.pp XI-1 to XI-7

CHAPTER II

WIND ENERGY CONVERSION SYSTEMS

2.1 Components and Subsystems

The components and subsystems of a WECS are shown in Figure 3. Wind energy is transformed into rotary mechanical energy by means of a wind turbine which generates aerodynamic torque. The turbine is coupled to the generator through a mechanical drive train consisting of a gear box that matches the turbine low speed to the higher speed required by the generator. Some of the new designs eliminate the need for a gearbox by using multi-pole large diameter low speed generators, typically alternators with field winding or permanent magnet excitation [11].

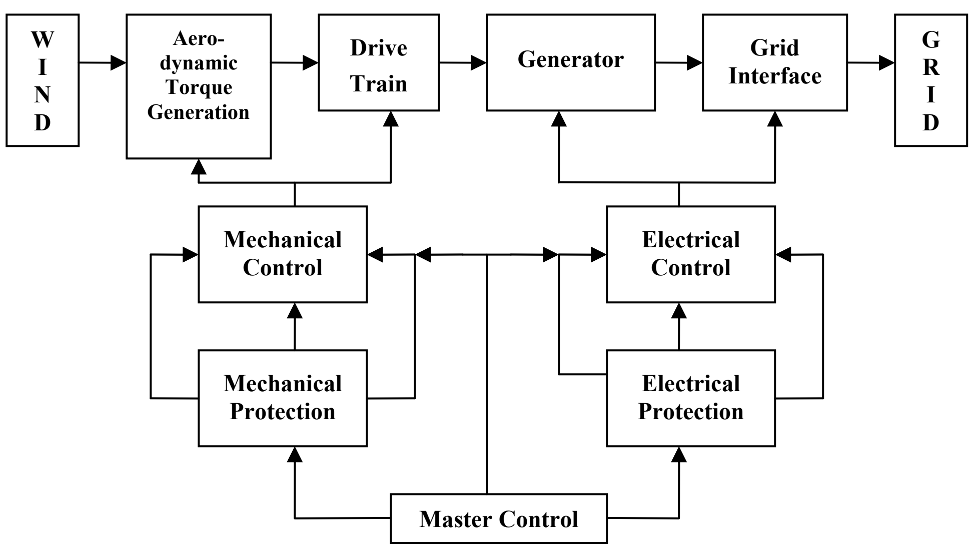

Figure 3: Wind Turbine Components and Subsystems [5]

Sectional view of a wind turbine is shown in Figure 4. Details of the components in the nacelle are identified.

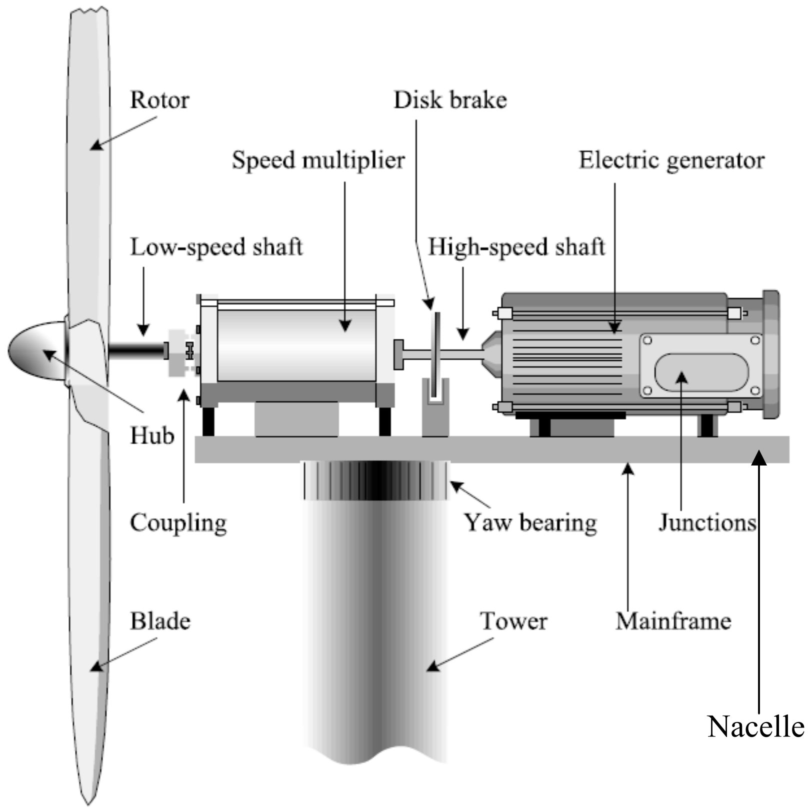

Figure 4: Main Elements of a Wind Turbine [12]

The electrical generator converts rotary mechanical energy into electrical energy. Nearly constant speed schemes are directly connected to the grid through step-up transformers and variable speed systems require a power electronic interface. Various generator and interface topologies are discussed in the next subsection. Electrical and mechanical control and protection systems must be designed to result in maximum efficiency and availability [13].

2.2 Speed Regulation

Wind turbines are classified according to their speed control and power control capabilities. There are two basic classes of wind turbines based on speed control methodologies: nearly constant speed and variable speed systems.

2.2.1 Nearly Constant Speed

Nearly constant speed (commonly known as ‘fixed speed’) wind turbines were popular in early 1990s in Europe and in the United States. This type of wind turbines employ self exited standard squirrel cage induction generators directly connected to the grid via a soft starter. Soft starter is used to reduce the starting and switching transients. The wind turbine rotor speed, which is governed by the grid frequency, is maintained almost constant irrespective of changes in wind speed. As such these wind turbines are designed to obtain maximum aerodynamic efficiency at only one wind speed [14]. Power generation capability can be improved by using two stator windings, where one is used at low wind speeds and the other at medium and high wind speeds [15]. This configuration is simple, robust and uses low cost electrical parts. However, due to high mechanical stresses resulting with this operating mode, uncontrollable reactive power consumption and poor power quality, large scale deployment of this type of systems has almost completely gone out of use..

2.2.2 Variable Speed

A variable speed wind turbine uses a fully or partially rated power electronic interface to connect to the power grid and thereby decouples the grid frequency and the generator rotor speed. This will allow the generator rotor to operate at variable rotational speeds as the wind speed changes and enables the wind turbine to continuously operate at its highest point of aerodynamic efficiency over a wide range of wind speeds [16]. Variable speed wind turbines are suitable for large scale power generation due to their increased power capture and high control capability. Their life times are higher than nearly constant speed wind turbines due to the resulting low mechanical stresses [17]. Presently variable speed operation is the preferred choice for MW-scale wind turbines throughout the world.

2.3 Power Regulation

All wind turbines have a method of power control. Power regulation is accomplished by limiting the aerodynamic efficiency in such a way as not to exceed the rated output power.

2.3.1 Stall Regulation

This is the oldest and simplest power control method of reducing the aerodynamic efficiency by using the stall effect in high winds without changes in the blade geometry. When the wind speed exceeds a certain level, the design of the rotor aerodynamics causes the rotor to stall. In stall controlled wind turbines, the rotor blades are firmly attached (no pitch control) to the hub and have a special blade profile design to provide accentuated stall effect around rated power without undesired collateral aerodynamic behavior [18]. This power control method suffers from high mechanical stresses caused by wind gusts. In addition no assisted start and variations in the maximum steady state power due to variations in air density and grid frequency are possible [19]. However, the blade design is very simple since no bearings or pitch mechanisms are required.

2.3.2 Pitch Regulation

In this power control method blade pitch angle is varied thereby changing the blade geometry. This will modify the wind speed seen by the blades, whereby the blades can be quickly turned away from or into the wind as the power output becomes too high or too low respectively. The advantages of controlling the pitch angle are good power control performance, assisted start-up and emergency-stop power reduction [20]. However, these systems add extra cost and complexity due to the pitch mechanism and its controller. This method is further split into pitch control and active stall control depending on the direction the blade is turned (upwind or down wind).

2.3.3 Active Stall Control

Here the wind turbine blade stall is actively controlled by pitching the blades to a larger angle of attack. The blades go into deeper stall at high wind speeds by pitching into a direction opposite to that of a pitch controlled wind turbine. Active stall controlled wind turbines can achieve smooth power reduction and can support assisted start-up [21].

2.4 Power Output Characteristics

The performance of a wind turbine is primarily characterized by the variation of the power output with wind speed. Further, torque and thrust are also important factors in determining the performance. Power conversion efficiency is characterized in terms of *tip speed ratio* (λ), which is the ratio between the peripheral blade speed and the wind speed [22]. It is given as,

$$\boldsymbol{\lambda = R * \Omega_l / v} \qquad (1)$$

where, **R** is the blade length, $\mathbf{\Omega_l}$ is the rotor angular speed and $\boldsymbol{v}$ is the wind speed. The power coefficient, C_p, quantifies the power extraction efficiency of a wind turbine. The aerodynamic performance of a wind turbine is given by the variation of the non-dimensional Cp with λ. A typical C_p vs λ curve is shown in Figure 5.

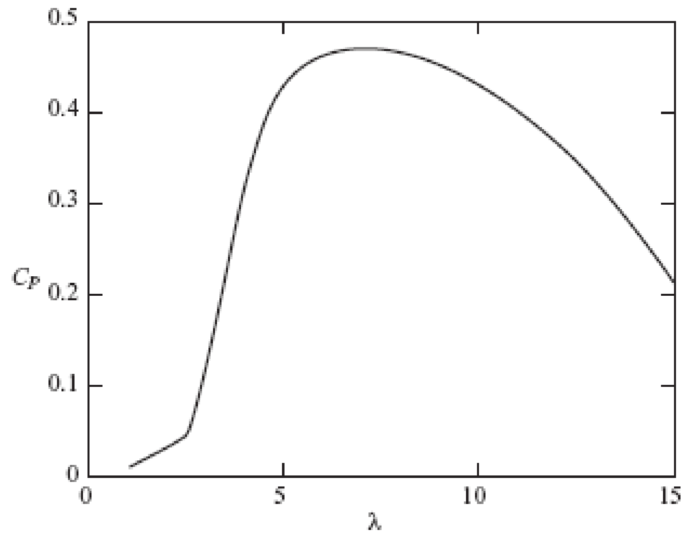

Figure 5: Cp-λ Performance Curve [15]

Power extracted by a wind turbine with a blade length of R is given by,

$$\mathbf{P = (½) .\rho. \pi . R^2 . \boldsymbol{v}^3 . C\boldsymbol{p}(\lambda)} \qquad \mathbf{(2)}$$

According to Figure 5, power conversion efficiency is lower than the Betz limit (0.59), which assumes a perfect blade design [13]. Further, power conversion efficiency has a maximum for a specific tip speed ratio (λ_{opt}) with a certain pitch angle.

Wind turbines operate over a wide range of wind speeds with varying outputs. The range is from the *cut-in* wind speed (3 to 4 m/s) to the *cut-out* wind speed (~25m/s) as shown in Figure 6.

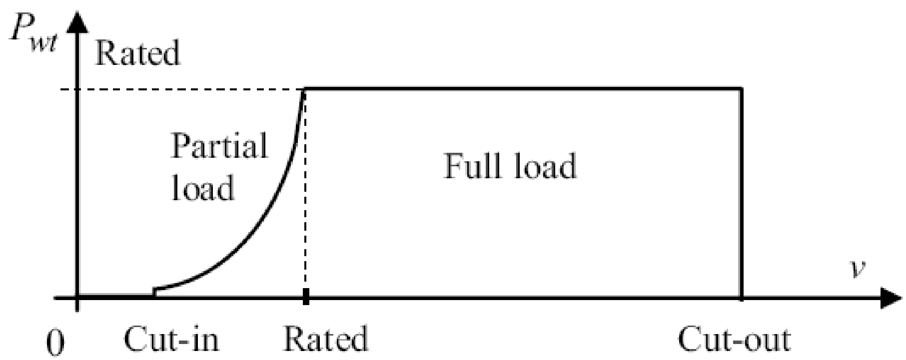

Figure 6: Output Power and Wind Speed Characteristics [13]

The power output is determined by Equation (2), ($P \alpha v^3$), until it reaches wind turbine rated power, which occurs at rated wind speed. Above rated wind speed, power output is limited to rated power through control mechanisms such as stall control or pitch control.

2.5 Generator Topologies

Technology used for wind power generation has been advancing for a couple of decades. Initial efforts were concentrated on nearly constant speed operation for small machines which were directly connected to power grid through a soft starter to reduce switching transients [23]. After the realization of the advantages of variable speed operation, large machines became feasible due to the resulting higher efficiencies and lower stresses. There are four basic types of wind power generators employed in wind farms [24].

2.5.1 Type A

Nearly constant speed or commonly known as "fixed speed" wind turbine, with an asynchronous squirrel cage induction generator directly connected to the grid via a step-up transformer.

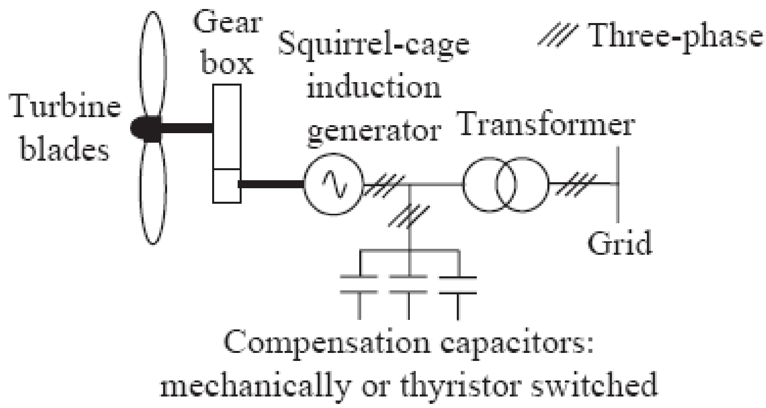

Figure 7: Nearly Constant Speed Wind Turbine Induction Generator [25]

These are driven by wind turbines at a speed just above the synchronous speed, normally up to 1% rated slip [25]. Since the speed variation from no load to full load is very small, the term "fixed" speed is widely used. Reactive power requirement of the induction generator is met with placing compensation capacitors near the generator terminals. Additional reactive power is drawn from the grid. Generator is directly coupled to the grid through a step-up transformer as shown in Figure 7.

2.5.2 Type B

Limited variable speed, pitch controlled wind turbine with wound rotor induction generator with variable rotor resistance.

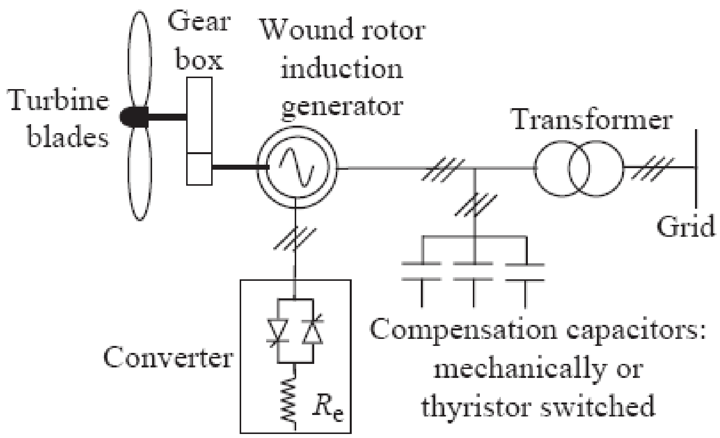

Figure 8: Wound Rotor Induction Generator [25]

The stator mechanical construction is similar to type A, but the rotor also has a three phase winding which is not shorted. Instead the rotor is connected to a converter through the slip rings as shown in Figure 8. The converter modifies the effective rotor circuit resistance by injecting a variable external resistance in the rotor circuit. This method facilitates the controlling of rotor current magnitudes and thereby electromagnetic torque. This enables the generator speed to vary over a small range, typically up to 10% [25]. This type also uses compensating capacitors to deliver reactive power to the generator and additional reactive power is drawn from the grid. The resistances introduced in the rotor circuit results in additional losses.

2.5.3 Type C

Variable speed, pitch controlled wind turbine with Doubly Fed Induction Generator (DFIG) and converter on the rotor side.

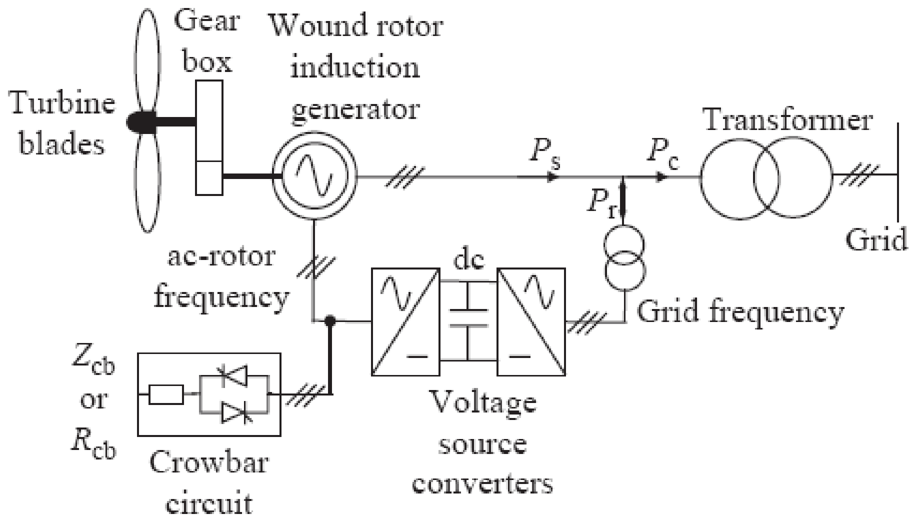

Figure 9: Variable Speed Doubly Fed Induction Generator [25]

The stator of the wound rotor induction generator is directly connected to the grid and the rotor terminals via bidirectional back-to-back static power electronic converters of the voltage source type as in Figure 9. The converters are rated at about 20-30% of full rated power, the same as the percentage variation in the operational speed. The purpose of the converter connected to the rotor winding, Rotor Side Converter (RSC), is to inject a three phase voltage at slip frequency into the rotor circuit. The injected voltage can be varied in both magnitude and phase by the RSC controller. This facilitates the variation of generator electromagnetic torque and thereby rotor speed [26]. In addition it will enable to control stator power factor. Crowbar circuit is placed to short the rotor circuit in case of an overvoltage or overcurrent in the converter dc link to protect the converters. Speed control range is between 70-120% of nominal synchronous speed [20,25,26].

2.5.4 Type D

Variable speed, pitch controlled wind turbine using a directly coupled generator (wound rotor alternator, wound rotor induction generator or permanent magnet alternator) that is connected to the grid through a frequency converter rated at full capacity.

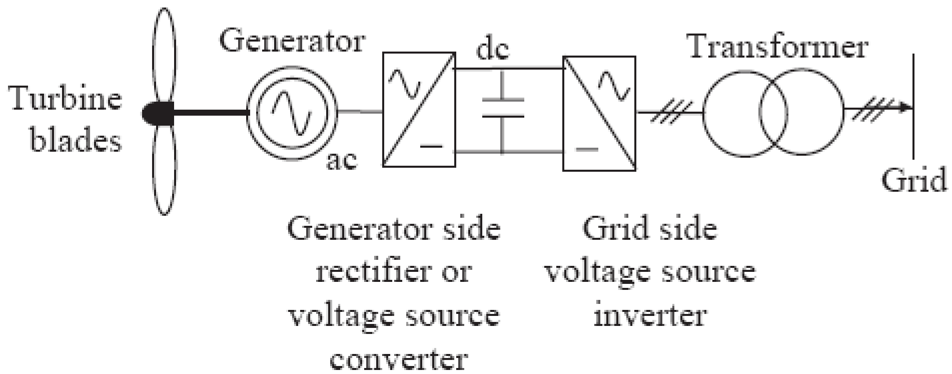

Figure 10: Variable Speed Series Converter Connected Wind Turbine Generator [25]

In this approach, gear box is eliminated by using multi-pole large diameter low-speed generators. In a series converter connected generator , the full output is fed in to a power electronic system or a voltage source converter, then through a dc link into a static power electronic inverter as shown in Figure 10. The electrical generator is isolated from the ac grid. The generator side converter is usually used for controlling the generator speed and the grid side inverter is usually used for voltage/reactive and real power control and dc link capacitor voltage control [11, 25, 27].

Before 2001, Types A and B were used in onshore locations and Types C and D in only some of the offshore wind farms. At present Type C is the dominant technology for large wind farms since this type allows a wider range of dynamic speed control compared to other types and the variable speed range comprises synchronous speed -30% to 20%. Also, only a small fraction of the power passes through the converter, and therefore it is smaller and cheaper when compared with rated capacity converter needed in type D. Further, Type B is not offered any more in Europe and Type A is being phased out of the market [28].

2.6 Future Trends

With increased interest in green power, high level of wind power penetration into the power system is expected. Future developments in the wind turbine industry will be focused on gradual improvements of present technology. Variable-speed pitch-controlled wind turbines will be the preferred type due to the need for full control of the power supplied to the grid. Higher turbine generator capacity and larger blade diameter is the current trend in large wind farms [12, 18]. Development of offshore wind energy is attractive due to the advantages of sites with better wind regimes. Research activities on offshore wind energy are concentrating on new foundation concepts, intelligent control and monitoring systems and utilization of remote locations where visual impact and noise are less important. On the downside, increased costs involved in installation and transmission of power to on-shore could impede progress in this area.

The penetration of wind power into the power system continues to increase dramatically year after year. Large wind farms are being connected to the power grid at transmission and sub-transmission voltage levels. This will have a considerable impact on grid stability, and thereby connection and optimized integration of large wind farms into the power system pose a major research challenge [18, 29]. To minimize the impact on power system operation, utility companies have imposed strict connection and operational requirements (fault ride through, voltage and frequency support) for integration of large wind farms. Consequently, much research is concentrated on the suitability of different wind turbine concepts in complying with utility requirements. These requirements are met by the power electronics within the wind turbines. Considerable research is in progress on controlling and optimizing the power electronic converters and their protection.

Variable speed wind turbine concepts (Type C and Type D) already have a larger market share in the wind power industry. Type C (Doubly Fed Induction Generator) has a cost advantage since only about 30% of generated power is passed through the power converter. However, type D has lesser integration problems since it is fully isolated from the grid [30-31]. Moreover, there is an intensive ongoing research on type D for gearless drives with permanent magnet alternators and gear-based drives with alternators and brushless DFIGs.

CHAPTER III

MODELING ASPECTS

3.1 Induction Machine Modeling

In this section modeling considerations in the phase reference frame and *dq* reference frame are discussed for a standard induction machine. This analysis is based on [25, 32-34].

3.1.1 Phase Reference Frame

Stator and rotor circuits of an induction machine can be represented as in Figure 11, where the axis of phase r rotor winding is leading by θ_r the axis of phase r stator winding. Even a squirrel cage rotor can be represented by a set of equivalent three phase windings. This is because induced currents in rotor produce an MMF with the same number of poles as that produced by the stator winding. Further, as the air gap is uniform, the rotor is symmetrical. This means that only the mutual inductance between stator and rotor windings are dependent on rotor angle position [35].

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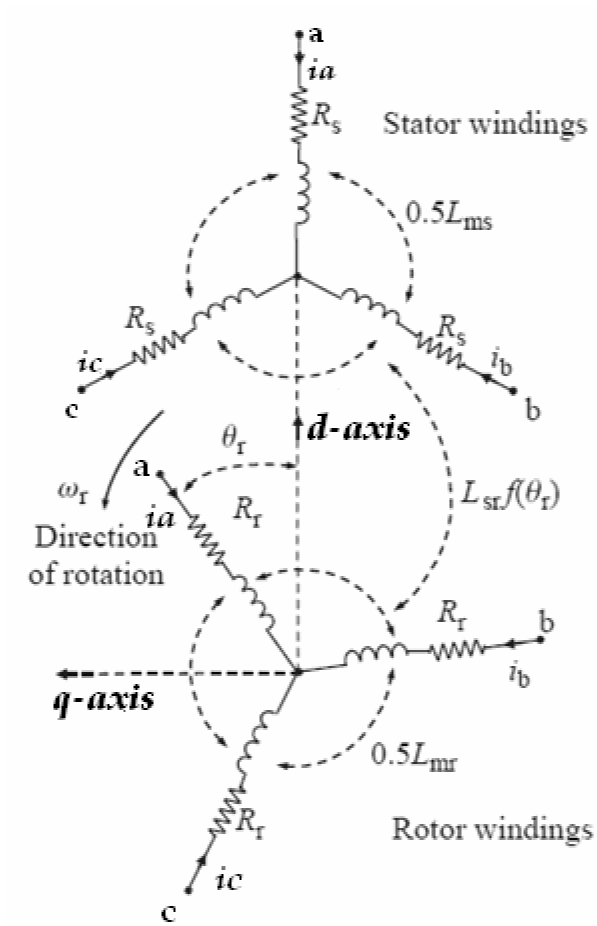

Figure 11: Stator and Rotor Circuits of an Induction Machine [25]

The time domain stator (s) and rotor (r) voltage equations, can be written in the matrix form as,

$$v_{abc\,(s)} = \mathbf{R}_s\, i_{abc\,(s)} + \frac{d}{dt}\psi_{abc\,(s)} \tag{3}$$

$$v_{abc\,(r)} = \mathbf{R}_r\, i_{abc\,(r)} + \frac{d}{dt}\psi_{abc\,(r)} \tag{4}$$

where $\boldsymbol{v}$, $\boldsymbol{i}$ and $\boldsymbol{\psi}$ are 3x1 column matrices and $\mathbf{R_s}$ and $\mathbf{R_r}$ are 3x3 diagonal matrices of R_s and R_r elements, respectively. The time domain stator and rotor flux linkage equations are given by:

$$\begin{bmatrix} \psi_{abc\,(s)} \\ \psi_{abc\,(r)} \end{bmatrix} = \begin{bmatrix} L_{ss} & L_{sr}(\theta_r) \\ L_{rs}(\theta_r) & L_{rr} \end{bmatrix} \begin{bmatrix} i_{abc\,(s)} \\ i_{abc\,(r)} \end{bmatrix} \tag{5}$$

$$L_{ss} = \begin{bmatrix} L_{\sigma s} + L_{ms} & -0.5\,L_{ms} & -0.5L_{ms} \\ -0.5L_{ms} & L_{\sigma s} + L_{ms} & -0.5L_{ms} \\ -0.5L_{ms} & -0.5L_{ms} & L_{\sigma s} + L_{ms} \end{bmatrix} \tag{6}$$

$$L_{rr} = \begin{bmatrix} L_{\sigma r} + L_{mr} & -0.5\,L_{mr} & -0.5L_{mr} \\ -0.5L_{mr} & L_{\sigma r} + L_{mr} & -0.5L_{mr} \\ -0.5L_{mr} & -0.5L_{mr} & L_{\sigma r} + L_{mr} \end{bmatrix} \tag{7}$$

$$L_{sr}(\theta_r) = L_{sr} \begin{bmatrix} \cos\theta_r & \cos(\theta r + 2\pi/3) & \cos(\theta r - 2\pi/3) \\ \cos(\theta r - 2\pi/3) & \cos\theta_r & \cos(\theta r + 2\pi/3) \\ \cos(\theta r + 2\pi/3) & \cos(\theta r - 2\pi/3) & \cos\theta_r \end{bmatrix} \tag{8}$$

$$L_{rs}(\theta_r) = L_{sr}^{T}(\theta_r) \tag{9}$$

The above equations completely describe the electrical performance of an induction machine. However, these equations contain inductance terms which vary with angle θ_r which in-turn varies with time. This introduces considerable complexity in solving machine and associated power system problems. Therefore the above Equations (3 through 9) for the induction machine are simplified by appropriate transformation of phase variables into components along direct and quadrature axes.

3.1.2 *dq* Reference Frame

Three phase stator and rotor windings of an induction machine can be represented by two sets of fictitious orthogonal coils, which are located along direct (*d*) and quadrature (*q*) axes [35] as shown in Figure 12. As in the case of synchronous machines, rotor reference frame is selected. As compared to Figure 11, a 90^0 clockwise rotation is implied in Figure 12.

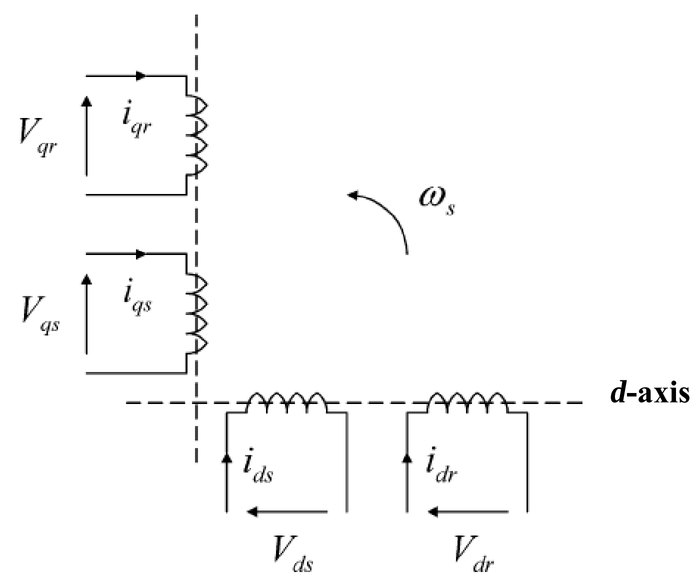

Figure 12 Direct (d) and Quadrature (q) Representation of Induction Machine [35]

The *d*-axis is chosen to coincide with stator phase 'a' axis at t=0 and the *q*-axis leads the *d*-axis by 90^0 in the direction of rotation (counter clock wise). Thus, the stator and rotor quantities can be transformed using the transformation matrix given below:

$$Ts = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta r - 2\pi/3) & \cos(\theta r + 2\pi/3) \\ \sin\theta_r & -\sin(\theta r - 2\pi/3) & -\sin(\theta r + 2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \qquad (10)$$

It can be shown that transformation of equations (3), (4) and (5) gives,

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_{\sigma s} + L_m & 0 & L_m & 0 \\ 0 & L_{\sigma s} + L_m & 0 & L_m \\ L_m & 0 & L'_{\sigma r} + L_m & 0 \\ 0 & L_m & 0 & L'_{\sigma r} + L_m \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \qquad (11)$$

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s i_{ds} \\ R_s i_{qs} \\ R'_r i_{dr} \\ R'_r i_{qr} \end{bmatrix} + \begin{bmatrix} \omega_r \psi_{qs} \\ -\omega_r \psi_{ds} \\ 0 \\ 0 \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} \qquad (12)$$

where,

$$L_m = 1.5\ L_{ms} \qquad (13)$$

$$L'_{\sigma r} = (N_s/N_r)^2 \text{ x } L'_{\sigma r} \qquad (14)$$

$$R'_r = (N_s/N_r)^2 \text{ x } R_r \qquad (15)$$

The speed voltage terms in the rotor voltages are zero in equation (12). This is because the selection of rotor reference frame, in which rotor quantities will coincide with the rotor rather than with the synchronously rotating MMF. The *d* and *q* axes equivalent circuits, which are identical due to the symmetric structure of the rotor, are obtained by substituting Equation (11) in (12). The steady state equivalent circuit can be derived as shown in Figure 12 by converting the time variables into phasors and setting all derivatives to zero.

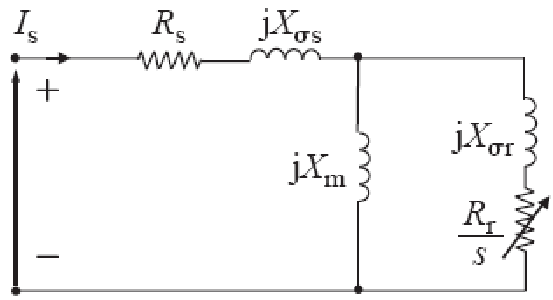

Figure 12: Steady State Equivalent Circuit [25]

The equations are in physical units. However, for power system studies it is desirable to use a per unit (pu) representation. This enables the conversion of the entire system to pu quantities on a single power base. In pu representation, the above equations take the same form since stator rated quantities are taken as base quantities [35].

3.1.3 Choice of Reference Frame

Analysis of machine dynamics could be carried out by selecting a reference frame that is used to convert input voltages (*abc* reference frame) to the *dq* reference frame, and output currents (*dq* reference frame) to the *abc* reference frame. It could be axes rotating with the rotor, axis rotating at synchronous speed or stationary [33]. For analyzing synchronous machine behavior, usually rotor reference frame is selected, assuming the stator voltages are balanced. If the stator voltages are not balanced, stationary reference frame is more suitable. A reference frame rotating at synchronous speed can be used if both rotor and stator voltages are balanced [34-36]. In this study rotor reference frame is selected for simplicity since rotor quantities will coincide with the rotor.

3.1.4 Model Order Selection

The order of the system model depends on the accuracy and resolution required to analyze the system. To study both network transients and generator stator transients higher order system model is required. This will limit the size of the system that can be simulated. Moreover a small time step is required for numerical integration, resulting in an increased computational time [35-37]. For these reasons, order of the generator model is reduced and network transients are neglected for stability analysis of large power systems [36]. A standard method of reducing the order of the machine is to neglect the rate of change of stator flux linkage, which removes the stator transients.

Induction machines could be modeled using higher or lower order representations, depending on the requirements. A third order model is sufficient for dynamic modeling, whereas a fifth order model provides a better resolution for detailed representation of short circuit behavior. However, behavior of converter control systems for wind turbine generators connected through power electronic converters will have a significant effect on short circuit behavior [38].

3.2 Doubly Fed Induction Generator Modeling for Short Circuit Analysis

The *dq* model for a DFIG is similar to the induction generator modeling equations given in Equations (3) to (9). However, the main difference is the *dq* rotor voltages ($\boldsymbol{v}_{dr}$ and $\boldsymbol{v}_{qr}$) are not zero [25]. Instead they are equal to the voltages injected by the rotor side converter. A steady state equivalent circuit of a DFIG is shown in Figure 14 with all rotor quantities referred to the stator side.

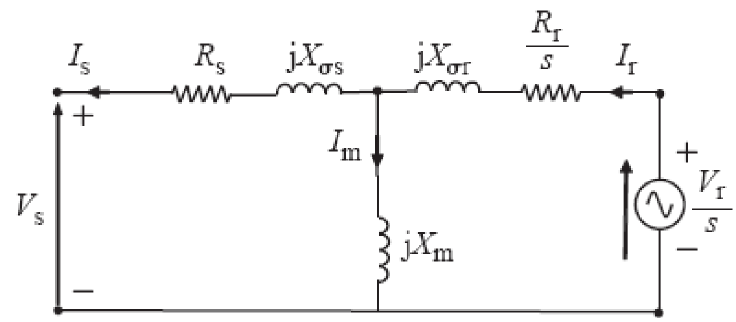

Figure 14: Steady State Equivalent Circuit of a Doubly Fed Induction Generator [25]

Faults in the network cause a voltage dip at the generator terminals and thereby resulting in oscillatory currents in the rotor winding which is connected to the rotor side converter (RSC) [39]. These rotor currents could damage the RSC switches and hence a protective circuit called 'crowbar' circuit is connected across the rotor winding through inverse-parallel thyristors as shown in Figure 9 in Chapter 2. This will block the RSC switches when large instantaneous rotor currents in any phase, which goes above the converter limit, are detected. Then the thyristors in the crowbar circuit are fired to prevent a large overvoltage on the dc link. Crowbar circuit is activated within 2ms [25].

Since the generator is operating at a speed considerably above synchronous speed, crowbar circuits usually have a resistor in series with the rotor winding in order to reduce the reactive power consumption of the generator and improve its electric torque/speed performance [40]. During the fault, after the crowbar operation, the rotor winding of the generator can be treated as a standard wound rotor induction generator with an external rotor (crowbar) resistance (R_{cb}) as in Figure 15.

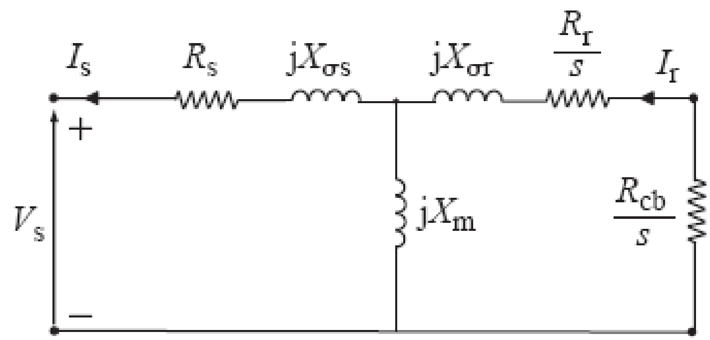

Figure 15: DFIG Rotor Side Converter Short Circuited with Crowbar through Resistance R_{cb} [25]

Once the converter is bypassed and rotor is short circuited through a resistance R_{cb}, the transient short circuit time constant (T'_{cb}) of DFIG is modified by the presencd of R_{cb}. The envelop of the maximum short circuit current is given by [25],

$$i_r(t) \approx \frac{\sqrt{2}V_{rms}}{(1-s)\sqrt{X'^2 + R^2{}_{cb}}}\left[e^{-t/T'_{cb}} + e^{-t/T_a}\right] \qquad (16)$$

Unlike a standard nearly constant speed induction machine whose slip is close to zero, the slip for a DFIG may vary between s=0.3 pu sub-synchronous and s=(-0.2) pu super-synchronous speed depending on machine rating and design. Thus, for a DFIG, the factor (1-s) in Equation (16) cannot be equated to unity. Detailed derivations and calculations of short circuit current contribution are given in [25]. According to equation (16), the magnitude of the fault current is inversely proportional to (1-s), i.e. if the generator initially operates at sub-synchronous speed, the initial fault current magnitude is higher. During a terminal voltage dip, according to the new grid codes, even if the terminal voltage drops to zero, stator should remain connected to the system for at least 150 ms

(9 cycles) [41]. After the rotor current decays, crowbar circuit can be disconnected and converter switches can be unblocked to resume rotor current control from RSC.

As an alternative to the crow bar circuit, a dc chopper circuit could be placed in parallel with the dc link capacitor to protect the converter by blocking converter switches [42]. The chopper circuit is a power electronics controlled resister. The impact of chopper resistance R_{Chop} in the machine equivalent circuit for short circuit analysis is given in Figure 16.

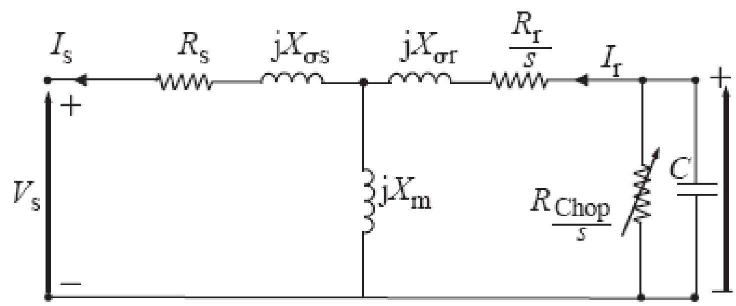

Figure 16: DFIG Rotor Side Converter Protected by a Chopper through Resistance R_{Chop} in Parallel with dc link Capacitor [25]

Short circuit current behavior with chopper resistance is similar to the analysis with crowbar resistor.

CHAPTER IV

FAULT ANALYSIS

4.1 Nature of Faults

A fault on a power system is an abnormal condition that involves an electrical failure of power system equipment operating at one of the primary voltages within the system [11, 25, 43]. There are two types of failures.

1. Insulation failure that results in a short circuit fault: This can occur due to overstressing and gradual degradation of the insulation.
2. Open circuit fault which results in a cessation of current flow

4.2 Causes of Faults

Majority of short circuit faults are related with the weather conditions. The associated weather factors are lightning strikes, accumulation of snow or ice, heavy rain, strong winds, salt pollution depositing on insulators on overhead lines and substations, floods and fires, etc. Low clearance between overhead lines and trees is also a cause for short circuit faults [44]. Short circuit faults can be originated from equipment (generators, transformers, reactors, cables, etc) failure, which can be caused by internal insulation failure due to aging and degradation, breakdown due to switching or lightning overvoltages etc. Further, short circuits faults may also be caused by human error.

Open circuit faults can be caused by the failure of joints on cables or overhead lines or the failure of all three phases of a circuit breaker or disconnector to open or close [25, 44].

4.3 Types of Faults

Different fault types can occur depending on the number of phases involved and whether or not the ground is involved. Short circuit faults may involve with all three phases (with or without the ground), phase to phase, two phases to ground, single phase to ground. Combination these faults happening simultaneously is also a rare possibility for a short circuit fault. A broken overhead line conductor that falls to ground is a simultaneous single phase open circuit and single phase short circuit fault at a particular location. Further, faults are classified as balanced and unbalanced. A three phase fault which symmetrically affects all the three phases is the only balanced fault and all other types of faults are unbalanced [45]. Any one of the fault types mentioned may or may not involve a certain amount of fault resistance.

4.4 Fault Calculations

Balanced faults can be analyzed on a single phase basis since knowing voltages and currents in one phase allows one to calculate those in the other two phases which are $\pm 120^0$ phase displaced from the known phase. Analyzing unbalanced faults can be simplified by using symmetrical components, which divides the unbalanced system to three balanced systems [46].

4.4.1 Symmetrical Components

The method of symmetrical components gives an elegant way of analyzing the operation of a power system during unbalanced conditions. This method was discovered by Charles L. Fortescue in 1913 [47], and practical application for system fault analysis was developed by C.F. Wagner, R.D. Evans [48] and W.A. Lewis in the 1930s. Here an unbalanced three phase system (voltages or currents) is represented by the sum of three sets of balanced or symmetrical systems. They are:

Positive Sequence System: Consists of three vectors equal in magnitude and symmetrically placed at 120^0 intervals with a phase order (positive sequence phase order) equal to the phase order of system generated voltages.

Negative Sequence System: Consists of three vectors equal in magnitude and symmetrically placed at 120^0 intervals with a phase order that is reverse of the positive sequence phase order.

Zero Sequence System: Consist of three vectors all of which are equal in both magnitude and phase.

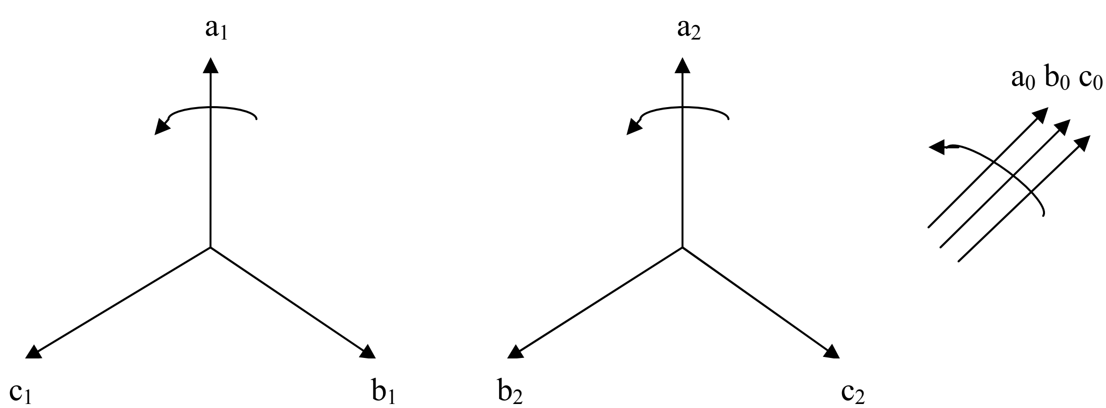

Figure 17: Phase Diagram Representation of Phase Sequence Components

The relationship between phase quantities and sequence quantities are given by the following equations [49, 50].

$$I_1 = 1/3\ (I_a + aI_b + a^2I_c) \tag{17}$$

$$I_2 = 1/3(I_a + a^2I_b + aI_c) \tag{18}$$

$$I_0 = 1/3\ (I_a + I_b + I_c) \tag{19}$$

These three sequence systems could be represented in its simplest form as viewed from the point of short circuit. Thus, positive sequence system can be represented by a driving voltage **E** in series with positive sequence impedance Z_1, negative sequence system by the negative sequence impedance Z_2 and zero sequence system by zero sequence impedance Z_0 as shown in Figure 18.

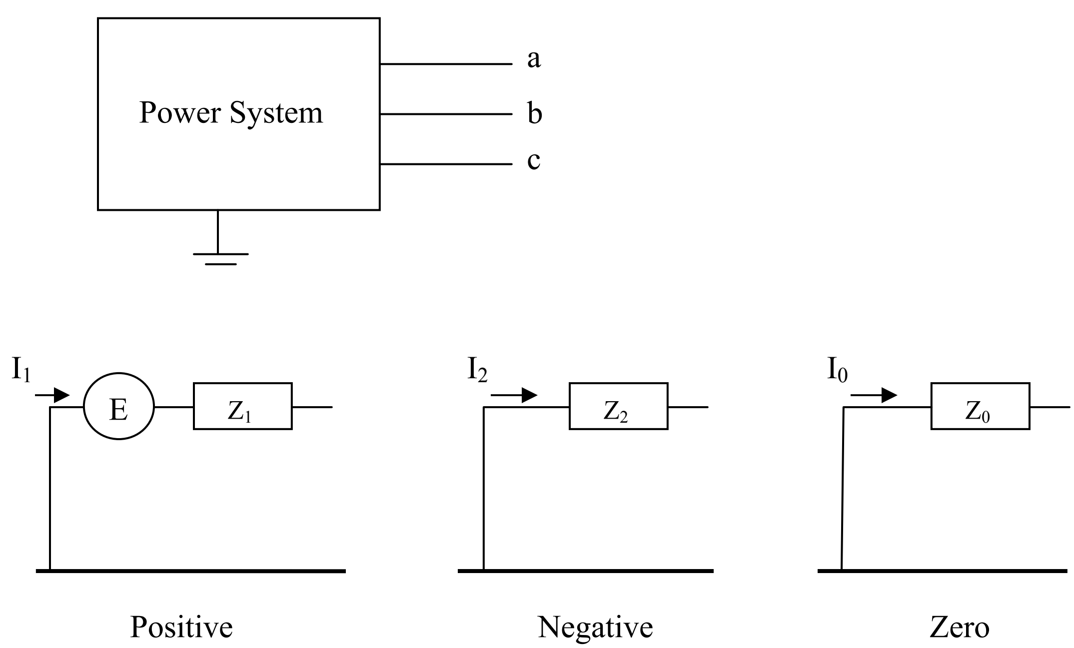

Figure 18: Equivalent Phase Sequence Circuits as seen from the Point of Fault

4.4.2 Three Phase Faults

A three phase fault is shown in Figure 19.

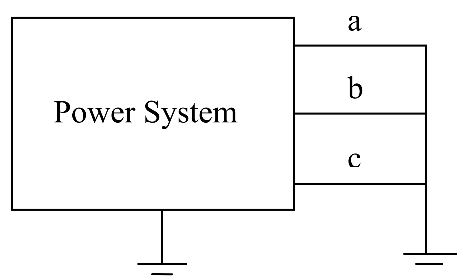

Figure 19: Three Phase Fault

Conditions at the point of fault are,

$$\mathbf{V_a} = \mathbf{V_b} = \mathbf{V_c} = 0 \quad (20)$$

$$\mathbf{I_a} + \mathbf{I_b} + \mathbf{I_c} = 0 \quad (21)$$

Phase and sequence values of currents and voltages are given in Table 2 and 3.

I_1	E / Z_1
I_2	0
I_0	0
I_a	E / Z_1
I_b	$a^2 E / Z_1$
I_c	$a E / Z_1$

Table 2: Sequence and phase currents

V_1	0
V_2	0
V_0	0
V_a	0
V_b	0
V_c	0

Table 3: Sequence and phase voltages

It can be seen from the Table 2 that three phase faults involve only positive sequence quantities.

4.4.3 Phase to Phase Faults

Consider a phase to phase fault between phases ‘a’ and ‘b’ as shown in Figure 20.

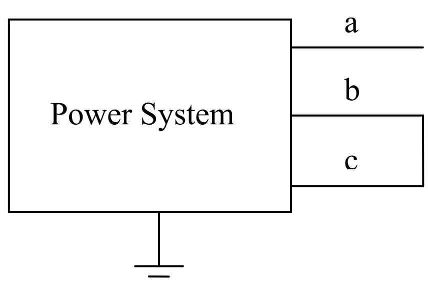

Figure 20: Phase to Phase Fault

Conditions at the point of fault are:

$$\mathbf{I_a} = 0 \qquad (22)$$

$$\mathbf{I_b} + \mathbf{I_c} = 0 \qquad (23)$$

$$\mathbf{V_b} = \mathbf{V_c} = V \qquad (24)$$

Phase and sequence values of currents and voltages are given in Table 4 and 5.

I_1	$E / (Z_1+Z_2)$
I_2	$-E / (Z_1+Z_2)$
I_0	0
I_a	0
I_b	$-j\sqrt{3}E / (Z_1+Z_2)$
I_c	$j\sqrt{3}E / (Z_1+Z_2)$

Table 4: Sequence and phase currents

V_1	$Z_2E / (Z_1+Z_2)$
V_2	$Z_2E / (Z_1+Z_2)$
V_0	0
V_a	$2Z_2E / (Z_1+Z_2)$
V_b	$-Z_2E / (Z_1+Z_2)$
V_c	$-Z_2E / (Z_1+Z_2)$

Table 5: Sequence and phase voltages

It can be seen from Tables 4 and 5 that phase to phase faults involve only the positive and negative sequence quantities.

4.4.4. Single Phase to Ground Fault

Consider a single phase to ground fault between phase 'a' and ground as shown in Figure 21.

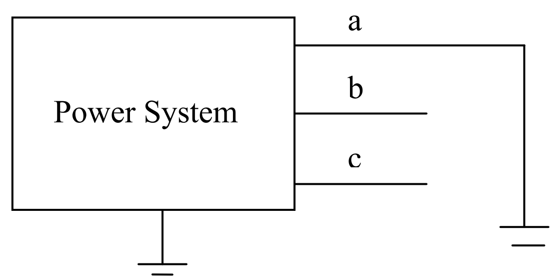

Figure 21: Single Phase to Ground Fault

Conditions at the point of fault are,

$$\mathbf{V_a} = 0 \qquad (25)$$

$$\mathbf{I_b} = \mathbf{I_c} = 0 \qquad (26)$$

Phase and sequence values of currents and voltages are given in Tables 6 and 7.

I_1	$E / (Z_1+Z_2+Z_0)$
I_2	$E / (Z_1+Z_2+Z_0)$
I_0	$E / (Z_1+Z_2+Z_0)$
I_a	$3E / (Z_1+Z_2+Z_0)$
I_b	0
I_c	0

Table 6: Sequence and phase currents

V_1	$(Z_2+Z_0)E / (Z_1+Z_2+Z_0)$
V_2	$-Z_2E / (Z_1+Z_2+Z_0)$
V_0	$-Z_0E / (Z_1+Z_2+Z_0)$
V_a	0
V_b	$[(a^2-a)Z_2+(a^2-1)Z_0]E / (Z_1+Z_2+Z_0)$
V_c	$[(a-a^2)Z_2+(a-1)Z_0]E / (Z_1+Z_2+Z_0)$

Table 7: Sequence and phase voltages

It can be seen from Table 6 that all three sequence currents are equal.

4.4.5 Phase to Phase to Ground Fault

Consider a phase to phase to ground fault between phase ‘b’ and phase ‘c’ and ground as shown in Figure 22.

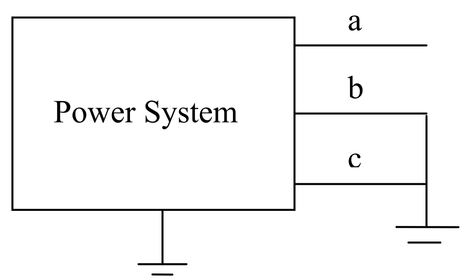

Figure 22: Phase to Phase to Ground Fault

Conditions at the point of fault are,

$$\mathbf{I_a} = 0 \qquad (27)$$

$$\mathbf{V_b} = \mathbf{V_c} = 0 \qquad (28)$$

Phase and sequence values of currents and voltages are given in Tables 8 and 9.

$\mathbf{I_1}$	$\mathbf{(Z_2 + Z_0)E / (Z_1Z_2 + Z_2Z_0 + Z_0Z_1)}$
$\mathbf{I_2}$	$\mathbf{-Z_0E / (Z_1Z_2 + Z_2Z_0 + Z_0Z_1)}$
$\mathbf{I_0}$	$\mathbf{-Z_2 E / (Z_1Z_2 + Z_2Z_0 + Z_0Z_1)}$
$\mathbf{I_a}$	**0**
$\mathbf{I_b}$	$\mathbf{-j\sqrt{3}(Z_2 - aZ_0)E / (Z_1Z_2 + Z_2Z_0 + Z_0Z_1)}$
$\mathbf{I_c}$	$\mathbf{-j\sqrt{3}(Z_2 - a^2Z_0)E / (Z_1Z_2 + Z_2Z_0 + Z_0Z_1)}$

Table 8: Sequence and Phase Currents

V_1	Z_2Z_0 E / $(Z_1Z_2+Z_2Z_0+Z_0Z_1)$
V_2	Z_2Z_0 E / $(Z_1Z_2+Z_2Z_0+Z_0Z_1)$
V_0	Z_2Z_0 E / $(Z_1Z_2+Z_2Z_0+Z_0Z_1)$
V_a	$3Z_2Z_0$ E / $(Z_1Z_2+Z_2Z_0+Z_0Z_1)$
V_b	0
V_c	0

Table 9: Sequence and Phase Voltages

It can be seen from Table 9 that all three sequence voltages are equal.

4.4.6 Phase to Phase plus Single Phase to Ground Fault

Consider a phase to phase fault between phase ‘b’ and phase ‘c’, and a single phase to ground fault between phase ‘a’ and ground as shown in Figure 23.

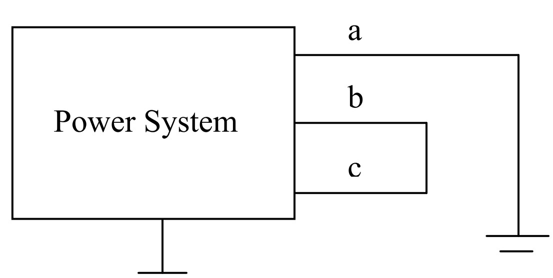

Figure 23: Phase to Phase to Ground Fault

Conditions at the point of fault are:

$$\mathbf{V_a} = 0 \quad (29)$$

$$\mathbf{V_b} = \mathbf{V_c} = V \quad (30)$$

$$\mathbf{I_b} + \mathbf{I_c} = 0 \quad (31)$$

Phase and sequence values of currents and voltages are given in Tables 10 and 11.

I_1	$(4Z_2 + Z_0)E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
I_2	$-Z_0E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
I_0	$2Z_2 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
I_a	$6Z_2 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
I_b	$-j\sqrt{3}(2Z_2 + Z_0)E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
I_c	$j\sqrt{3}(2Z_2 + Z_0)E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$

Table 10: Sequence and phase currents

V_1	$Z_2Z_0 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
V_2	$Z_2Z_0 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
V_0	$-2Z_2Z_0 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
V_a	0
V_b	$-3Z_2Z_0 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$
V_c	$-3Z_2Z_0 E / (4Z_1Z_2 + Z_2Z_0 + Z_0Z_1)$

Table 11: Sequence and Phase Voltages

It can be seen from Table 11 that positive and negative sequence voltages are equal and have a value equal to one-half of the zero sequence voltage.

4.5 Factors Affecting the Fault Current Contribution in a Wind Farm

There are several factors which determine the level of fault current contribution from wind farms.

4.5.1 Number and Size of Wind Farms

In a wind farm there can be a few or large number of generators. If there are more parallel connected generators, they will present a lesser source impedance to the power system and more fault current contribution in case of a fault on the power system side or in the wind farm collector system. Further, size of generators, generator transient/ sub-transient impedance and their short circuit ratios (SCR), will have an significant impact on fault current contribution [51].

4.5.2 Type of Wind Turbine Generators

Over the years different types of generators have been used in wind farms as discussed in section 2.5 in Chapter 2. Fault current contribution of synchronous generators, induction generators and generators with full/partial power electronic interfaces are briefly discussed below.

4.5.2.1 Synchronous Generator

A Synchronous generator when subject to a three phase fault at its terminals will contribute fault current as shown in Figure 24. This will encompass a sub-transient period, transient period and a steady state period [52]. Since sub-transient period (time constant) is comparatively small, transient period (thereby transient reactance) will determine the fault current contribution.

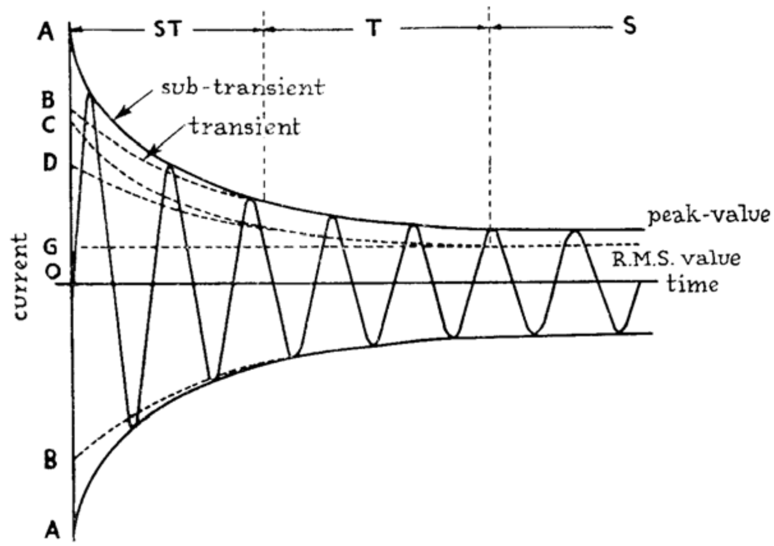

Figure 24 –Synchronous Generator Short Circuit Current Characteristics [52] (ST-Sub-transient period, T-Transient period, S-Steady state period)

4.5.2.2 Induction Generators

Behavior of an induction generator under fault condition is different from a synchronous generator since induction generators do not have field windings to develop the required electro-magnetic field in the machine's air gap. A three phase fault on the generator terminals will interrupt the reactive power import, which is required to maintain the excitation of the induction generator [15, 30]. As shown in Figure 25, fault current diminishes rapidly as the stored magnetic energy in the machine decays. As a result the fault current contribution is limited to sub-transient period.

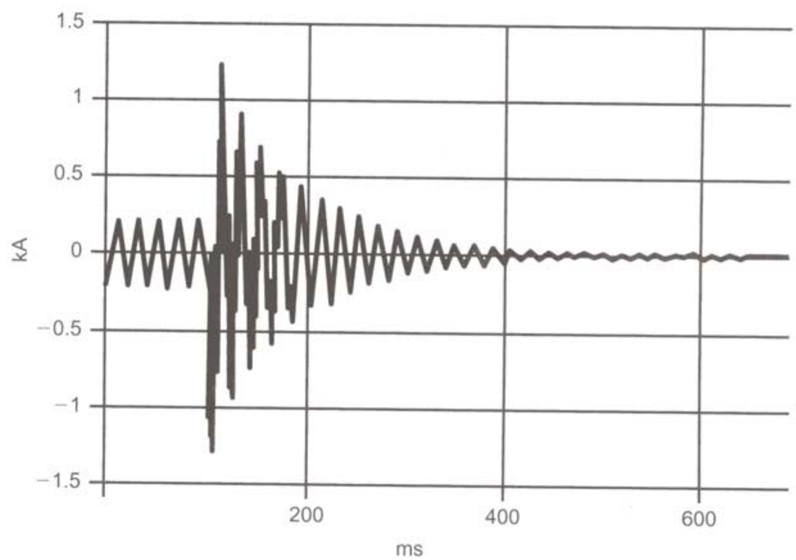

Figure 25 – Fault Current of Induction Generator when a Three-phase Fault occurs at its Terminals (phase shown with minimum offset) [15]

4.5.2.4 Power Electronic Interface

Variable speed wind turbines are connected to the grid via full/partial power electronic interfaces, which comprise of ac/dc converters, dc links and dc/ac inverters. Normally these are self commutated Pulse Width Modulated (PWM) converters. This interface allows the wind turbine generator to configure and control functions such as reactive power control, power system stabilization and power system damping as can be implemented in ac synchronous generators through the excitation system [53]. DC injection into the power system through the inverters can create high frequency harmonic components in load currents as well as fault currents, which should be controlled. Fault current contribution from a power electronic converter interfaced wind turbine generator is lesser as compared to a similar synchronous generator. However, large wind farms with MW scale wind turbines can have an impact on transient fault currents.

4.5.3 Transformer Winding Configuration

The selection of the interconnection transformer configuration has a major impact on how the wind farm will interact with the connected power system [54]. Figure 26 shows five commonly used transformer connections. Here the High Voltage (HV) terminal is the utility side and the Low Voltage (LV) terminal is the wind farm side.

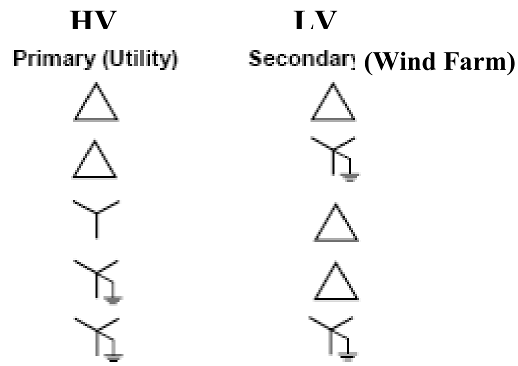

Figure 26: Interconnection Transformer Connections [54]

In first three connections, Delta(HV)/Delta (LV), Delta(HV)/Grounded Wye (LV) and Ungrounded Wye (HV) /Delta (LV), there is no connection to ground on the HV side and thereby no source of ground fault current to interact with utility side relaying. A ground fault on the LV side of the transformer will not be detected by the utility side. With this ungrounded connection, phase faults will have two sources of fault currents. The last two connections, Grounded Wye (HV)/Delta (LV) and Grounded Wye (HV)/ Grounded Wye (LV), will have a source of earth fault current on the HV side, which increases the ground fault current level on the utility side [54, 55]. Large number of wind farms with several interconnection transformers can make a significant impact to the phase and ground fault contribution and thereby maloperate existing protective devices.

4.5.4 Grounding Arrangement

Different grounding practices are used in wind farms for generator, generator transformer and substation step-up transformer. Depending on the grounding method (ungrounded, solidly grounded, impedance grounded etc.) used, fault loop impedance for internal and through (external) faults could change. Descriptions of power system grounding methods are given in Appendix-B.

4.6 Potential Fault Locations in a Wind Farm

- Generator winding
- Generator terminals
- Cable connecting generator and local transformer (tower cable)
- Generator step-up transformer
- Collector feeder cable
- MV bus
- Step-up transformer
- PCC (Point of Common Coupling)
- Power system

CHAPTER V

METHODOLOGY

5.1 Wind Farm Layout

The wind farm considered in this study has a total installed capacity of 9 MW, consisting of six wind turbines, each having a capacity of 1.5 MW and a rated output voltage of 575V. These wind turbines are variable speed, pitch regulated Doubly Fed Induction Generators (DFIG). An adjustable tower cable will connect the generator output to a pad mounted generator step-up transformer (575V/34.5 kV), which is located close to the tower base. Medium voltage side of the step-up transformer is connected to a collector feeder, which is connected to the Medium Voltage (MV) bus rated at 34.5kV. Further stepping up of voltage is done by the main step-up transformer (34.5/240 kV), which is located at the substation and then connected to the power system (240 kV) at Point of Common Coupling (PCC). Figure 27 shows the layout of the wind farm. Parameters of generator, transformers and cables are given in Appendix-A.

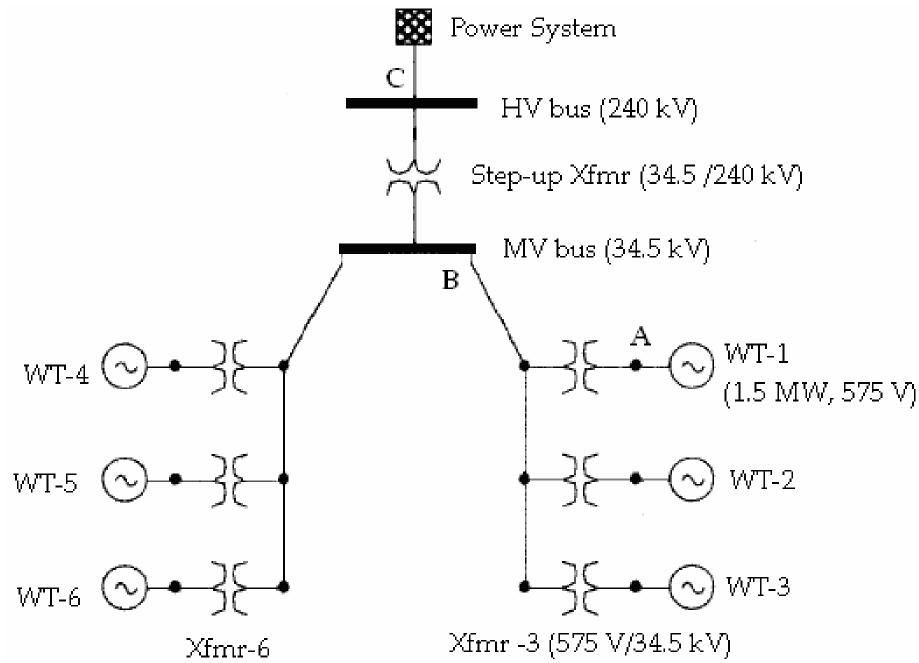

Figure 27: Wind Farm Layout

5.2 Wind Farm Modeling in Matlab/Simulink/SimPowerSystems

This wind farm is modeled in the power system simulation software Matlab/Simulink/SimPowerSystems. Figure 28 shows the wind farm model, which is developed using SimPowerSystems [56] library components.

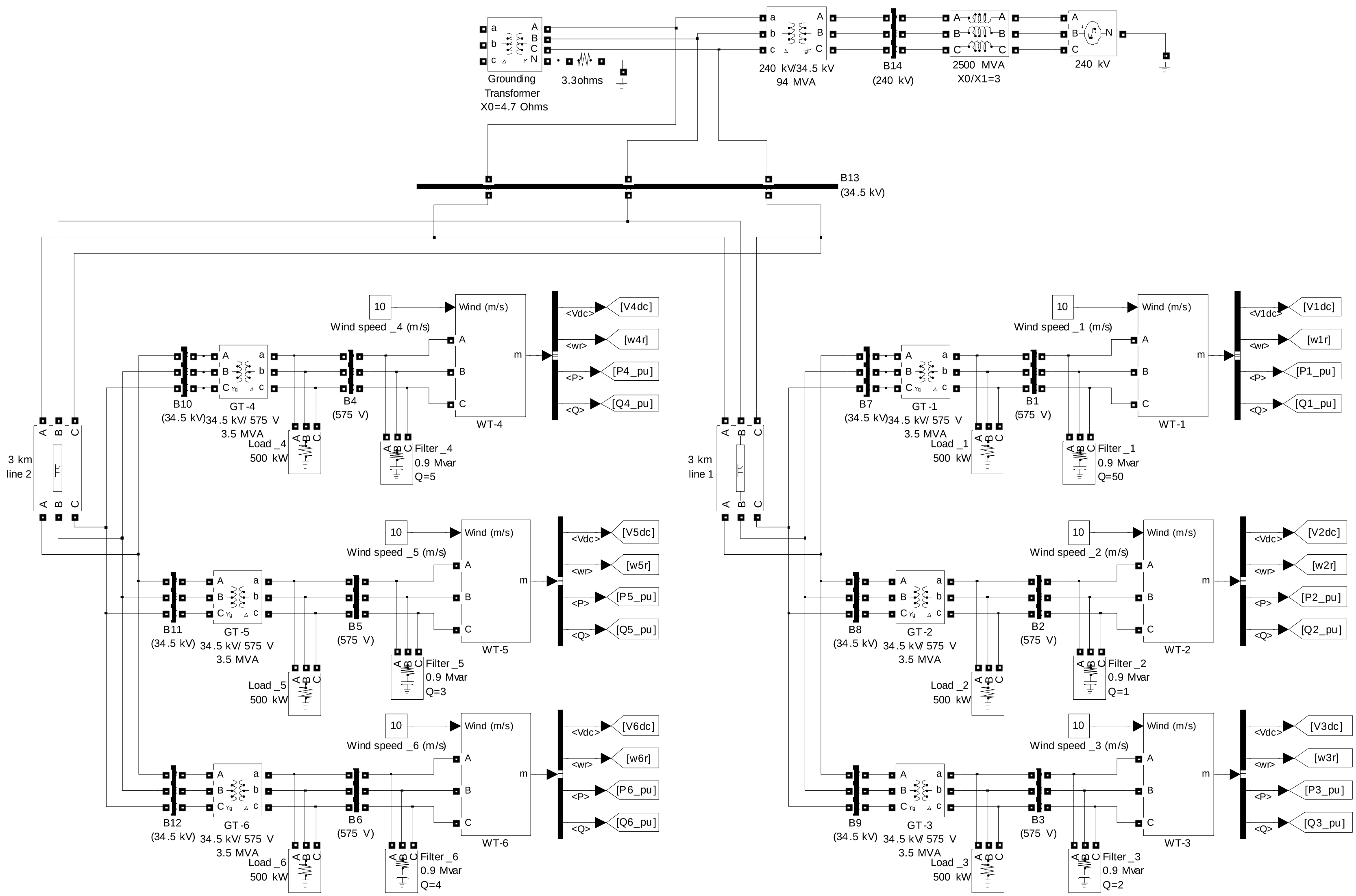

Figure 28: Wind Farm Model in Matlab

5.3 Procedure

Symmetrical (three phase) and asymmetrical (phase to phase and single phase to ground) faults have been created at the following locations:

1. Close to High Voltage bus
2. Close to Medium Voltage bus
3. Generator terminal

Time domain voltage and current waveforms at generator-1 terminal, medium voltage bus and high voltage bus were observed for 1.5 seconds. Simulations start at t=0 sec and faults are created at t=0.5sec. Faults are cleared after 0.1 sec at t=0.6 sec. Fault resistance has been kept constant at 0.001Ω. The simulation results obtained are presented and discussed in the next chapter.

CHAPTER VI

FAULT SIMULATIONS AND DISCUSSION OF RESULTS

Different types of faults are created at wind generator terminal, medium voltage bus and in the power system close to the HV bus. Voltage and current waveforms are observed for all three phases during the simulation period and the results are presented and discussed in this chapter.

6.1 Three Phase Faults

6.1.1 On Generator-1 Terminal

A three phase fault is created at the generator -1 terminal (at location marked A in Figure 27 in Chapter 5) at t=0.5s and cleared at t=0.6s. Figure 29 and Figure 30 show the voltage and current waveforms respectively at the generator-1 terminal. During the fault, voltages of all three phases reach very low values as shown in Figure 29. Ideally this should reach to zero, but in practice, there will be some fault resistance and hence there will be a very small magnitude voltage value. In this study the fault resistance is kept constant at 0.001Ω.

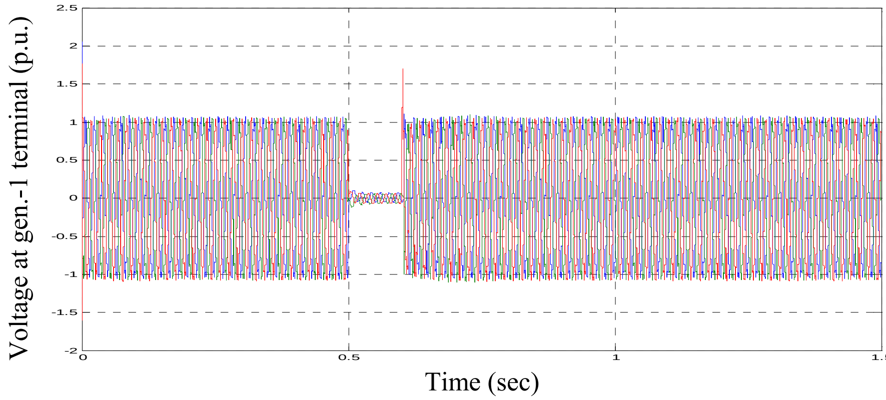

Figure 29: Voltage at Gen.-1 Terminal for 3φ Fault on Gen.-1 Terminal

Generator terminal current will suddenly increase at the instant of fault initiation as shown in Figure 30, followed by a rapid decay as determined by the transient time constant of the generator.

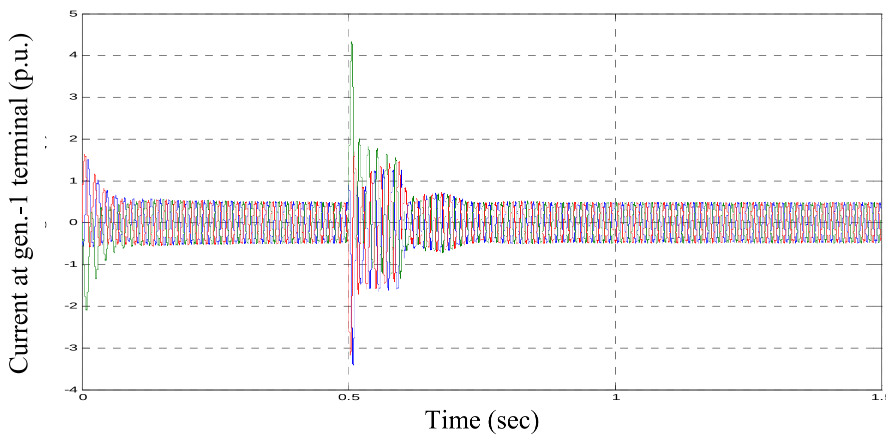

Figure 30: Current at Gen.-1 Terminal for a 3-ph Fault on Gen.-1 Terminal

Doubly Fed Induction Generators (DFIG) are not equipped with external capacitor compensation devices. However, since the rotor side converter is blocked and rotor is short circuited during a fault, DFIG will behave as a normal induction generator with crowbar resistance as discussed in section 3.2 in Chapter 3. Thus, there will be no reactive power source to the generator in order to continuously feed the fault and thereby fault currents will experience a fast decay. After the instant of fault clearance, decaying fault current will reach steady state values after few transients.

For the same fault, voltage and current waveforms were observed at the Medium Voltage (MV) bus (location B in Figure 27) as shown in Figure 31 and Figure 32, respectively.

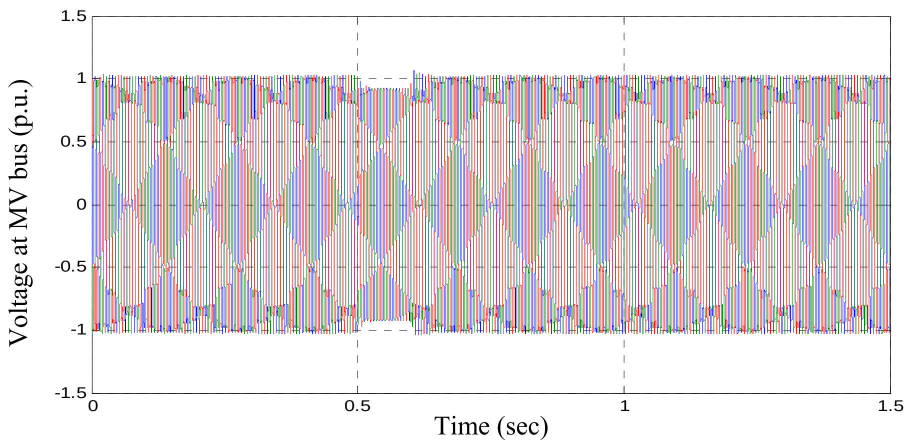

Figure 31: Voltage at MV bus for a 3-ph Fault on Gen.-1 Terminal

Voltage drop on the MV bus is marginal when compared to the voltage drop at the generator terminal as seen in the Figure 31. This is due do the positive sequence generator step-up transformer impedance, positive sequence impedance of the collector cable section and the fault resistance.

During the fault period, current at MV bus jumps to a high value and will not experience an appreciable decay as shown in Figure 32. This is due to the expected feed from other generators and from the power system.

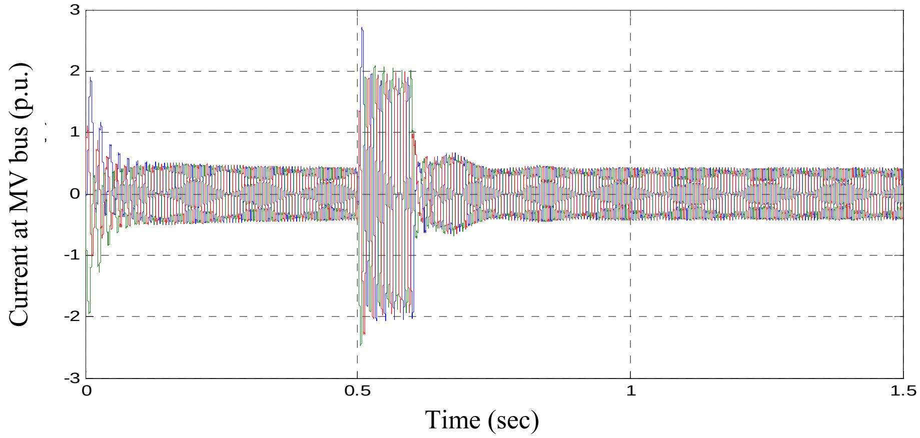

Figure 32: Current at MV bus for a 3-ph Fault on Generator-1 Terminal

Other generators will also see the fault at generator-1 and will start feeding the fault until the fault is cleared. The fault current contributions from other generators are comparatively lower since those generators are at a distance from the fault with additional impedances of collector feeder and generator transformer. Generator-3 current behavior is shown in Figure 33.

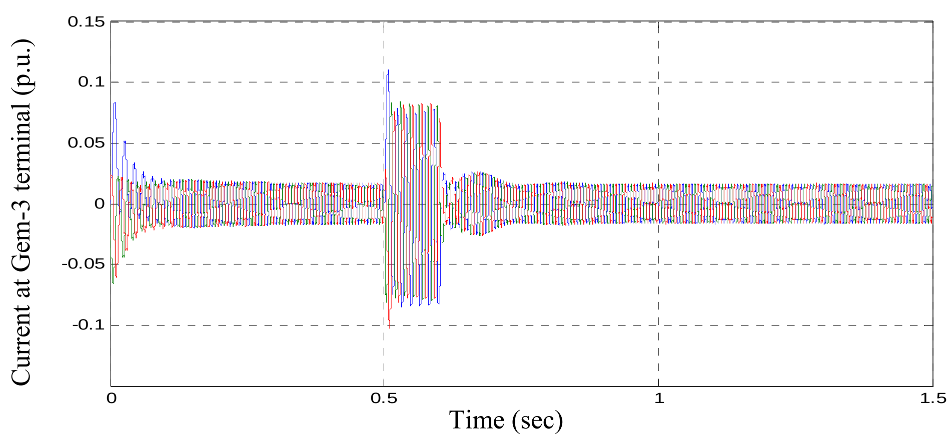

Figure 33: Current at Generator-3 for a 3 ph Fault at gen-1 Terminal

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6.1.2. Three Phase Fault on Power System (Close to HV bus)

A three phase fault is created close to the high voltage bus (at location marked C in Figure 27) at t=0.5s and cleared at t=0.6s. Voltage and current waveforms at generator-1 terminal are shown in Figure 34 and Figure 35, respectively. Voltage collapse at the instant of the fault initiation and a small residual voltage are present during the fault period. This is due to the additional fault loop impedance introduced by step-up transformers and cables. Results are similar to a three-phase fault at the generator terminal.

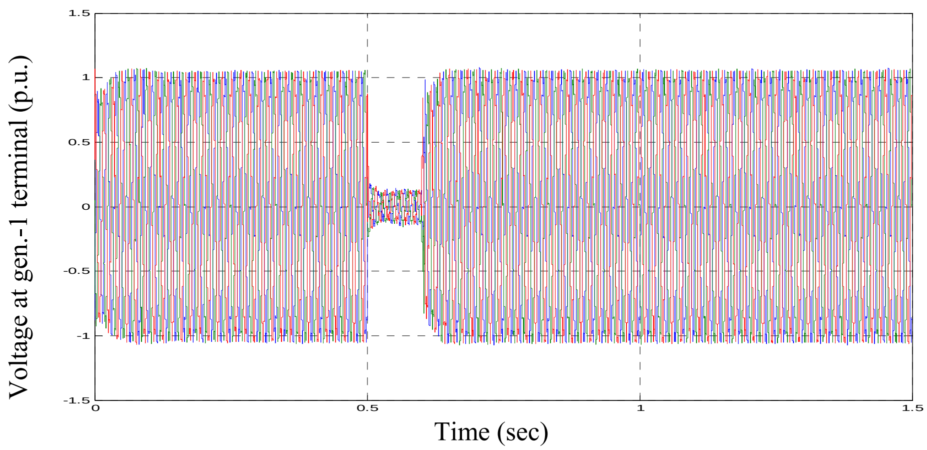

Figure 34: Voltage at Generator-1 Terminal for a Fault on HV Bus

For the same fault, current waveforms observed at generator-1 terminal are shown in Figure 35. At the instant of the fault initiation, generator terminal current will suddenly increase. Gradual decay of fault current can be seen, which is determined by the impedance present in the fault loop. The time constant for the fault current decay is less as compared to a three phase fault at generator terminal, because of the additional impedance (transformer and cable impedance) present in the fault loop. Unlike in the case of a three phase fault at generator terminal, capacitor banks connected to MV bus and generator grid side converter of DFIG will contribute reactive power to the fault. This is a reason for the current transients experienced for about 0.2 seconds after the instant of fault clearance.

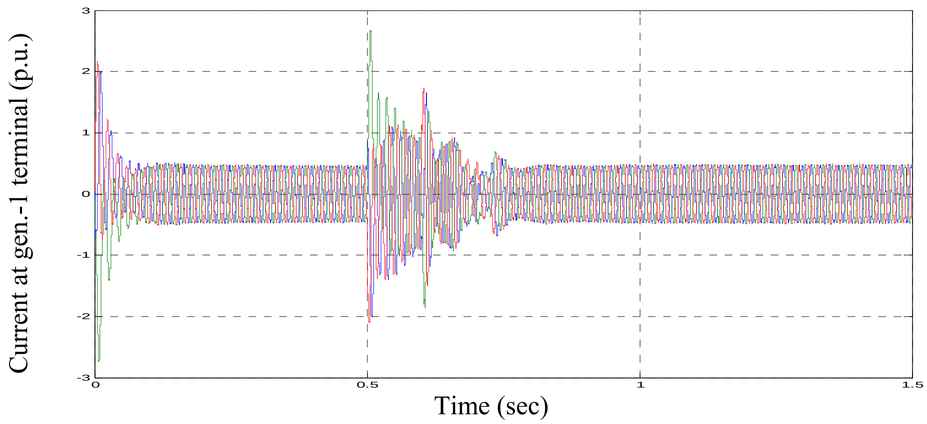

Fig.35. Current at generator-1 terminal for a fault on HV bus

Similar results can be seen for the current and voltage waveforms measured at MV bus for a three phase fault created close to the HV bus (at location marked 'C' in Figure 27) as shown in Figure 36 and Figure 37 respectively. Voltage drop at the instant of the fault and the residual voltage are less compared to the voltage measured at the generator terminal (Figure 34). This is due to the low fault loop impedance.

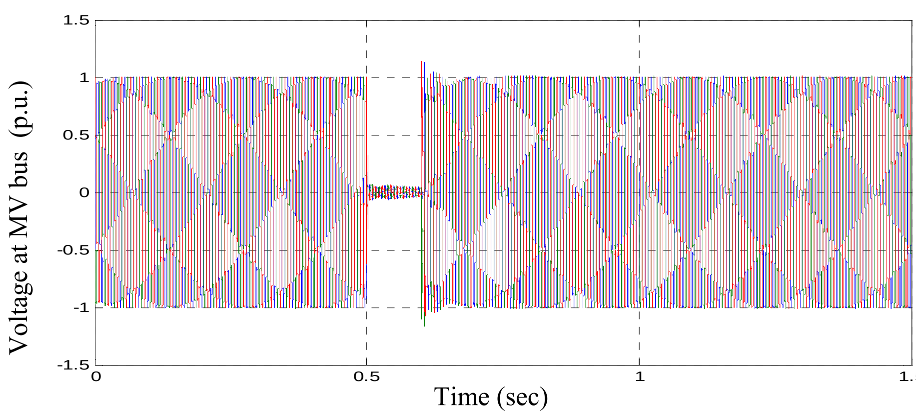

Fig.36. Voltage at MV Bus for a Fault on HV Bus

Current waveforms also behave similar to the generator terminal current. However, post fault transients prolong for a few milliseconds. This is due to the reactive power supplied by the capacitor banks at MV bus.

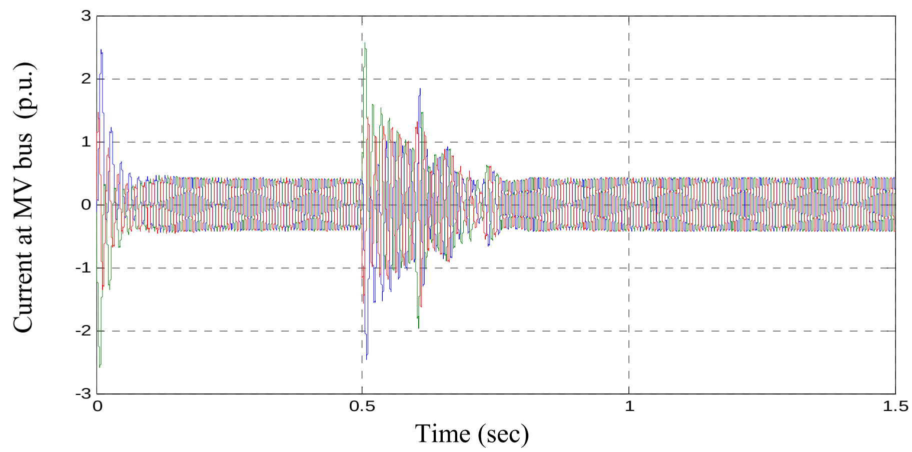

Fig.37. Current at MV bus for a fault on HV bus

6.2 Phase to Phase Faults

A phase to phase (phase ‘a’ to phase ‘b’) fault is created at generator-1 terminal (at location marked A in Figure 27) at t=0.5s and cleared at t=0.6s. Voltage and current waveforms are obtained at generator-1 terminal as shown in Figure 38 and Figure 39 respectively.

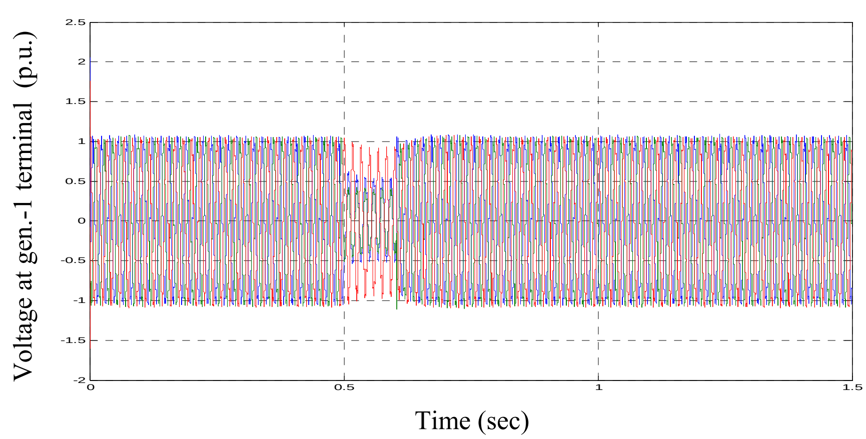

Figure 38: Voltage at Generator-1 Terminal for φ-φ Fault on Generator-1 Terminal

During the fault, phase ‘a’ and phase ‘b’ voltages drop considerably and a marginal drop can be seen in phase ‘c’ (red color) voltage as shown in Figure 38. This behavior is inline with the expected voltage, which is given in section 4.4.3 in Chapter 4.

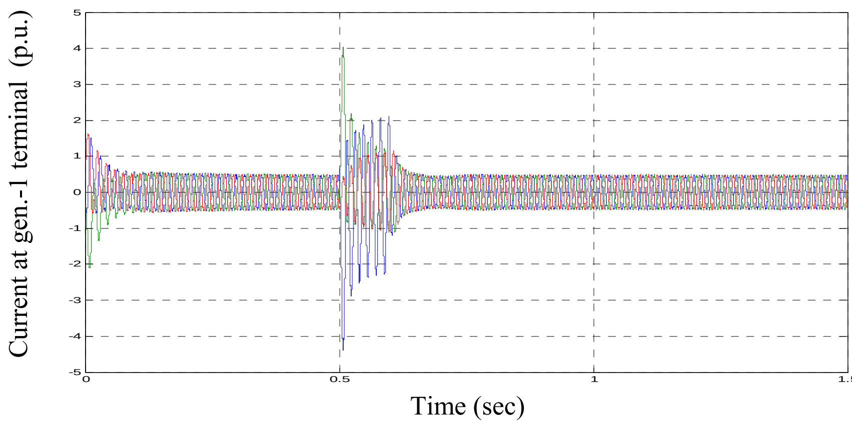

Figure 39: Current at Generator-1 Terminal for φ-φ Fault on Generator-1 Terminal

Current going through phase ‘a’ should return through phase ‘b’ during the fault condition. After the fault initiation, this can be seen as $I_a = -I_b$, phase ‘a’ current (blue color) and phase ‘b’ current (green color) going in opposite directions as shown in Fig.39. Ideally, phase ‘c’ current should decay to zero. Initially there is a marginal drop of phase ‘c’ current and afterwards a transient condition results. This is due to the feed from other wind generators and from the power system.

6.3 Single Phase to Ground Faults

6.3.1. On Generator Terminal

Single phase to ground (phase ‘a’ to ground) fault is created on generator-1 terminal (at location marked A in Figure 27) at t=0.5s and cleared at t=0.6s. Observed voltages and currents are shown in Figure 40 and Figure 41 respectively. Phase ‘a’ voltage (blue color) has dropped and phase ‘b’ (green color) and phase ‘c’ (red color) have experienced an overvoltage as shown in Figure 40. This overvoltage condition is in line with the ideal conditions for a single phase to ground fault given in section 4.4.4 in Chapter 4. Further, this will depend on the grounding method employed at the generator step-up transformer. If the generator step up transformer is solidly grounded, voltages at unfaulted phases will remain at the phase to ground value, and if it is ungrounded or grounded through a resistor, voltages could go all the way up to line to line voltage. Low voltage side of the generator transformer is directly grounded (without any intentional resistance) is this study. However, there will be some leakage and coupling capacitance to ground in addition to the resistance of the grounding wires. This is the reason for the overvoltages of phase ‘b’ (green) and ‘c’ (red) as shown in Figure 40.

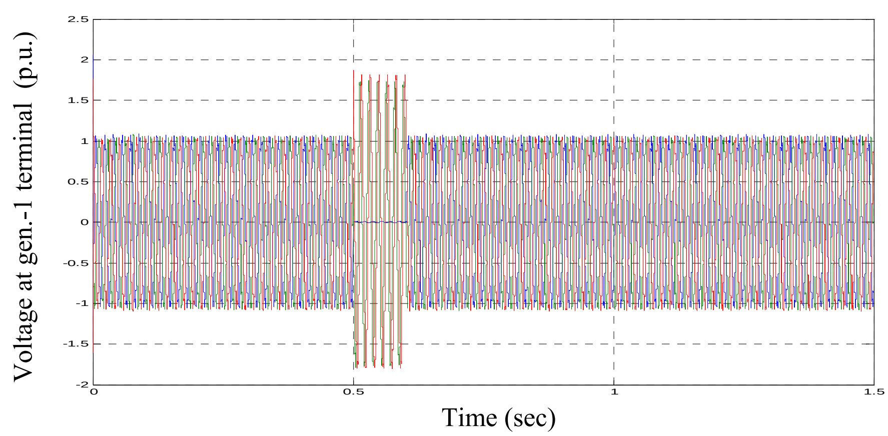

Figure 40: Voltage at Generator-1 Terminal for φ-G Fault on Generator-1 Terminal

Current waveforms at generator terminal for the single phase to ground fault on generator-1 terminal is shown in Figure 41. Ideally, phase ‘b’ (green color) and phase ‘c’ (red color) currents should drop to zero, and phase ‘a’ (blue color) should experience an overcurrent as given in section 4.4.4 in Chapter 4. A marginal increase in phase ‘a’ (blue color) is observed and a reduction in phase ‘b’ and ‘c’ voltages can be seen in Figure 41.

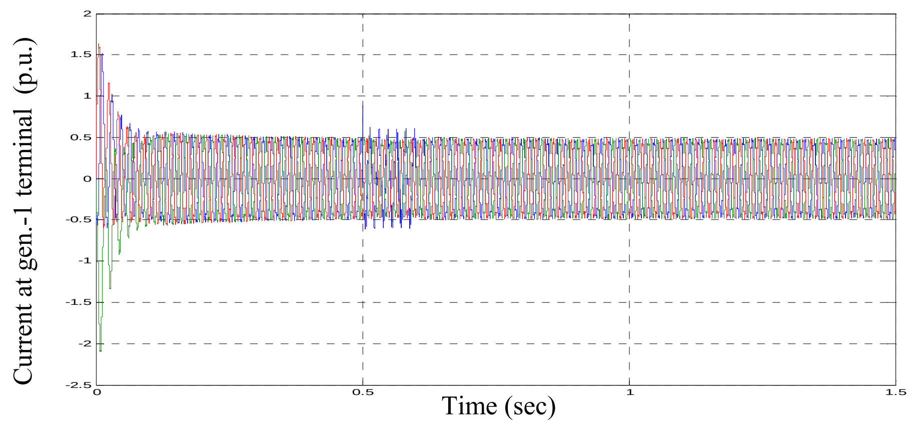

Figure 41: Current at Gen.-1 Terminal for φ-G Fault on Gen.-1 Terminal

6.3.2. On Medium Voltage Bus

Single phase to ground (phase ‘a’ to ground) fault is created close to medium voltage bus (at location marked B in Figure 27) and voltage and current waveforms are observed at MV bus as shown in Figure 42 and Figure 43 respectively. Phase ‘a’ (blue color) voltage drops close to zero and other two phases will experience an overvoltage as shown in Figure 42.

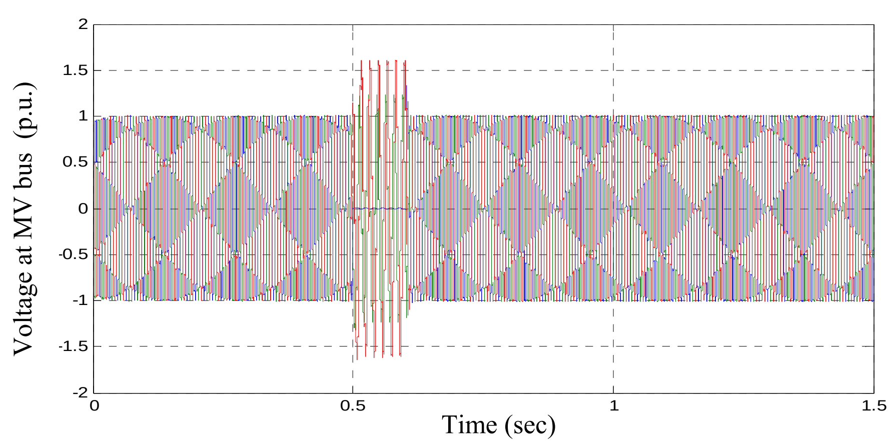

Figure 42: Voltage at MV Bus for a Phase ‘a’ to Ground Fault on MV Bus

This behavior is inline with the ideal conditions for a single phase to ground fault which is given in section 4.4.4 of Chapter 4.

Usually the MV side of main step-up transformer winding is wye-grounded or delta with a grounding transformer which has a zigzag winding. Grounding transformer is grounded through a resistor or a grounding inductor to limit ground current contribution. Thus, an overvoltage could occur in phase 'b' and 'c' due to the grounding method. However, whether the grounding transformer is solidly grounded or grounded through a small impedance, there will be an overvoltage in other unfaulted phases for a ground fault. This is due to the coupling capacitance of the cables and transformer to ground.

Current waveform for the above ground fault is shown in Figure 43. Phase 'a' (blue color) current will increase at the instant of the fault and will experience a gradual decay.

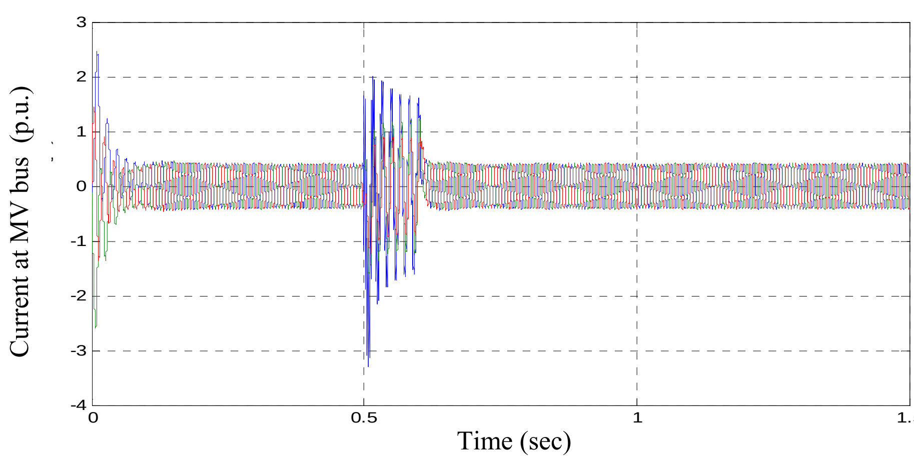

Figure 43: Current at MV Bus for a Phase 'a' to Ground Fault on MV Bus

CHAPTER VII

WIND FARM PROTECTION

7.1 Protection Zones

Electrical protection system associated with a wind farm is divided into several protection zones as shown in Figure 44.

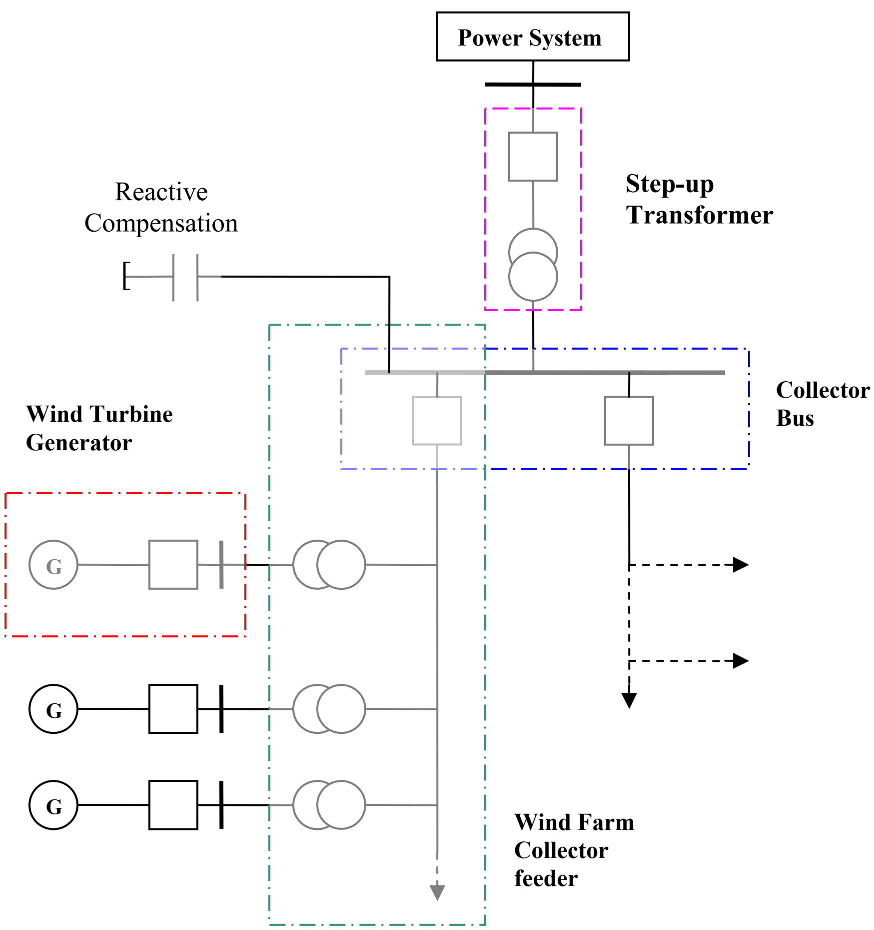

Figure 44: Protection Zones of a Wind Farm

Protection zones are wind turbine generator, collector feeder including generator transformers, collector bus, substation step-up transformer and the power system. These can be overlapped depending on the redundancies required in protection functions [57].

7.2 Instrument Transformer Requirements

Instrument transformers are the main input devices for a protection system. Current transformers provide a secure secondary current input to protection, control and measuring systems. Secondary voltage is obtained from voltage transformers.

7.2.1 Current Transformers

Current transformers are located in every protection zone and provide secondary current input to primary and secondary protection functions. They are selected based on the rated current and the maximum expected fault current in the protection zone. Further, different classes of current transformers are used depending on the protection function and the required level of accuracy [58].

7.2.2 Voltage Transformers

Voltage transformers (VT) are used to obtain effective and secure secondary voltages for metering, control and protection equipments. For HV and extra HV (EHV) applications, electromagnetic voltage transformers are not economical due to their larger sizes and higher costs [59]. Thus, Capacitive Voltage Transformers (CVT) are preferred at HV and EHV levels. VTs are installed in a large wind farm at collector feeders, medium voltage bus and HV side of the main step-up transformer(s). CVTs are placed at the HV side of the step-up transformer, to obtain secondary voltage inputs to step-up transformer protection relay, interconnected line current differential relay, breaker failure relay, SCADA (Supervisory Control And Data Acquisition) equipments, etc.

7.2.2.1 Capacitive Voltage Transformers

During steady state conditions, CVTs produce a secondary voltage signal which is acceptable for proper functioning of protection and control equipments. However, during transient conditions, such as faults which cause very depressed phase voltages, the CVTs' output voltage may not closely follow its input voltage due to the internal energy storage elements [57]. This will have a major impact on protection relays and control equipments.

7.3 Generator

Generator protection is inbuilt with the generator control system. It has under/over voltage (27/59)*, under/over frequency (81U/81O)* protection function coordinated with collector system and substation protection settings.

*IEEE/ANSI Standard Device Numbers

7.4 Generator Transformer

Generator transformer will step up the generator output voltage (575 V) to collector system voltage (34.5 kV). Normally it is a pad mounted transformer located close to the base of the tower. However, some wind turbine manufacturers design the generator transformer for location inside the nacelle as a dry type transformer to reduce losses. Generator transformer is protected with a fuse on the MV side. In some installations, the fuse is replaced by a Molded Case Circuit Breaker (MCCB) which has adjustable thermal and magnetic settings.

7.5 Collector Feeder System

Wind farm collector feeder system, which is typically rated at 34.5 kV, consists of radial feeders which collect the output from wind turbine generators and connects to the collector bus at the wind farm substation. In most wind farms, collector feeders are underground cables and each may run up to several miles. The underground cable distributed capacitance is insufficient to compensate for the reactive losses in the collector cable and the wind turbine induction generators. Therefore a reactive compensation should be provided at the collector bus [60]. This could be a switched capacitor bank or a dynamic VAr control system.

Wind turbine generators are connected to the collector feeder and no other independent load is connected to the feeder. Moreover, for a fault in the collector feeder, fault current contributions from the wind generators are less when compared with that of the contribution from the power system. Thus, collector feeders can be considered as radial distribution feeders and their protection can be provided by overcurrent (50/51)*, ground fault (50G/51G)* with synchronism check (25)* devices. In-feeds and fault current contribution from wind turbines for different fault types are important considerations when setting the collector feeder protection relay.

*IEEE/ANSI Standard Device Numbers

7.6 Collector Bus

Collector bus is placed in the wind farm substation and all collector feeders are connected to the collector bus bar. Bus bar differential protection is used in large wind farms to protect the bus bar. This needs Class X current transformers in each outgoing collector feeder close to the bus bar, and on the medium voltage side of the substation step-up transformer. In addition, breaker failure protection is provided in case of a failure of a circuit breaker to open.

7.7 Substation Step-up Transformer

Substation step-up transformer steps up the 34.5 kV collector system voltage to power system voltage to which the wind farm is connected. Large wind farms are connected to the high voltage power grid typically at 138kV or 240 kV. Transformer winding configuration can be delta on the medium voltage side and grounded-Wye on the high voltage side, or a three winding transformer with grounded-Wye on MV and HV side, and delta on the tertiary winding. In the former case, grounding transformer with a zig-zag winding is used on the MV delta side to provide a grounding path to the collector system. Step-up transformer is protected with transformer differential (87T)* protection as the primary protection and time overcurrent (51)* protection as the back-up protection.

7.8 Interconnection

During the 1990's wind turbine generators were expected to disconnect for disturbances in the power system network or in case of loss of the network supply. In order to detect such conditions, Rate Of Change Of Frequency (ROCOF) and Voltage Vector Shift (VVS) protection functions were used and wind turbines were tripped immediately to avoid islanding conditions which can lead to overvoltage and ferroresonnace conditions. Further, wind turbine generators are not grounded at the neutral point and in case of an islanding condition wind farm will be isolated with its captive load from the grid. In such a case, to detect loss of ground, Neutral Voltage Displacement (NVD) protection is employed. Since this protection will activate after a time delay, it is insufficient to detect loss of the network supply [4, 8, 28]. However, with the development of wind power industry and associated high penetration levels, new grid code requirements were introduced by Transmission System Operators (TSO), where the protection functions discussed above cannot be applied for large wind farm as before. Hence, providing adequate protection for wind farms as well as for the system is a challenging issue.

In the case of large wind farms located in remote areas, depending on whether they are onshore or offshore, wind farms are connected to the power system through overhead lines, underground cables or submarine cables. Distance protection and / or current differential protection could be used for protecting the interconnected line as well as providing backup protection for the wind farm. These protections should be properly coordinated with wind farm protection, as well as grid protection at the Point of Common Coupling (PCC).

7.9 Lightning Protection

In this section, a review of lightning protection of wind farms is given which is based on [28]

7.9.1 Protection of Blades

Initially it was thought that since wind turbine blades were made from non conducting materials (Glass Reinforced Plastic (GRP) or wood epoxy), there was no need to provide separate protection. However, on-site experience has shown that lightning will attach to these blades and can cause catastrophic damages. With the development of the wind power sector different techniques (as shown in Figure 45) have been employed to protect blades from lightning strikes [61].

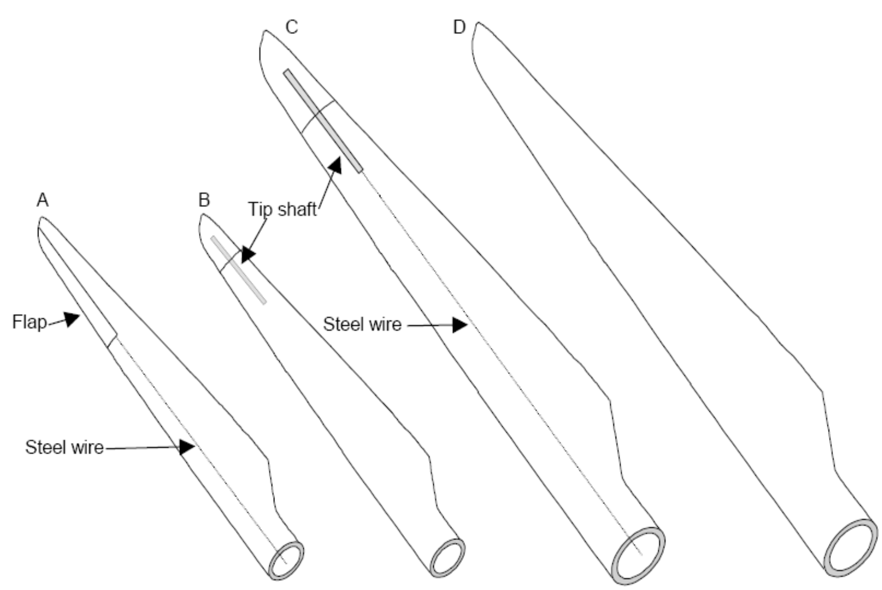

Figure 45 : Lightning protection method for WT blades [62]

In type A the steel control wire of the tip brake is used as the down conductor. An additional conductor is installed in type B since these blades have no movable tips. Type C has the down conductor located on the leading and trailing edges of the blade. An embedded conducting mesh on each side of the blade is used in type D.

The most severe damage to wind turbine blades is caused when lightning forms arcs inside the blades or when the lightning current flows in or between layers of composite materials since such layers may hold some moisture. The pressure shock wave caused by the arc may explode the blade or cause cracks in the blade structure. Therefore it is important to divert the lightning current down the length of the blade through a metallic conductor of sufficient cross section. Experience has shown that the use of tip receptor works effectively for blades of up to 20m in length [62].

7.9.2 Protection of Mechanical Drive Train

When lightning strikes a blade the current must safely pass to the tower and down to the earth. It is necessary for the current to pass through the pitch, main shaft, gear box/generator and yaw bearings as depicted in Figure 46, while not damaging the generator, gear box and sensitive control equipment in the nacelle. Up till now there is no effective alternative path for the lightning current to bypass the bearing, as the bearing itself is the lowest inductance path for high frequency currents.

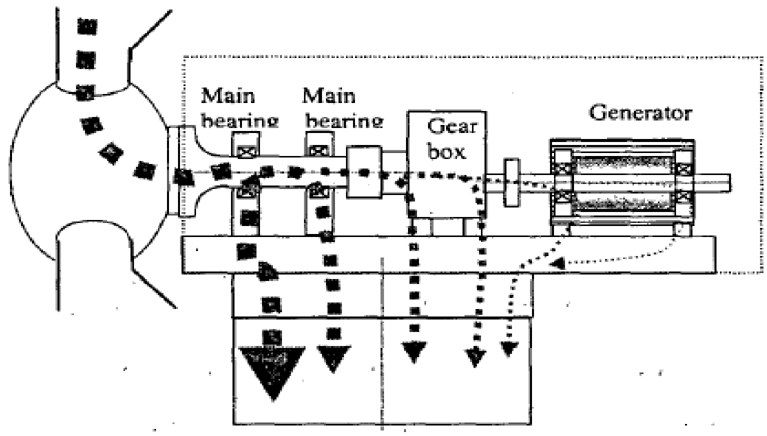

Figure 46: Lightning Current Paths [62]

Some manufacturers use spark gap, brush or sliding contact systems on the main shaft to divert lightning currents to the machinery bed plates and away from the bearing.

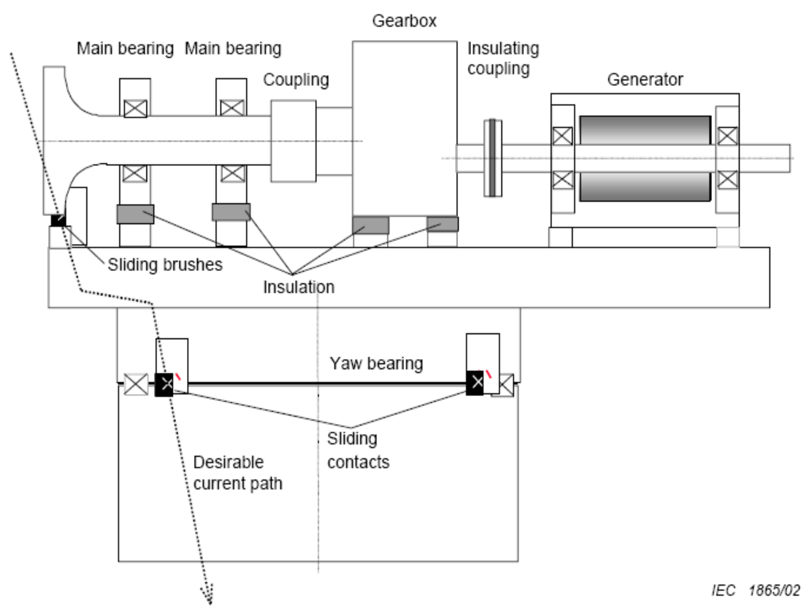

Figure 47: Alternative Current Paths to Reduce Lightning Current [62]

Another suggestion (as shown in Figure 47) is to insert resistive or insulation layers in the current path through bearings and gear box to reduce the amount of lightning current along with using the above diverter system. However, there are mechanical difficulties involved in implementing this option [62]. Alternatively, lightning current can be diverted from the blade root directly to the housing over the machinery. Further, in offshore wind farms more effective lightning protection is needed (especially for mechanical drive train) since replacing major components will be very costly.

7.9.3 Protection of Electrical and Control Systems

Electrical system includes the generator, located in the nacelle and a high voltage transformer, located in the tower base or by the side of the wind turbine. Control system includes control and measurement sensors distributed throughout the wind turbine. Normally there are two microprocessors one located at the tower base and the other in the nacelle, both connected using data cables. For remote data monitoring and control, wind turbines are equipped with SCADA (Supervisory Control And Data Acquisition) systems and communication channels to these can be in the form of PLC (Power Line Carrier), fibre optic cable, twisted pair cable or wireless communication [62]. All the electrical and control components are exposed to high level of electromagnetic fields and induced voltages when a lightning current passes through the nacelle. These probable indirect lightning damages are a major concern in the development of large wind farms. For providing adequate protection to all components of the wind turbine, it is divided into Lightning Protection Zones (LPZ) as shown in Figure 48 and Figure 49.

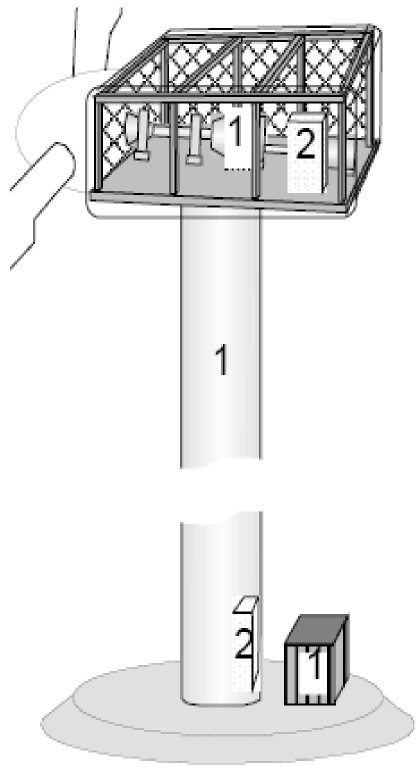

Figure 48: Lightning Protection Zones [62]

These zones (O_A, O_B, 1 & 2) are defined depending on whether or not direct lightning attachment is possible, the magnitude of the lightning current and the associated electromagnetic field expected. It is the sensitivity of the components in a given zone (withstand limits) that defines the level to which the lightning influences (current, voltage and electromagnetic field) must be reduced in that zone.

Boundary between LPZ 0_A and LPZ 0_B is determined by "Rolling Sphere Model" where, as shown in the Figure 49, lightning strikes cannot attach to the shaded areas (Zone 0_B) and rest of the wind turbine surface is Zone 0_A [63]. According to this method, locations against which the sphere cannot be rolled are protected against direct strikes. Meteorological instruments at the top of the nacelle could be protected against a direct lightning strike by placing an air termination (lightning rod) at the rear edge of the nacelle cover.

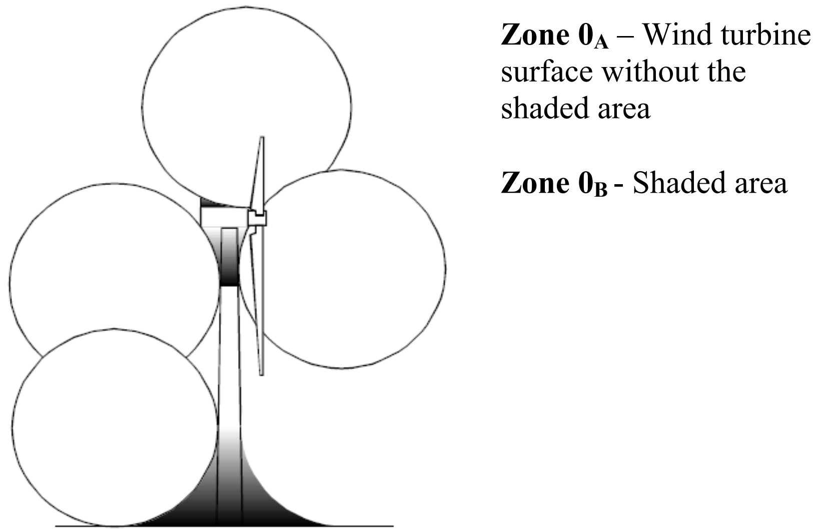

Figure 49: Rolling Sphere Model [63]

This is done by creating a Zone 0_B on top of the nacelle. At the foot of the wind turbine there is also a Zone 0_B where the wind turbine transformer can be located which will have protection against direct strokes.

The boundary between Zone 0_A or 0_B and Zone 1 can be made at the tower or at the top cover of the nacelle if there is a metal cover to protect components beneath employing a Faraday cage. In the case of GRP (Glass Fibre Reinforced Plastic) nacelle covers, a metal frame or strapping should be integrated into the nacelle cover to protect the nacelle components from a direct strike. This frame or strapping should be bonded thoroughly to the bed plate.

The interior of the wind turbine is divided into the nacelle, the tower, and the transformer cubical as protection Zone 1 and the devices inside the metal cabinets in Zone 1, as Zone 2. For instance, controls inside a cabinet, which is inside a metal tower are in Zone 2 but the metal cabinet, which is outside the tower, is in Zone 1. Further, very sensitive equipments such as control and communication components can be placed in separate cabinet with a higher order protection level.

Effective protection is required to reduce the current and voltage levels tolerable for the equipment placed inside the protection zone. Therefore, cables and wires crossing each protection zone boundary should not conduct a large portion of the lightning current or voltage transients into the higher order protection zone. This can be achieved by means of proper bonding and shielding practices coupled with overvoltage protection of cables and wires at the zone boundary. Overvoltage protection can be improved by using optical fibres for transmission of signals and data, using shielded cables and appropriate positioning of cables. Alternatively, surge protective devices can be used, however they are expensive, bulky and they are proven to be unreliable [63].

7.9.3 Wind Turbine Grounding

There are special considerations for wind turbine grounding over the normal grounding practices. This is due to wind farms stretching over large areas, often subject to lightning strikes because of the height of the modern wind turbine and in offshore or high resistivity ground locations.

Grounding system is required to operate effectively for both lightning surges and power frequency currents. Even though the same grounding system is used, the response of the grounding system is completely different for protection against lightning current and power frequency currents [62, 63].

A low impedance ground termination system is required to disperse lightning currents flowing from a wind turbine to the ground. The lightning protection ground termination system should be designed in accordance with IEC 61024-1[64], where a ring electrode is placed around the foundation at a depth of about 1m and held in place with vertical rods driven into the ground. This local ground is bonded to the wind turbine foundation reinforced concrete as shown in Figure 50. Horizontal electrodes are used to connect each wind turbine grounding system within the wind farm.

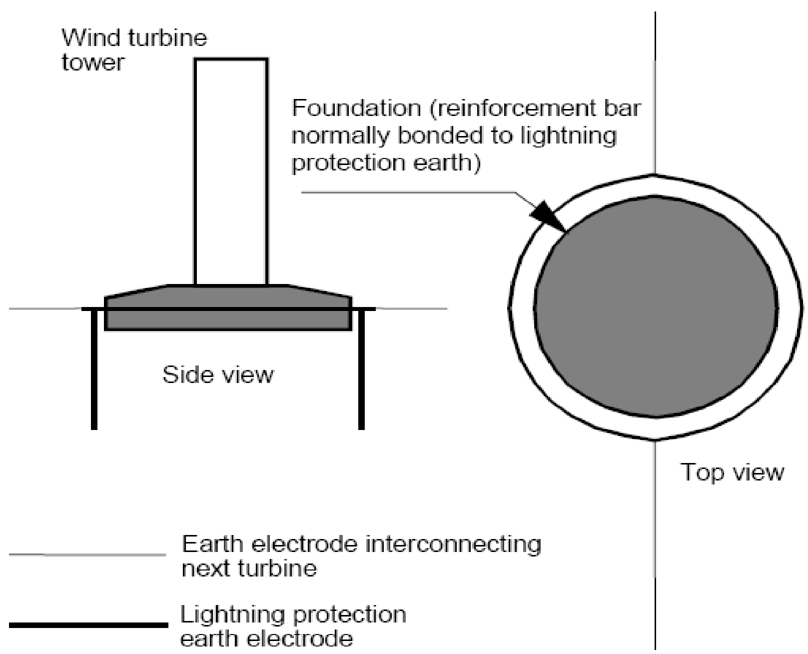

Figure 50: Wind Turbine Grounding Arrangement [62]

The radius of the ring electrode is determined by considering the level of lightning protection required for the wind turbine and the local soil resistivity. This ground termination system should have a resistance to ground of less than 10Ω in accordance with the regulations and for personnel and plant safety.

If the horizontal electrodes which connect the grounding system of adjacent wind turbines are greater than 50m in length, it may have a very low earth resistance but could have high transient impedance, since horizontal electrode will contribute a significant inductance to the grounding system. Since lightning current contains many high frequency components, these interact with inductance of the grounding system to produce very high transient impedances. Hence in such a case it is recommended to use multiple electrodes of shorter lengths instead of one long conductor.

Horizontal electrode(s) between WTs are laid in the same cable trench as power system cables and/or SCADA system cables. They prevent power or SCADA cables from conducting high lighting current and reduce induced voltage levels at remote wind turbines [62, 64]. Entire wind farm should have a continuous metallic ground system connecting substation, wind turbine generators, transformers, towers and electronic equipments.

CHAPTER VIII

CONCLUDING REMARKS

8.1 Concluding Remarks

Technical impacts associated with high penetration of wind power could affect the protection and control performance of the power system. Fault current contribution could have an adverse impact on the instrument transformer behavior, protection coordination and control performance. In this study, a 9 MW wind farm with six units of 1.5 MW DFIGs has been modeled in Matlab / Simulink / SimPowerSystems for simulation of different types of faults within and outside the wind farm. Matlab / Simulink / SimPowerSystems library components are used to represent generators, transformers, cables, bus bars etc. DFIG detailed model in Matlab/ Simulink/ SimPowerSystems is used as the base to develop the model for six units of wind turbine generators operating in parallel. Detailed representation of DFIG rotor side power electronic converter is employed with the d-q model for the wound rotor induction generator.

Symmetrical and asymmetrical faults are created at the wind turbine generator terminal, medium voltage bus and close to the high voltage bus. Voltage and current waveforms are observed and discussed with the ideal conditions in power system fault calculations. Impact of grounding methods employed for the generator step-up transformer and for the main step-up transformer on the fault voltage and current is discussed. Understanding fault current behavior will help in selecting proper instrument transformers, switchgear and control gear, and in designing effective protection systems. Further, electrical protection of wind farms is discussed in the context of different protection functions used in practical wind farms. Protection against lightning and the protection methods in use at present are reviewed.

8.2 Scope for Future Work

Importance of assessing the impact of wind electric power generation on the power system performance has become increasingly important with high penetration of wind power into the power system. Protection of large wind farms and the impact on overall power system protection have not been adequately investigated. Instrument transformer transient operation is an important factor contributing to maloperation of protective devices. Investigating current transformer transient performance including saturation effects will be helpful in current transformer selection and protection settings.

Protection of collector feeders used in large wind farms is inadequate in its present form since with the onset of a fault on one generator, if not cleared on time, all other generators will feed the fault. Possibility of using directional protection for collector feeders needs further investigation. Considerable research is in progress on DFIG operation and control. DFIG’s voltage control capabilities and possibilities of contributing to frequency support are also being investigated.

Better wind regimes exist in remote locations where there are no strong transmission lines. Presently, many offshore wind farms are also being planned. Overhead power line transmission from wind farms to load centers over long distances result in considerable losses. Therefore, HVDC-based power transmission is an option worth consideration. Control and protection issues of wind farms with HVDC links will increase in significance in the future.

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APPENDIX A

DFIG DATA

Wind Farm Parameters are taken from [56]

A.1 Doubly Fed Induction Generator

Rated Power:	1.5 MW
Rated Voltage:	575 V (Line-Line)
Frequency:	60 Hz
Stator Resistance:	0.00706 pu
Rotor Resistance:	0.005 pu
Stator Leakage Inductance:	0.171 pu
Rotor Leakage Inductance:	0.156 pu
Magnetizing Inductance:	2.9 pu
Inertia Constant:	5.04 s

A.2 Generator Step-up Transformer

Rated Power	3.5 MVA
Frequency	60 Hz
LV Winding Voltage	34.5 kV
LV Winding Resistance	0.00833 pu
LV Winding Reactance	0.025 pu

MV Winding Voltage	34.5 kV
MV Winding Resistance	0.00833 pu
MV Winding Reactance	0.025 pu

A.3 Local Load

Resistive Load	500 kW

A.4 Filter

Norminal Voltage	575 V
Frequency	60 Hz
Norminal power	150 kW
Capacitive reactive power	150 kVAr

A.5 Underground Cable

Cable Length	3 km
Rated Voltage	34.5 kV
Positive Sequence Resistance	0.1153 Ω/km
Zero Sequence resistance	0.413 Ω/km
Positive Sequence Reactance	1.05 mH/km
Zero Sequence Reactance	3.32 mH/km
Positive Sequence Capacitance	11.33 nF/km
Zero Sequence Capacitance	5.01 nF/km

A.6 Substation Step-up Transformer

Nominal Power	94 MVA
Frequency	60 Hz
MV Winding Voltage	34.5 kV
MV Winding Resistance	0.0266 pu
MV Winding Reactance	0.08 pu
HV Winding Voltage	240 kV
HV Winding Resistance	0.0266 pu
HV Winding Reactance	0.08 pu

A.7 Grounding Transformer

Nominal Power	100 MVA
Frequency	60 Hz
Winding- 1 /Winding-2 Voltage	34.5 kV
Winding-1 Resistance	1.1846 pu
Winding-1 Reactance	0.3948 pu

A.8 Power System

Interconnection Voltage:	240 kV
Positive Sequence Resistance:	2.304 Ω
Positive Sequence Reactance	0.0611 H
Zero Sequence Resistance	6.912 Ω
Zero Sequence Reactance	0.1833 H

APPENDIX B

POWER SYETEM GROUNDING METHODS

B.1 Grounding Methods

The purpose of system grounding is to reduce voltage and thermal stresses on equipment, provide personnel safety, reduce communications systems interference, and give assistance in quick detection and elimination of ground faults [65]. Brief description of the grounding methods are given in the following sections.

B.1.1 Ungrounded or Isolated Neutral System

In an ungrounded system, the neutral has no intentional connection to ground. The only way the system is connected to the ground is through the line-to-ground capacitances as shown in Figure B.1.

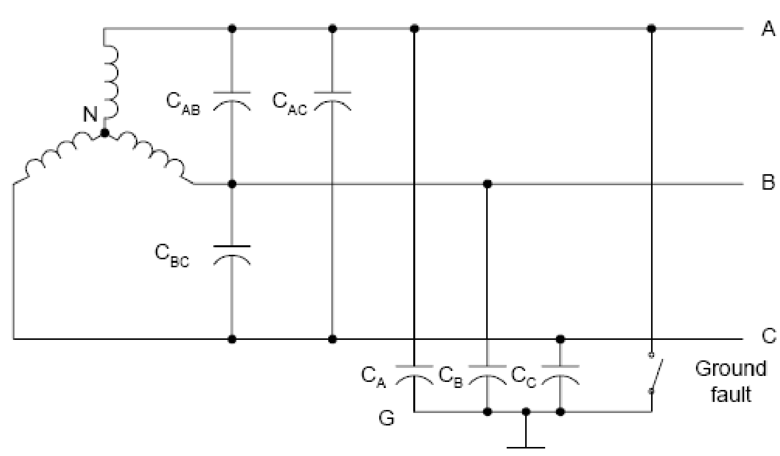


Figure B.1: Isolated Neutral System [66]

For these systems, magnitude of ground fault current depends on the zero sequence line-to-ground capacitance and fault resistance. During a single line-to-ground fault, system neutral voltage is shifted but phase-to-phase voltage triangle is not disturbed as shown in Figure B.2.

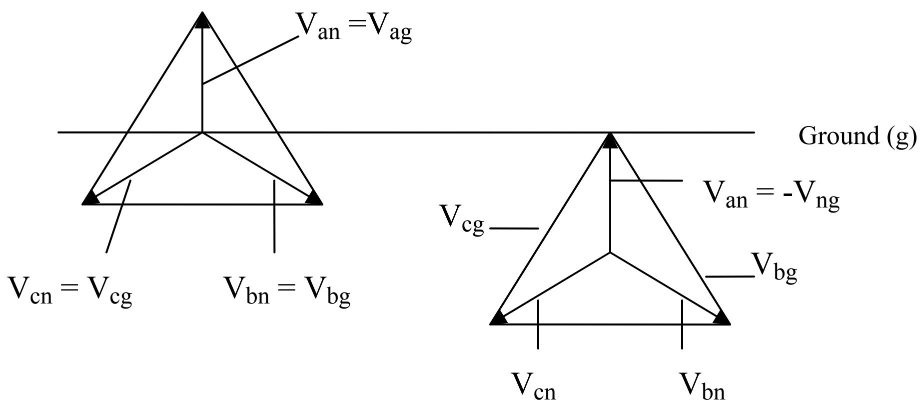


Figure B.2: Voltage Shift for a Phase 'a' to Ground Fault on an Ungrounded System [46]

These systems can remain operational during sustained, low magnitude faults since the voltage triangle is undisturbed.

B.1.2 Solidly or Effectively Grounded System

In solidly grounded systems, power system neutrals are connected to earth (or ground) without any intentional impedance between the neutral and the ground. Effective or solidly grounded systems should have $(X_0/X_1) \leq 3$ and $(R_0/X_1) \leq 1$, where X_0 and R_0 are the zero sequence reactance and resistance, and X_1 is the positive sequence reactance of the power system [58]. Ground fault currents can vary considerably from very small currents to currents greater than the three-phase fault value. Solidly grounded system can be implemented in two different ways, unigrounded and multigrounded. Unigrounded systems have only three wires with all loads connected phase-to-phase as shown in Figure B.3 or four wires with an isolated neutral and all loads connected phase to neutral as shown in Figure B.4.

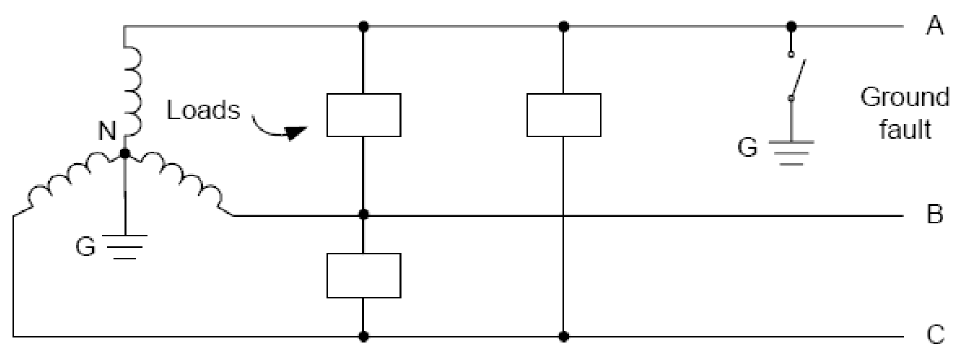


Figure B.3: Solidly Grounded System with Three-wire Unigrounded [66]

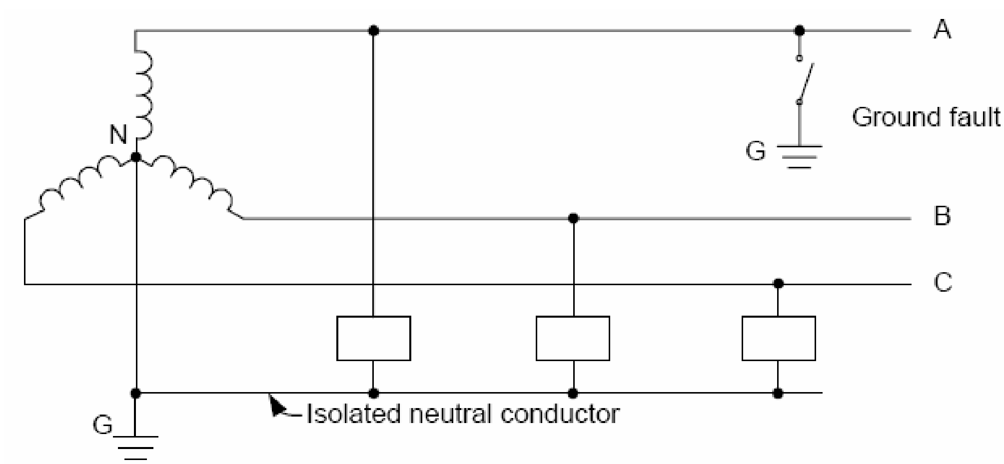


Figure B.4: Four wire Unigrounded System [66]

Multigrounded systems have four wires and phase-to-neutral loads as shown in Figure B.5. The system is grounded at the substation and at every transformer location along the circuit. In some cases, single-phase branch loads are connected to a line and ground without running a neural conductor. In these systems, both load unbalance and ground fault current divide between the neutral conductor and ground [66].

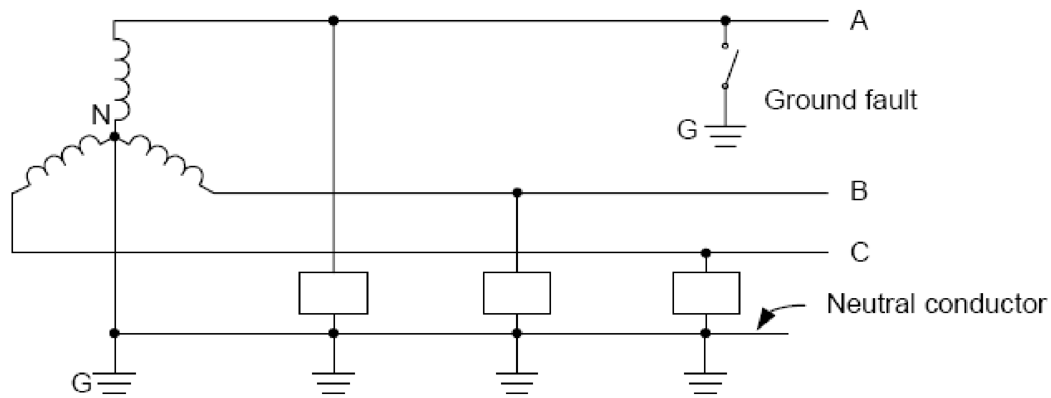
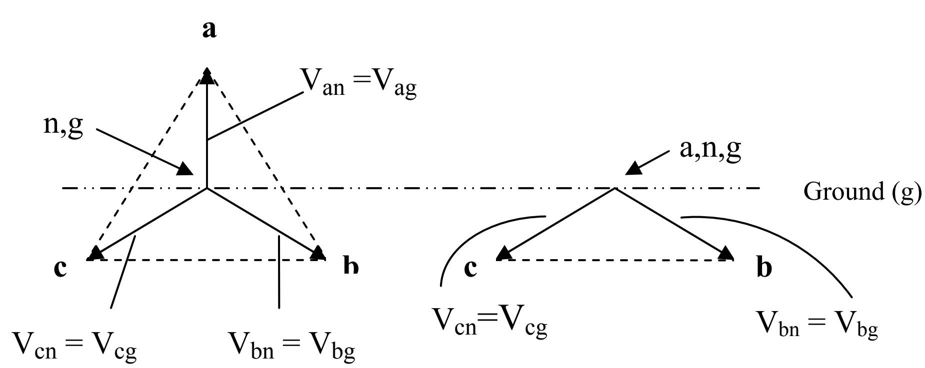


Figure B.5: Multigrounded System [66]

Solid grounding reduces the possibility of overvoltages during ground faults. In these systems, the system neutral is not shifted away as shown in the following illustration in Figure B.6. As a result the system does not require a high voltage insulation level as does as isolated neutral system [66].



FigureB.6: Phasor Diagram –Changes from Normal Operation to a Ground Fault [66]

B.1.3 Low Impedance Grounded System

In this method the system is grounded through a low impedance resistor or reactor. The low impedance grounding limits the line-to-ground fault current to approximately 50-600A primary [67, 68], and thereby can reduce the equipment thermal stress, which allows to use less expensive switchgear.

B.1.4 High Impedance Grounded System

Here the system is grounded through a high-impedance resistor or reactor with impedance equal to or slightly less than the total system line-to-ground capacitive reactance. This method limits the ground fault current to 25A or less [43]. In the case of high resistance grounding, transient overvoltages are limited to safer values during ground faults. The grounding resistor is connected in the neutral of a power transformer, generator or generator grounding bus, or across a broken-delta connection of distribution transformers [59, 69, 70]. High-impedance grounded systems also shift the neutral voltage for ground faults, without changing the phase-to-phase voltage triangle.

B.1.5 Resonance Grounded System

In resonant grounding, the system is grounded through a high-impedance reactor as shown in Figure B.7, which is tuned to the overall system phase-to-ground capacitance. The variable reactor is called as Petersen coil, arc-suppression coil or ground-fault neutralizer [70, 71].

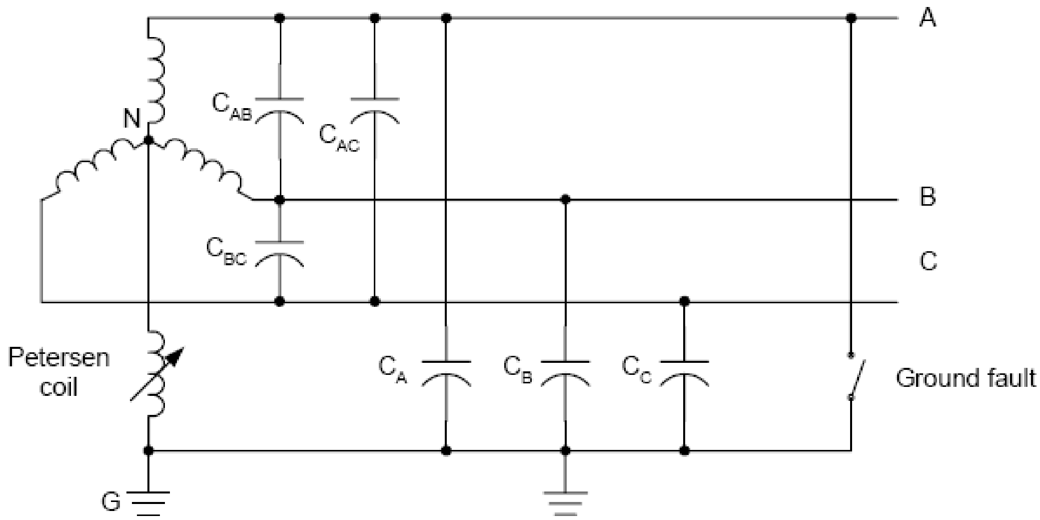


Figure B.7: Resonant Grounding System [66]

Resonant grounded system can limit the ground fault current up to about 3 to 10 percent compared to an ungrounded system.

VITA

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Master of Science

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Title of Study: FAULT ANALYSIS AND PROTECTION OF DOUBLY FED INDUCTION GENERATOR-BASED WIND FARMS

Pages in Study: 93 Candidate for the Degree of Master of Science

Major Field: Electrical Engineering

Scope and Method of Study: The purpose of this thesis is to study the fault current behavior of a wind farm with Doubly Fed Induction Generators (DFIG), and identify the electrical protection requirements for a large wind farm. Brief description of wind energy conversion systems including types of wind turbine generators are given in the beginning of the thesis followed by a review of induction machine modeling and the special modeling considerations for a DFIG during a short circuit condition. Fault calculations using symmetrical components and factors which determine the fault current contribution are also discussed. A nine MW wind farm with six units of 1.5 MW DFIGs are modeled using Matlab/Simulink/SimPowerSystems and simulated for symmetrical and asymmetrical faults within the wind farm and in the power system close to the wind farm. Voltage and current profiles are observed for pre-fault, fault and post-fault periods and the results are presented and discussed.

Findings and Conclusions: The simulated voltage and current waveforms during faults nearly conform with the ideal conditions expected. This gives a clear view of each phase current and phase voltage behavior during different fault conditions. Knowledge of fault levels in a wind farm is important in determining the ratings of current transformers, voltage transformers and circuit breakers. Further, protection functions are graded and settings are selected based on the fault current contribution from the wind turbine generators and the power system.

ADVISER’S APPROVAL: Dr. Rama G. Ramakumar