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VOLTAGE CONTROL AND PROTECTION OF DFIG BASED WIND TURBINE

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***Abstract*—** For electricity production through wind energy, DFIG are commonly used and generally installed in the remote areas where the rural grids are weak and voltage imbalances often occur. DFIG structure uses two back-to-back converters which is Rotor Side Convertor (RSC) and Grid Side Convertor (GSC). RSC support the rotor windings and GSC grid stabilizes the DC-link voltage. These convertors provided with PI controllers achieve voltage control, reactive power compensation etc.

In this paper, a 1.5MW DFIG model is connected with grid voltage of 100KV and simulated under normal operation. For abnormal operation a fault for a certain time period is created from the grid thereby the convertors and DFIG are protected using Crowbar resistance which short circuits the terminals thereby high fault currents are grounded. Therefore, the DFIG is not disconnected during the fault and maintains normal operation after the fault. The GSC provides necessary reactive power compensation for stabilization of voltage profile through STATCOM under grid fault conditions.

Keywords—DFIG (Double Fed Induction Generator), RSC (Rotor Sided Converter), GSC (Grid Side Converter), Crowbar, Reactive power compensation, STATCOM.

I. INTRODUCTION

Today, the modern energy industry faces a growing awareness regarding the impact of conventional power generation on the environment. Issues such as limited fossil fuel reserves, climate change due to CO_2 emissions, brings attention on alternative technologies to generate electricity in a more sustainable manner. In the trend of diversifying the energy market, alternative energy is that the most speedily growing sector. After the oil crisis three decades ago, the wind power industry started to flourish. Over the last years, there has been a strong penetration of renewable energy resources into the power supply network. Wind energy generation has played and will continue to play a very important role in this area for the coming years. Doubly Fed Induction Machine (DFIM) based wind turbines have undoubtedly arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost-effective, efficient and reliable solution. To ensure the stability of the power system, regarding power quality and voltage level, all the grid codes demand that the Wind Power Plant (WPP) must be able to produce reactive power at the Point of Common Coupling (PCC). When managing WPP, adding the reactive power capability of every individual Wind Turbine (WT) might not be comfortable to accommodate the grid codes. This is due to the losses in connection cables and line losses between WPP and PCC. One solution is to use external reactive power compensation, for example installing Static synchronous compensator (STATCOM) at the PCC. The main objective of this paper is to develop a reliable control strategy for WPP and STATCOM and investigation of the impact on reactive power losses during steady state. To fulfill the main goal of the paper, some basic considerations have to be stated. Simulation models have to be developed such as wind model, rotor model, drive train model, Doubly Fed Induction Generator (DFIG) model, converter models, STATCOM model, and connection line model. On integrating these models, simulations are performed in MATLAB for different conditions. During the fault conditions, the DFIG should not be disconnected and should maintain supply power after the fault conditions.

II. DFIG SYSTEM CONFIGURATION

Firstly, the steady state electric circuit of the machine is based on developed steady state equations, from which the modes of operation of the machine are presented and analyzed. Finally, based also on the model equations, a detailed performance evaluation of the machine is carried out. Steady state performance curves can reveal current, voltage or different magnitude requirements, depending on the specific operating conditions of the machine.

A. *Basic Principles Of DFIG*

The Doubly Fed Induction Generator (DFIG) or Wound Rotor Induction Generator (WRIG) are terms commonly used to describe an electrical machine, which has been used over many decades in various applications, often in the range of megawatts of power and also less common in the range of a few kilowatts

The mechanical device is equipped by three phase voltages directly from the grid at constant amplitude and frequency, making the mechanical device field of force. The rotor is also supplied by three phase voltages that take a different amplitude and frequency at steady state in order to reach different operating conditions of the machine (speed, torque, etc.). This is achieved by using a back-to-back three phase converter, as represented in the simple schematic in figure 2.1. This converter, together with the appropriate control strategy, is in charge of imposing the required rotor AC voltages to control the overall DFIG operating point and to perform the power exchange through the rotor to the grid. Although a voltage source converter is shown, different sufficiently converter topologies could be utilized. Further details regarding the operation of the machine are described in subsequent sections.

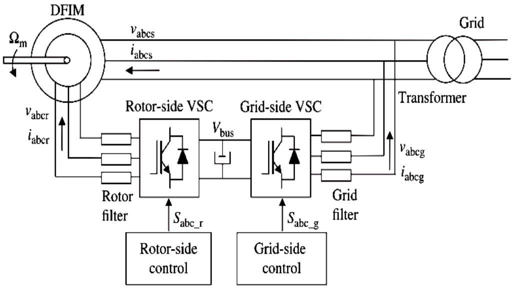


Figure 2.1 Basic structure of DFIG

B. *Steady State Equivalent Circuit*

The steady state equivalent electric circuit of the DFIG can be ideally simplified, as depicted in figure 2.2, with the following assumptions:

- It is assumed that both the stator and the rotor are connected in the star configuration; however, only one phase of the stator and rotor three-phase windings is represented.
- The stator is supplied by the grid at constant and balanced three-phase AC voltage amplitude and frequency.
- The rotor is supplied also at constant and balanced AC voltage amplitude and frequency, independently from the stator, for instance, by a back-to-back voltage source converter.
- To represent steady state voltage and current magnitudes, the analysis is carried out using classical phasor theory:

V_s : stator voltage
V_r : rotor voltage
I_s : stator current
I_r : rotor current
E_s : emf in the stator
E_r : emf in the rotor.

- The electrical parameters of the stator and rotor are:

R_s : stator resistance
R'_r : rotor resistance
$X_{\sigma s}$: stator leakage impedance
$X'_{\sigma r}$: rotor leakage impedance
N_s : number of turns per phase of stator winding
Nr : number of turns per phase of rotor winding

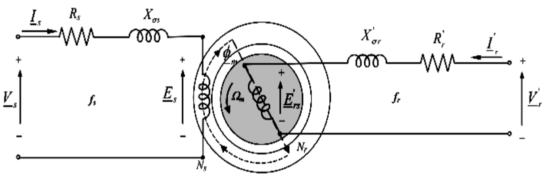


Figure 2.2 Single Phase Steady State Equivalent Circuit of DFIG with Different Stator and Rotor Frequencies

III. BACK TO BACK POWER ELECTRONICS CONVERTER

A. *Grid Side System*

The grid side system is composed of the Grid Side Converter (GSC), the grid side filter and the grid voltage.

- The GSC is modelled with ideal bidirectional switches. It converts voltage and currents from DC to AC, while the exchange of power can be in both directions from AC to DC (rectifier mode) and from DC to AC (inverter mode). The ideal switch normally is created by a controlled semiconductor with a diode in antiparallel to allow the flow of current in both directions. In this exposition, the controlled semiconductor used is an Insulated Gate Bipolar Transistor (IGBT).

- The grid side filter is normally composed of at least three inductances, which are the link between each output phase of the converter and the grid voltage. When a high filter requirement is needed, each inductance can be accompanied by one capacitor or even by one capacitor and one more inductance.

- The grid voltage is normally supplied through a transformer. This AC voltage is supposed to be balanced and sinusoidal under normal operation conditions.

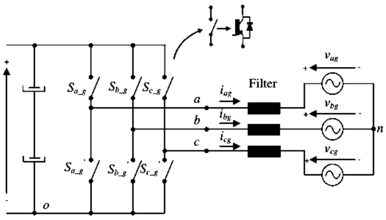


Figure 3.1 Simplified Converter, Filter and Grid Model

B. *Rotor Side System*

The Rotor Side Converter (RSC) that supplies the rotor of the DFIG, in general terms, is equal to the grid side converter. Figure 3.2 illustrates the converter and the dv/dt filter used to supply the rotor of the DFIG. In this case also, a two-level Voltage Source Converter (VSC) feeds the rotor. Between the rotor and the converter, in general, a dv/dt filter is located mainly with the objective to protect the machine from the harmful effects of the VSC, such as capacitive leakage currents, bearing currents, and increased stress on the motor insulation.

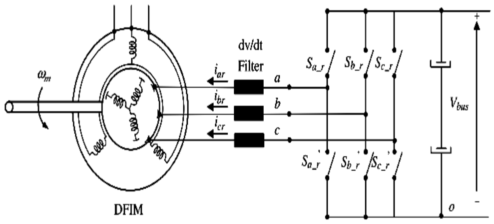


Figure 3.2 Rotor Side Converter and dv/dt Filter Supplying the Rotor.

The rotor side converter is connected to the grid side converter by the DC link. The dv/dt filter mainly tries to attenuate the step voltages in the rotor terminals of the machine, coming from the converter. The combination of mainly three factors determines how harmful the effects are on the machine, which the dv/dt filter tends to mitigate. These factors are the type of voltage steps generated by the converter, the characteristics and length of cable used for connecting the converter and the machine, finally the characteristics of the machine that is being supplied. The attenuation of the step voltages can be achieved, in general, by different types of filters. Therefore, one possible solution to attenuate the overvoltages at the terminals of the motor is to locate a resistance and an inductance in parallel at the output of the converter. The resistance damps the reflection in the cable, while the inductance is necessary to reduce the voltage drop and the losses due to low frequencies. Among different solutions, it is possible to locate an RC or an RLC filter. Finally, at the output of the converter it is also possible to locate filter networks, to reduce the dv/dt at the converter itself.

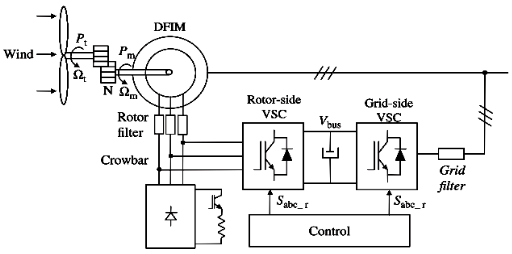
IV. PROTECTION OF DFIG

A. *Crowbar Protection*

Crowbar protects when a voltage dip occurs in the network, current transients in the stator windings (due to the stator's direct connection to the grid) and grid side converter is produced. A crowbar circuit is connected to the rotor to protect the RSC. The crowbar avoids voltage bus when it exceed his maximum value once the RSC loses current control providing a path for the rotor currents. The crowbar short-circuits the rotor and the machine operates as a squirrel cage machine. After a voltage dip, the rotor current regulators lose control and energy flow from the stator to the rotor charges the bus capacitor. To avoid the bus voltage from reaching the converter limits, it is necessary to break this energy flow and the simplest method is to short-circuit the rotor when the bus voltage reaches a limiting value. The simplest technique consists of comparing the bus voltage with its maximum and normal operation reference values and depending on that comparison, keeping the crowbar circuit open or closed. This technique is called active crowbar control. The bus capacitor load dynamics is determined by the rotor bus energy flow and the discharge is determined by the capacity of the grid side inverter (bus to grid energy flow).

B. *Performance During Severe Grid Voltage Dips*

The system needs a crowbar for protection from the over currents and over voltages caused by the loss of control during the dip. In DFIG based wind turbines, the crowbar is installed at the rotor terminals, as shown in figure 5.4a, which prevents damage to the rotor converter. It is activated when one abnormal situation is detected. The rotor current is then diverted to the crowbar and the rotor converter is switched off. Figure 5.4b shows the equivalent circuit of the system when crowbar is activated.



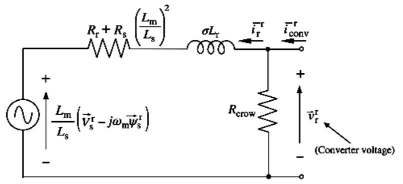


Figure 5.4a: System equipped with three-phase DC crowbar protection

Figure 5.4b: One phase equivalent circuit of the system when the crowbar is activated

As can be seen, when the crowbar is activated, the circuit becomes an impedance divider. As demanded by the grid codes, in order to provide Low Voltage Ride Through (LVRT) capability, the wind turbine must remain connected during the voltage dip; therefore, the crowbar must be activated and deactivated without disconnecting the DFIG from the grid. In this way, the sequence of events that typically occurs during severe voltage dips can be summarized as follows:

- The DFIG is generating power at steady state at one efficient operating point.
- When the voltage dip occurs, there are a few milliseconds (typically 0.5–5) until the wind turbines control detects the dip. Thus, during this period the system cannot guarantee control and in general, there is a high rise of currents through the rotor converter, which also provokes a DC bus voltage increase. The dip is detected by supervising the following anomalies: (a) over current in the rotor, (b) overvoltage in the DC link, (c) grid voltage drop, detected by PLLs or synchronizing methods.
- Once the dip has been detected, the crowbar is activated quickly, which demagnetizes the machine. The rotor converter is inhibited, keeping it safe and ensuring that the entire rotor current circulates through the crowbar. Depending on the machine's design, the time during which the crowbar is active can range for several cycles.
- Once the flux has decayed and the available converter voltage can control the machine, the crowbar is disconnected and the rotor converter inactivated again. In general, because at this moment, the flux has not been totally damped, it is preferable to contribute to the total stabilization of the stator flux by injecting demagnetizing rotor currents by control. At the same time, as demanded by the grid codes, it is possible to provide progressively reactive power through the stator by increasing the corresponding rotor current component. This situation will last until the grid voltage is progressively recovered, the fault is cleared and normal operation is resumed.

Once the dip occurs, the rotor side converter is inhibited owing to the quick over current detected in the rotor. At the same instant, the crowbar is activated, connecting the additional resistance path in the rotor and damping the big energy fluctuation of the machine. During the instants of the dip, large torque and peak stator and rotor currents occur. After few milliseconds, the crowbar can be disconnected and at the same instant, the rotor converter is activated, which injects demagnetizing currents through the rotor, at the same time as injecting stator capacitive reactive power in the ramp. Finally, it must be highlighted that the DC bus voltage normally suffers a transient because the grid-side converter is also affected by the dip. Under that situation, the converter alone can control the system without the need for the crowbar protection. The resistance of the crowbar Rc must be chosen carefully. In general, it can be selected by a simulation-based analysis that attempts to in a compromise between the following aspects:

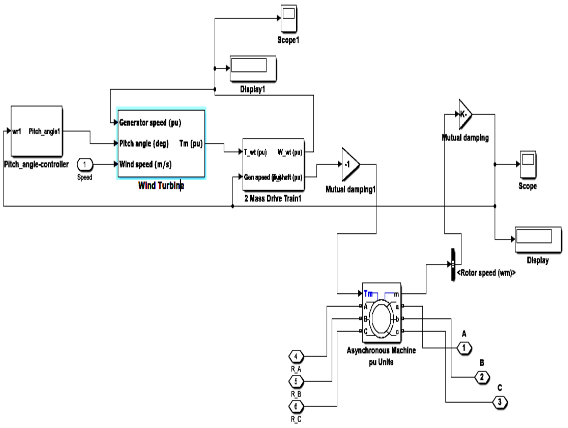
- If a very low value is chosen, the current during the dip will be very large. Thus, the crowbar elements should be oversized and the electromagnetic torque will present a big peak.
- The rotor current can be minimized by using a higher resistance. However, if the resistance is too big, the crowbar will not pull the rotor voltage low enough and the rotor current will circulate across the rotor converter via its freewheeling diodes, even if it is inactive, increasing the DC bus voltage. Therefore, it is very important that the resistance is efficiently high that the diodes of the rotor converter do not operate, thus allowing the entire rotor current to circulate through the crowbar resistance

V. SIMULATION AND RESULTS

In this section, the dynamic interaction between variable speed DFIG wind turbine and power transmission system during grid failure is illustrated and explained. A 1.5 MW DFIG wind farm connected with a grid voltage of 100kKV is implemented in the MATLAB, crowbar protection is given at the rotor terminals of the generator thereby it protects the system by short-circuiting the terminals, thereby the fault currents are bypassed through the ground without affecting the converters and generators. A fault for a certain time period of 0.2 to 0.3 seconds is created from grid and the breaker operating time is also set for the same time period hence when the faults occur, the protection is activated at the same time thereby the DFIG is not disconnected from the system during fault conditions and continued to supply power after fault conditions, this

the feature is called fault ride through capability, a detailed analysis and results are shown below. Figure 6.1 simulink model shown is the overall model of

DFIG based wind turbine where the DFIG is connected to the grid through the Rotor Side Converter (RSC) and Grid Side Converter (GSC) and the protection is given at the terminal of rotor. The scope is given at each node where the status of voltage and currents can be seen.



A. *Behaviour of DFIG on RSC Failure*

During the fault condition, first the rotor side is shortcut to protect the rotor side converter. On the other hand, there is a voltage drop on the stator side, so that a limited current not enough electrical power is transferred to the grid. Thus the crowbar performance can be analyzed separately. The results of these considerations are serving to describe a part of behavior of DFIG in case of a grid failure as well as in case of a rotor side converter failure.

In case of a rotor side converter failure and switching on of crowbar, the DFIG is changed to an induction generator with an additional rotor resistance. Now the induction generator is trying to reach the stationary operating of a machine with rotor nearly short cut near synchronous operation point depending on the mechanical torque. This behavior causes high rotor and stator currents, which are necessary to reach the stationary operating point. The crowbar resistor is limiting these currents as well as the electrical torque.

B. *Behaviour Of DFIG On GSC Failure*

In case of a grid failure the grid voltage drops down the stator voltage respectively, immediate dropping is assumed. The DFIG reacts with rising stator and rotor currents. To protect the rotor side inverter the crowbar will be switched to rotor circuit of DFIG. The simulation results show the relation between the crowbar resistor value and the electrical values of DFIG, rotor currents voltages and the electrical torque, during grid failure.

Figure 6.2 Wind Turbine Model

Figure 6.2 shows the wind turbine simulink model along with pitch angle control and the drive train mechanism is connected between turbine and the generator which mitigates the torsional oscillations on the shaft caused by mechanical and electrical disturbances.

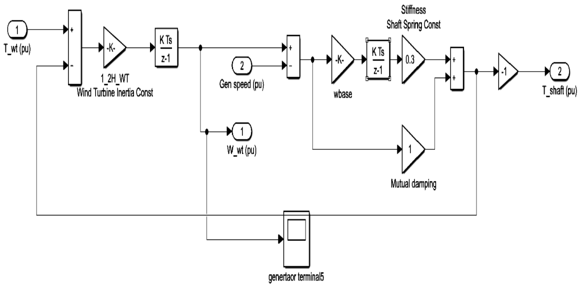


Figure 6.3 Drive Train Mechanism

The simulink model for drive train mechanism is shown in figure 6.3 which has the input of generator actual speed and the actual torque for m the turbine

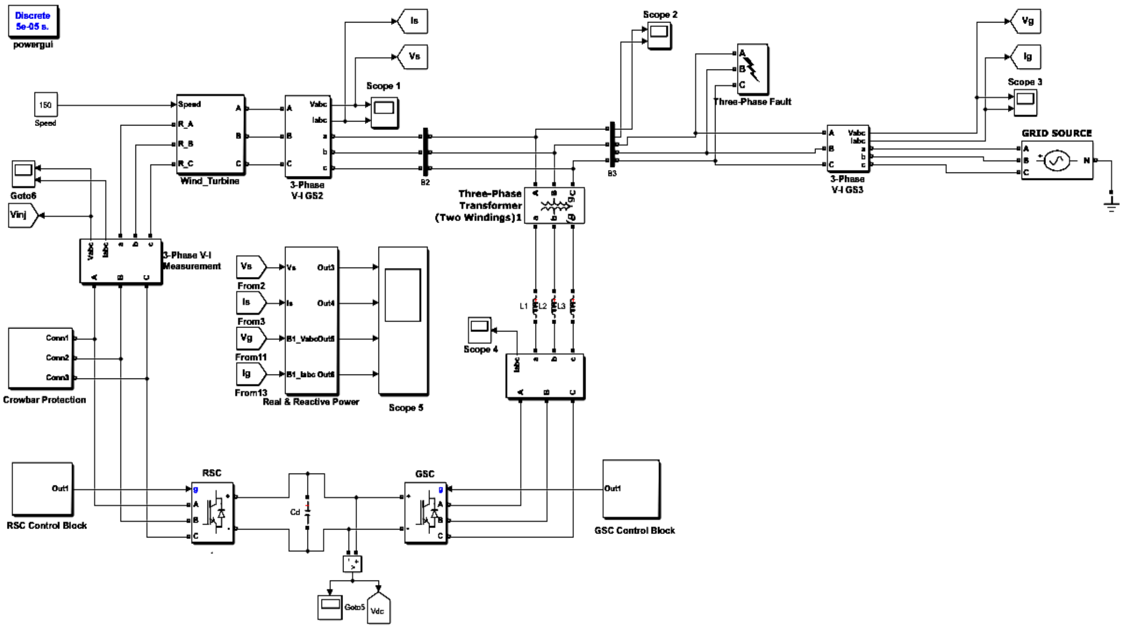


Figure 6.1 Overall Model of DFIG based Wind Turbine

then it converts the turbine torque to the generator shaft torque thereby it controls the torque of the generator

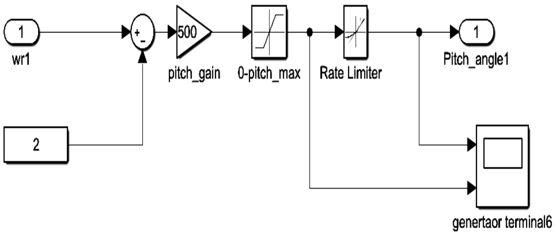


Figure 6.4 Pitch Angle Control for Speed Control

Figure 6.4 shows the simulink model of pitch angle control. In the present work, the pitch angle control is implemented in such a way that the pitch angle controls the generator speed, i.e. the input in the controller is the error signal between the measured generator speed and the reference generator speed. In the case of over-speeding, the speed is controlled to its rated value, while the aerodynamic power is automatically reduced by increasing the pitch angle. This control is able to prevent over-speeding both in normal operations and during grid faults. The rate-of-change limitation for the pitch angle is very important during grid faults, because it decides how fast the aerodynamic power can be reduced in order to prevent over-speeding during faults. The dynamic stability of the generator is increased by the pitch angle control.

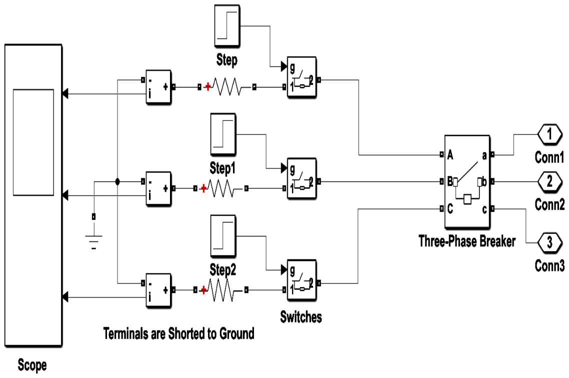


Figure 6.5 Crowbar Protection

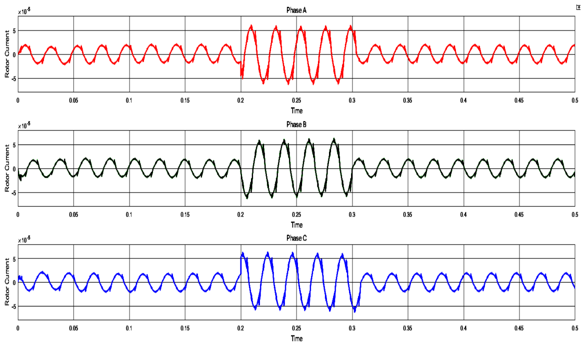


Figure 6.5 shows the simulink model for crowbar protection where the rotor terminals are short circuited during fault conditions through having very low resistance value of 0.01Ω thereby the high fault currents are grounded without affecting the converters. The terminals from the rotor are taken and given to the three phase breaker then it short-circuits and grounded through a very low resistance value.

C. *Parameter Settings*

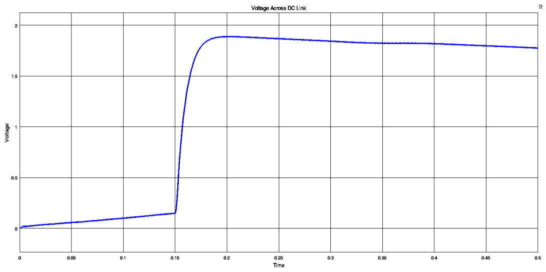
A Three phase fault (L-L-L-G) is created from the grid for a time period of 0.2 to 0.3 seconds.

- For three phase fault which has the fault resistance of 0.001Ω and ground resistance of 0.01Ω.
- For three phase breaker where the same time period of 0.2 to 0.3 seconds is given to operate the breaker when the fault is created thereby the converters and generators are protected.

D. *STATCOM Model*

Figure 6.6 shows the simulink block of STATCOM connected with the grid to improve the voltage profile under fault conditions. STATCOM is operated with multilevel inverter where switching pulses are given to the converter with equidistant time width as input pulses. The pulses are generated in accordance with the variation of control parameters which are rotor voltages/currents, stator voltages/currents and wind speed. Generally, STATCOMs are connected in shunt with the load side or the terminal where the control is to be performed. Here it is connected at the PCC where the voltage is to be controlled.

Figure 6.8 Rotor Currents of Phase A, Phase B & Phase C



VI. SIMULATION OUTPUT

Figure 6.7: Grid Voltage and Current during fault Condition

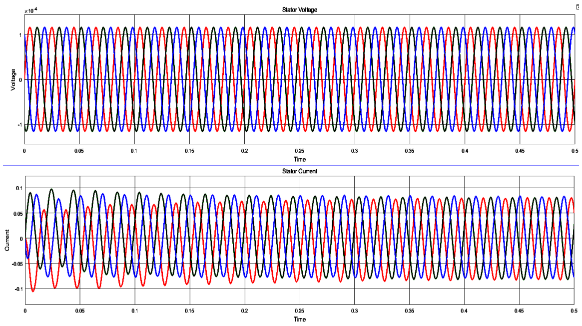


Figure 6.7 shows the simulation output of grid voltage and current, initially when the three phase fault occurred on the grid, high fault current flows through the period of 0.2 to 0.3 seconds since the fault here created is for 0.2 to 0.3 seconds.

Figure 6.8 shows the phase currents of rotor terminals, during the fault period, the high fault flows through the rotor terminals of phase A, phase B and phase C for the time period of 0.2 to 0.3 seconds, which can be measured through the current measurement block. It can be seen that the operation before the fault condition and after the fault condition was same, that is, during the faulted conditions the DFIG managed to stay in grid supplying voltage and this feature is an added advantage to this model.

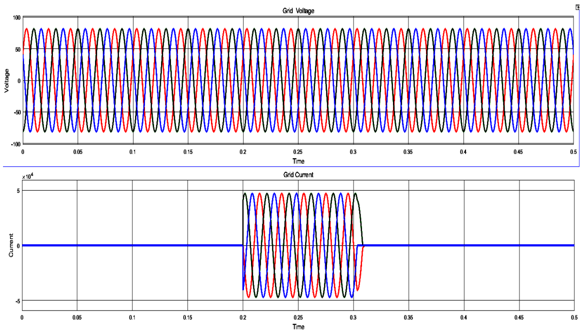


Figure 6.9 Voltage at the Point of Common Coupling

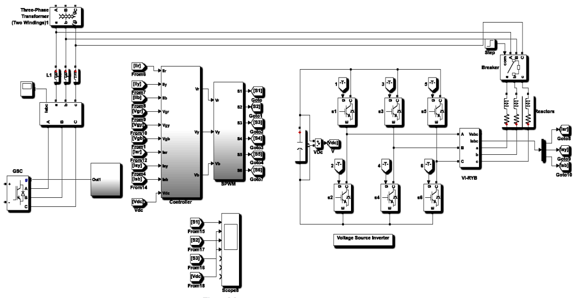


Figure 6.6 STATCOM Model connected with Grid

The voltage at the Point of Common Coupling (PCC) is shown in Figure 6.9. It is to be noted that the fault condition occurred through the grid affects the voltage at the PCC at fault time period then the normal operation is restored.

Figure 6.10 Voltage Across DC link

Figure 6.10 shows the graph of voltage across DC link, that is, across the capacitor. Initially the voltage is increased in linear and after few seconds it rises to the peak value and remains constant.

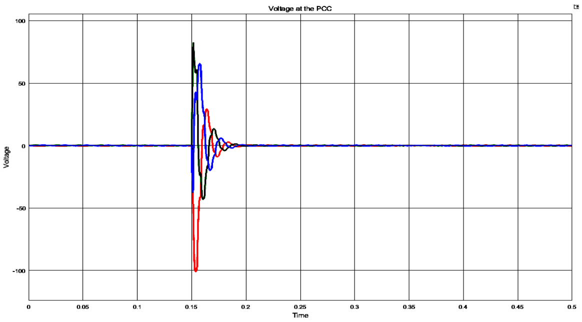
Figure 6.11 Stator Voltage and Current

Figure 6.11 shows the simulation output of stator voltage and current after fault conditions. The voltages are normalized after the fault without the disconnection of DFIG.

VII. CONCLUSION AND FUTURE SCOPE

A. *Conclusion*

In this paper, the analysis on the performance of a wind power station with DFIG and its interaction with the mains in case of grid failure is discussed. The voltage drop related problems during a grid fault can be split up into two parts in general. The first part is the drop of stator (grid) voltage and the second part is the switch-in process of the crowbar resistor which converts the DFIG configuration with increased rotor resistance. First of all the switching in of the crowbar resistor at the full grid and thus full stator voltage has been presented and analyzed. Secondly, the drop down in stator voltages with additional switching in of the crowbar resistor has been analyzed. With simulations, the increasing rotor current, rotor voltage, and torque are presented, and their dependency on the crowbar resistance. It has been shown that a coffee wrecking bar resistance results in higher electrical force, over currents and low rotor voltages. On the other hand,



high values for the crowbar resistor will result in a lower electrical torque and rotor currents but also to higher rotor voltages.

VIII. FUTURE SCOPE

- Analysis of grid-connected variable speed WECS can be performed with artificial intelligent controllers.
- A detailed analysis of Total Harmonic Distortion (THD) can be carried out in the future for reducing the harmonic level
- Impact of replacing the aged fixed speed wind farms with variable speed wind farms can be investigated.
- The inclusion of the load characteristics and its time variation can be studied to analyze the dynamics of the power system operation.
- The damping methods can be tested to reduce high transient values of current and voltages at different parts of WECS.

IX. REFERENCES

- [1]. Yipeng Song, Heng Nian, 2015, “Modularized Control Strategy and Performance Analysis of DFIG System Under Unbalanced and Harmonic Grid Voltage” IEEE Transactions On Power Electronics, Vol. 30, No. 9, September 2015
- [2]. S. Muller, M. Deicke, and R. W. De Doncker, 2002, “Doubly fed induction generator systems for wind turbines,” IEEE Ind. Appl. Mag., Vol. 8, No. 3, pp. 26–33, May/Jun. 2002.
- [3]. D.Zhi and L.Xu, 2007, “Direct power control of DFIG with constant switching frequency and improved transient performance,” IEEE Trans. on Energy Convers., Vol. 22, No. 2, pp. 110–118, Mar. 2007
- [4]. Y. Huang, X. Yuan, J. Hu and P. Zhou, 2015, “Modeling of VSC connected to weak grid for stability analysis of DC-link voltage control,” Emerging and Selected Topics in Power Electronics, IEEE Journal of Power Electronics 2015
- [5]. J. G. Slootweg and W. L. Kling, 2003 “The impact of large scale wind power generation on power system oscillations,” Electr. Power Syst. Res., Vol. 67, No. 1, pp. 9-20, Oct. 2003
- [6]. G. Tsourakis, B.M. Nomikos and C.D. Vournas, 2009, “Contribution of doubly fed wind generators to oscillation damping,” IEEE Trans. Energy Convers., Vol. 24, No. 3, pp. 783-791, Sep. 2009
- [7]. A. Daneshi, N. S. Momtazi, H. Daneshi, J. Javan, 2010, “Impact of SVC and STATCOM on Power System Including a Wind Farm”, Proc. of 2010 9th International Conference on Environment and Electrical Engineering (EEEIC) 2010
- [8]. Haitham Abu, Mariusz Malinowski, Kamal Al-Haddad, 2014, “Power Electronics For Renewable Energy Systems, Transportation And Industrial Applications” IEEE Press and John Wiley & Sons Ltd.