FAULT TOLERANCE AND POWER QUALITY STUDY OF DFIG BASED WIND TURBINE SYSTEM

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ABSTRACT

Wind power is the fastest growing renewable source of electrical energy hence it has become necessary to address problems associated with maintaining a stable electric power system. The wind generated power is always fluctuating due to its time varying nature and causing stability problem. Unified Power Flow Controller (UPFC) is used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. This controller offers advantages in terms of static and dynamic operation of the power system. A Unified Power Flow Controller (UPFC) is an electrical device for providing fast-sensation on high-voltage electricity transmission networks. The measurement and assessment of power quality characteristics of grid connected wind turbines are specified in International Electro-technical Commission standard IEC-61400-Part 21. Another effort is given in this report to make a comparative study of the fault current and voltages of a DFIG (Doubly Fed Induction Generator) system with using a relay protection system and incorporating UPFC in the system. The UPFC control scheme for the grid connected wind energy generation system for mitigating power quality issues is simulated using MATLAB/SIMULINK environment, and a DFIG is also used to study the response of the system during grid disturbances.

Keywords: Doubly Fed Induction Generator (DFIG), Fault Tolerance, Grid Connected DFIG System, Relay Protection System, Unified Power Flow Controller (UPFC).

1. INTRODUCTION

In recent years, world vigorously development clean energy especially wind power in order to carry out and practicable the sustainable development measure an implement the economy and environment coordinated development, and with the wind power generation techniques increasingly
mature, large scale capacity wind power growingly dive into the network. Wind power solves the energy crisis problem in a certain extent, but the large scale wind power dive into power system has brought a series of technical problems, one of the problems is that the impact on the protection configuration can't neglect. To increase the system efficiency, high efficiency devices based on power electronics equipments have been increasingly used in many applications. This causes increasing harmonic levels on power systems and concerns about the future impact on system capabilities. So, if there is any fault in the subsystems there will be disturbances, disruptions and the other effects, which decrease the power quality in the system. To maintain the power quality and to improve the fault protection techniques of a wind energy system, several research scholars all over the world are trying to find a solution. [1] presents a control strategy to improve the low-voltage ride-through capability of a doubly fed induction generator and the necessary simulations and experiments are carried out, but the application of FACTS devices are not revealed in the work. [2] proposes a new converter protection method, based on Series Dynamic Resistor (SDR) and also the conventional crowbar protection method. Performance comparison of crowbar protection and SDR has been analyzed with simulation, but still this paper does not produce enough details of the power quality. [3] demonstrates the power quality problem due to wind turbine installation with the grid. In that proposed scheme, Unified Power Quality Conditioner (UPQC) is used with a battery energy storage system (BESS) to palliate the power quality issues, but the paper does not illuminate the fault protection issues. In [4] STATCOM is used with energy storage system to reduce the power quality problems. The paper clearly shows that the power quality problem exists due to wind turbine installation with the grid. [5] employs the Pulse Width Modulation (PWM) inverter scheme for the grid connected wind energy generation for power quality improvement and simulation is done using power system block set in MATLAB/SIMULINK. All the approaches definitely elucidated the power quality issues and the various fault protection schemes of a wind energy system, but the need of a combined approach can still be felt. The present work proposes a grid connected DFIG system using UPFC which will produce a better quality of power than the conventional DFIG system. Also, a relay protection system has been used in the proposed model to minimize the effect of fault in any grid disturbances. The simulation has been carried out using MATLAB software.

2. THEORY

A doubly fed induction generator is basically a standard, wound rotor induction generator with its stator windings directly connected to the grid and its rotor windings connected to the grid and its rotor windings connected to the grid through a converter. The AC to DC and DC to AC Converter is divided into two parts: the rotor side converter and the grid side converter. Force commutated power electronic devices are used in these voltage source converters to synthesize an AC Voltage from a DC source. A capacitor connected on the DC side acts as the DC voltage source. The grid side converter is connected to the grid by using a coupling inductor. The three phase rotor winding is connected to the rotor side converter by slip rings and brushes and the three phase stator windings are directly connected to the grid. The power of the wind turbine, the DC voltage and the reactive power or the grid terminal voltage are controlled by the pitch angle command and the voltage command signals $V_r$ and $V_{gc}$ generated by the control system for the rotor and grid side converters respectively.
Fig. 1 shows the flow of power in a Doubly Fed Induction Generator. The absolute value of slip is generally much lower than 1 and accordingly the electrical power output of the rotor $P_r$ is only a fraction of the real power output of the stator $P_s$. $W_s$ is positive and constant for a constant frequency grid voltage and also the electromagnetic torque $T_m$ is positive for power generation, so the sign of $P_r$ is a function of the slip sign. $P_r$ is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). $P_r$ is transmitted to DC bus capacitor and tries to set up the DC voltage for super synchronous speed operation. $P_r$ is taken out of the DC bus capacitor and tries to reduce the DC bus voltage for sub synchronous speed operation. The DC voltage is kept constant by generating or absorbing the grid electrical power $P_{ge}$ from the grid side converter. For a lossless AC/DC/AC converter $P_{ge}$ is equal to $P_r$ in steady state and the wind turbine speed is determined by the absorbed or generated power $P_r$ by the rotor side converter. The voltage measured at the grid terminals can be controlled by controlling the grid side converter DC bus voltage of the capacitor can be regulated and by controlling the rotor side converter. The phase sequence of the AC voltage generated by the rotor side converter is positive for sub synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. The reactive power or the voltage at the grid terminals can be controlled by the capability of the rotor and grid side converter of generating or absorbing reactive power. The rotor side converter is used to control the wind turbine output power and the voltage (reactive power) measured at the grid terminals. The voltage regulation of the DC bus capacitor is done by using the grid side converter. The rotor power converter as a vulnerable part of the DFIG power converter, which has a restricted over-current limit, needs special attention especially during faults in the grid. When faults occur and cause voltage dips, subsequently the current flowing through the power converter may be very high (over-current). During this situation, it is common to block the converter to avoid any risk of damage, and then to disconnect the generator from the grid. Motivated by the reason above, this report provides a study of the dynamics of the grid connected wind turbine with DFIG. In steady-state at fixed turbine speed with a lossless DFIG system, the mechanical power from the aerodynamic system is balanced by the DFIG power. $P_m = P_s + P_r$. It follows that

$$P_r = P_m - P_s = T_m\omega_r - T_m\frac{\omega_s - \omega_r}{\omega_s} = -s$$

$$T_m\omega_s = -sP_s$$

where $s$ is defined as the slip of the generator.
2.1 POWER QUALITY ISSUES

Power quality problem is any power problem manifested in voltage, current, or frequency deviation that results in failure or malfunctioning of customer equipment. Power quality is a two-pronged issue, with electronic equipment playing both villain and victim. The causes and consequences of power quality problems can be traced to a specific type of electrical disturbance. In most of industry, more than 90% of the electric motor with inverter driven application. Poor power quality causes trouble in receptacle/transmission equipment and electronic equipment malfunctions / Failure. Power quality is a common problem for both electric power suppliers and users. It is not easy to identify whether the cause of poor power supply quality is at the supplier’s system or the user’s system. Voltage fluctuations are changes or swings in the steady-state voltage above or below the designated input range for a piece of equipment. Fluctuations include both sags and swells and it causes large equipment start-up or shut down; sudden change in load.

2.2 FAULT PROTECTION ISSUES

The rotor power converter as a vulnerable part of the DFIG power converter, which has a restricted over-current limit, needs special attention especially during faults in the grid. When faults occur and cause voltage dips, subsequently the current flowing through the power converter may be very high (over-current). During this situation, it is common to block the converter to avoid any risk of damage, and then to disconnect the generator from the grid. Actuated by the above reason, this paper furnishes a study of the dynamics of the wind turbine which is grid connected with DFIG. The report begins with the development of a wind turbine model with DFIG in Matlab, Simulink, followed by simulations of the model during grid disturbance. In the simulation, the ability of the DFIG to recover terminal voltage after grid disturbance is introduced. The reaction of the DFIG to faults and subsequent action of the over-current protection is described. Two different operation modes, i.e. sub-synchronous and super-synchronous operation, are cared for individually. The results from the two operation modes are then evaluated. The inclusion of the saturation effect in the generator to provide better prediction of current magnitude is included as well. The relay protection system block consists of following:

- Instantaneous AC Overcurrent, AC Overcurrent (positive-sequence), AC Current unbalance, AC Undervoltage (positive-sequence), AC Overvoltage (positive-sequence), AC Voltage Unbalance (Negative-sequence), AC Voltage Unbalance (Zero-sequence), DC Overvoltage, Under Speed, Over Speed.

The parameters and ratings are given in the table-1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Instantaneous AC Overcurrent (pu)</td>
<td>10</td>
</tr>
<tr>
<td>Maximum AC Current [ I_{\text{Imax(pu), Delay(s)}} ]</td>
<td>1.1, 5</td>
</tr>
<tr>
<td>Maximum AC Current Unbalance [ I_2/I_{\text{Imax(pu), Delay(s)}} ]</td>
<td>0.4, 0.2</td>
</tr>
<tr>
<td>AC Under/Over Voltage [ V_{\text{Vmin(pu), V_{\text{Vmax(pu), Delay(s)}}}} ]</td>
<td>0.75, 1.1, 0.1</td>
</tr>
<tr>
<td>Maximum Voltage Unbalance [ V_2/V_{\text{Vmax(pu)}} ]</td>
<td>0.05, 0.05, 0.2</td>
</tr>
<tr>
<td>V0/V1max(pu), Delay(s) ]</td>
<td></td>
</tr>
<tr>
<td>Maximum DC Voltage [ V_{\text{Vmax(V), Delay(s)}} ]</td>
<td>1900,0.001</td>
</tr>
<tr>
<td>Under/Over Speed [ Speedmin (pu), Speedmax (pu), Delay(s)]</td>
<td>0.3, 1.5, 5</td>
</tr>
<tr>
<td>Start time for protection system (sec)</td>
<td>5</td>
</tr>
</tbody>
</table>
2.3 OPERATING PRINCIPAL OF UPFC

Line outage, congestion, cascading line tripping, power system stability loss are the major issues where capability and utilization of FACTS are noticed. Example of the terminal generation of FACTS devices is the Unified Power Flow Controller (UPFC). The UPFC is a gimmick which can control simultaneously all three parameters of line power flow (line impedance, electric potential and phase angle). Such "new" FACTS device combines together the features of two "old" FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC).

The shunt inverter is used for voltage regulation at the degree of connection injecting an opportune reactive power flow into the lineage and to balance the actual power flow exchanged between the series inverter and the transmission line. The series inverter can be applied to curb the real and reactive line power flow inserting an opportune voltage with controllable magnitude and phase in series with the transmission line.

The series inverter is controlled to inject a symmetrical three phase voltage system of controllable magnitude and phase angle in series with the line to control active and reactive power flows along the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is channeled to the DC terminals. The shunt inverter operates in such a fashion as to demand this DC terminal power (positive or negative) from the line keeping the potential difference across the storage capacitor Vdc constant. So, the net real power absorbed from the crease by the UPFC is equal only to the losses of the two inverters and their transformers. The remaining content of the shunt inverter can be employed to exchange reactive power with the line and then to provide a voltage regulation at the point of connection.

3. PROPOSED MODEL

In the proposed Simulink model of wind farm we have introduced-

Unified Power Flow Controller (UPFC) mode, when the shunt and series converters are interconnected through the DC bus. When the disconnect switches between the DC buses of the shunt and series converter are opened, two additional modes are available i.e. Shunt converter
operating as a Static Synchronous Compensator (STATCOM) controlling voltage and Series converter operating as a Static Synchronous Series Capacitor (SSSC) controlling injected voltage, while keeping injected voltage in quadrature with current. Unified Power Flow Controller (UPFC) are being used extensively in power systems because of their ability to provide flexible power flow control. The main motivation for choosing SVC in wind farms is its ability to provide bus bar system voltage support either by supplying and/or absorbing reactive power into the system. As a main stream configuration for large wind turbines, DFIG wind turbines are required to remain grid connected during grid faults so that they can contribute to the stability of the power transmission system. This raises problems in terms of generator/converter protection and control. In the case of grid faults, the controllability of the DFIG variable speed wind turbine embraces both the wind turbine control for preventing over-speeding of the wind turbine and the control and protection of the power converter during and after grid faults.

A Unified Power Flow Controller (UPFC) is used to control the power flow in a 120 kV/25 kV transmission systems. The system connected in a loop configuration consists essentially of three buses (B575, B25, B120) interconnected through transmission line (L1) and two transformer banks. The model of DFIG based 9MW wind farm with UPFC is designed using MATLAB/SIMULINK is shown in Fig.3.

![Simulink model of the system with UPFC & Relay protection system](image)

The UPFC located at the right end of the 30-km line L1 between the 120 kV buses B25 and B575 is used to control the active and reactive powers flowing through bus B25, while controlling voltage at bus B575. The UPFC consists of two 100-MVA, three-level, 48-pulse GTO-based converters, one connected in shunt at bus B25 and one connected in series between wind B575 and B25. The shunt and series converters can exchange power through a DC bus.
This pair of converters can be run in three ways:

Unified Power Flow Controller (UPFC) mode, when the shunt and series converters are interconnected through the DC bus. When the disconnect switches between the DC buses of the shunt and series converter are opened, two additional modes are available. Shunt converter operating as a Static Synchronous Compensator (STATCOM) controlling voltage at bus B1.

Series converter operating as a Static Synchronous Series Capacitor (SSSC) controlling injected voltage, while keeping injected voltage in quadrature with current.

4. SIMULATION RESULTS

Initially started simulation, wind speed is set at 12 m/s, then at t = 10s, wind speed increases suddenly at 16 m/s. Start simulation and observe the signals along the "Wind Turbine" scope monitoring the wind turbine voltage, current, generated active and Reactive powers, DC bus voltage and turbine speed.

Now unfold the "Fault" block menu and select "Phase A Fault". Find out that the fault is programmed to apply a 9-cycle, single-stage to earth break in t = 10s. We noticed that when the wind turbine is in "Voltage regulation" mode, the positive-sequence voltage at wind-turbine terminals (B575) drops to 0.8 pu during the break, which is above the under voltage protection threshold (0.75 pu for at > 0.1 s). The wind farm therefore stays in service.

Fig.4: Fault tolerance at time of fault

The voltage (Vabc_25) and current (Iabc_25) at bus B25 without UPFC controller and with UPFC controller are shown in Fig5 and Fig6 respectively.
Fig. 5: The voltage, current at bus B25 without UPFC

Fig. 6: The voltage, current at bus B25 with UPFC
Now, the fault voltages and currents characteristics of the simulink diagram of fig.7 is shown below:

**Fig.7:** Fault Voltages & currents with UPFC & relay protection system in the proposed model

5. CONCLUSION

This paper presents the grid connected wind energy system for power quality improvement by using UPFC. The power quality problems, its consequences and their mitigation techniques are presented here. In this proposed scheme to eliminate the harmonic content of the load current the UPFC-based control system is used. So that power quality is maintained at the point of common coupling. Therefore, to control the power from one end to another end, this concept of power flow control and voltage injection is applied. Modeling the system and studying the results have given an indication that UPFC are very useful when it comes to organize and maintain power system. The UPFC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle). The UPFC controller mitigates the harmonic distortion that caused by the nonlinear load where all values of THD for voltage and current at all AC buses are decreased to values within allowable limits of IEEE standard. Wind power generation with DFIG provides better performance for terminal voltage recovery after fault clearance owing to its ability to control reactive power. However DFIG is sensitive to severe voltage dips that result in an excessive stator and rotor current, which leads to the rotor converter being blocked. The shaft oscillation caused by the fault should be considered when examining the dynamic response of the DFIG. Special attention should be paid to the blocking that occurs when the DFIG operates at far below synchronous speed. Since, in this case, the abrupt change in the rotor speed has more serious impacts on the electrical response of the system. As regards the saturation effect during fault, it can be seen in the simulation that the peak value of the stator and rotor current in the model with saturation is higher than in the model without saturation. Therefore it is important to take the saturation effect into account, especially when designing a protection setting. However, the prediction of the current magnitude in the model with saturation is characterized by the saturation curve of the generator.
When UPFC is only present in the proposed system, the oscillations are created in the fault voltages and currents, that is undesirable. With using only the relay protection system, the oscillations are absent, but the effect of fault is greater in the fault voltages and currents, that is not acceptable. So, the model with both UPFC and relay protection system is acceptable in terms of a better fault tolerance capacity and power quality.

6. FUTURE SCOPE

The scope can be extended by using other FACTS device and also a fault detection system based on microcontroller can be used to detect and minimize the effect of fault in the overall performance of the system.

7. ACKNOWLEDGEMENT

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REFERENCES


