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Research Article

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Modeling, Simulation of UPFC and Its Effect on Power System Protection

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Abstract—

The continuously growing demand for wind power generation capacity forces the revision of the grid codes requirements, to remain connected during grid faults, i.e., to ride through the faults, and contribute to system stability during fault condition. In a typical fault condition, the voltage at the Point of Common Coupling (PCC) drops below 80% immediately and the rotor speed of induction generators becomes unstable. In this paper, Unified Power Flow Controller (UPFC) is used to improve the low voltage ride- through (LVRT) of wind energy conversion system (WECS) and to damp the rotor speed oscillations of induction generator under fault conditions. By controlling the UPFC as a virtual inductor, we aim to increase the voltage at the terminals of the wind energy conversion system (WECS) and thereby mitigate the destabilizing electrical torque and power during the fault. The DFIG-based WECS is considered for study here, equipped with a doubly fed induction generator (DFIG). The simulation results show that UPFC can improve the LVRT of DFIG-based WECS and hence maintaining wind turbine connection to the grid during certain levels of voltage fluctuation at the grid side.

Keywords— ***LVRT, Indian Electricity Grid code, UPFC, DFIG-WECS***

I. INTRODUCTION

Recently non-conventional energy sources are becoming very popular and as they are infinite and clean source of electricity . Wind energy is most popular dominant source among renewable sources of energy . Among the wind turbine concepts, turbines using the doubly fed induction generator (DFIG) are dominant due to its variable-speed operation, its separately controllable active and reactive power, and its partially rated power converter. But the reaction of DFIGs to grid voltage disturbances is sensitive, for symmetrical and unsymmetrical voltage dips, and requires additional compensation support to keep the voltage within area bounded by the LVRT and HVRT margins of the electricity grid codes.The detailed settings of the reactive power control system are provided by the respective system utility (SU). The wind farm must have adequate reactive power

Capacity to be able to operate with zero reactive exchange with the network measured at the connection point, when the voltage and the frequency are within normal operation limits. The following points are the standards being framed by the IEGC for reactive power exchange within the network:

- VAR drawn from the grid at voltages below 97 % of nominal will be penalized.
- VAR injection into the grid at voltages below 97 % of nominal will be given incentive.
- VAR drawl from the grid at voltages above 103 % of nominal will be given incentive.
- VAR injection into the grid at voltages above 103 % of nominal will be penalized

Fault-ride through (FRT) requirement is imposed on a wind power generator so that it remains stable and connected to the network during the network faults. Disconnection from grid may worsen the situation and can threaten the security standards at high wind penetration. The wind farm must be able to operate satisfactorily during and after the disturbances in the distribution/ transmission network, and remain connected to the grid without tripping from the grid for a specified period of time during a voltage drop (LVRT) or voltage swell (HVRT) at the PCC.

Flexible AC transmission system (FACTS) devices have been used to maintain the WTGs penetration to the electricity grid during fault conditions and wind speed variation. This work investigates the application of unified power flow controller (UPFC) to improve the wind turbine FRT capability in compliance with Indian Electricity grid codes. FACTS devices are needed to which can either, compensate the voltage, phase shift, or both the increase of voltage and phase shift, and real and reactive power enhancement. Among various FACTS devices we have analyzed the performance of grid connected DFIG-WES system without and with UPFC as this custom power device has unique capability of series as well shunt compensation .

II. SYSTEM UNDER STUDY

Fig.1 shows the system under study, which consists of 9 MW DFIG connected to a grid that is simulated as an ideal 3-phase voltage source of constant voltage and frequency through 21 km transmission line and two transformers.

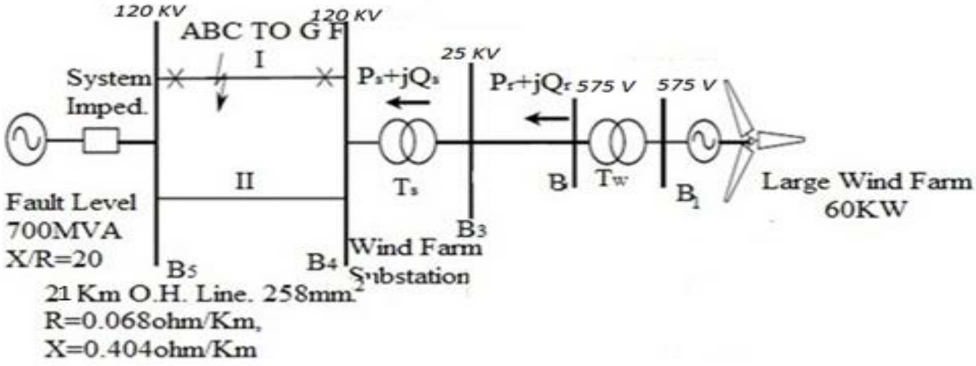


Fig.1 Single line diagram of system under study

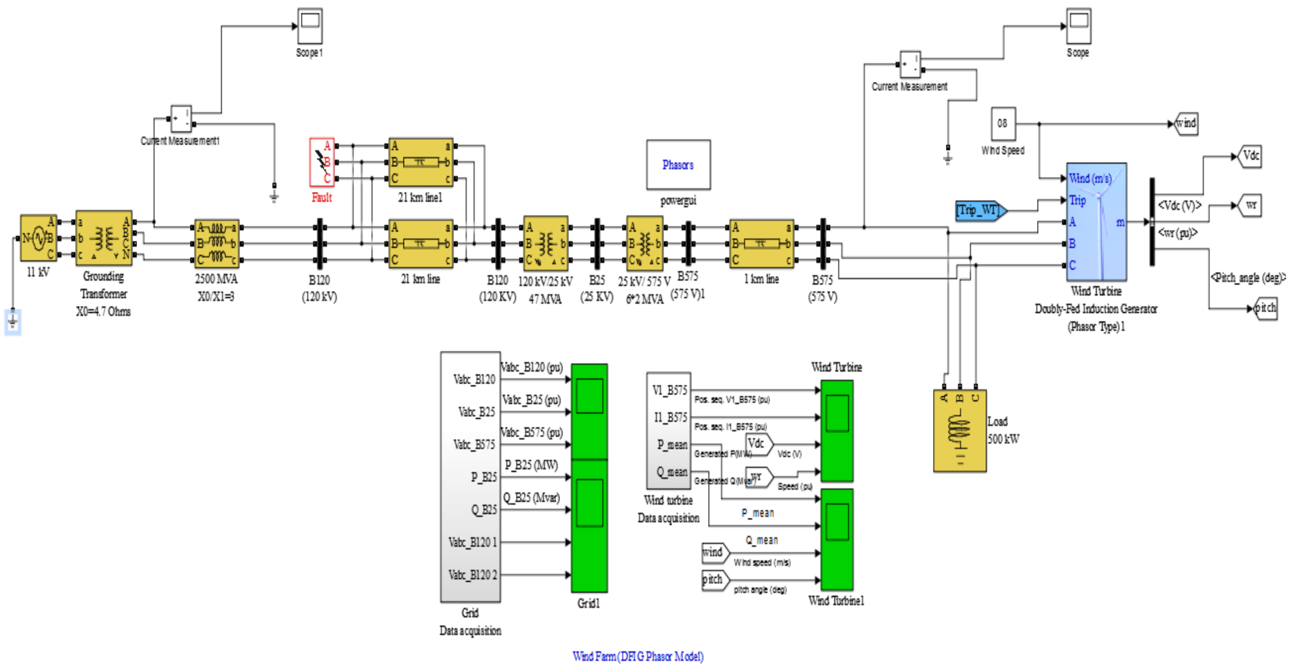


Fig.2 Simulink Model of Uncompensated System Without UPFC

The 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 21 km, 25 kV feeder. A 500 kW resistive load or Inductive load of $50*10^6$ henry and a 0.9 Mvar (Q=50) filter are connected at the 575 V generation bus. The turbine parameters specifying ratings of power components of the wind turbine are as follows: The wind turbine model is a phasor model that allows transient stability type studies with long simulation times. In this case study, the system is observed during 30 s. The 6-wind-turbine farm is simulated by a single wind-turbine block by multiplying the following three parameters by six, as follows:

- Nominal wind turbine mechanical output power: 6*1.5e6 watts, specified in the Turbine data menu.
- Generator rated power: 6*1.5/0.9 MVA (6*1.5 MW at 0.9 PF).
- Nominal DC bus capacitor: 6*10000 microfarads.

mode of operation is set to Voltage regulation in the Control Parameters dialog box. The terminal voltage is controlled to a value imposed by the reference voltage (Vref=1 pu) and the voltage droop (Xs=0.02 pu). In this model the wind speed is maintained constant at 14 m/s. The control system uses a torque controller in order to maintain the speed at 1.09 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar. For a wind speed of 14 m/s, the maximum turbine output is 0.55 pu of its rated power (0.55*9MW=4.95 MW) at a speed of 1.09 pu of generator synchronous.
We connect a UPFC to the PCC bus to increase the WTG damping and to provide support to the system during fault conditions. The model of the power system scheme for case study is illustrated in Fig. 2, including the controllers with the control strategy, is implemented using Matlab/Simulink software. During normal operation, the reactive power produced by the wind turbines is regulated at 0 Mvar to achieve unity power factor operation. For an average wind speed of 12 m/s, which is used in this study, the turbine output active power is 1.0 pu and the generator speed is 1.0 pu. The UPFC is used to improve the FRT of the WTGs, by controlling the active and reactive power at the bus it is connected. Numerical simulations are performed to determine and then compensate voltage fluctuation due to wind power variation, and voltage regulation problems due to a sudden load connection.

III. UNIFIED POWER FLOW CONTROLLER

With the enormous global growth in electrical power demand, there has been a challenge to deliver the required electrical power considering the quality sustainability and reliability of the delivered power. To achieve this goal, it is essential to control the existing transmission systems for efficient utilization and to avoid new costly installations .

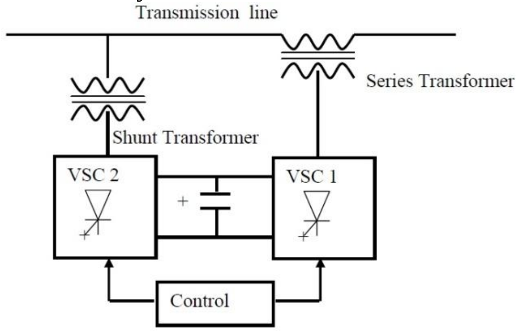


Fig. 3 UPFC configuration

FACTS technology play an important role in improving the utilization of the existing power system as it can provide technical solutions to improve the power system performance . As a FACTS device, unified power flow controller allows power systems to be more flexible by using high-speed response and decoupled active and reactive power compensations and by installing UPFC at particular locations of the transmission system, the power dispatch can be increased up to the power rating of generators, transformers and thermal limits of line conductors, by increasing the stability margin. Shunt and series converters of the UPFC can control both active and reactive powers in four quadrants smoothly, rapidly and independently.

We have connected a UPFC to the PCC bus to increase the WTG damping and to provide support to the system during fault conditions. The model of the power system scheme for case study is illustrated in Fig.2, including the controllers with the control strategy, is implemented using Matlab/Simulink software. During normal operation, the reactive power produced by the wind turbines is regulated at 0 Mvar to achieve unity power factor operation. For an average wind speed of 12 m/s, which is used in this study, the turbine output active power is 1.0 pu and the generator speed is 1.0 pu. The UPFC is used to improve the FRT of the WTGs, by controlling the active and reactive power at the bus it is connected. Numerical simulations are performed to determine and then compensate voltage fluctuation due to wind power variation, and voltage regulation problems due to a sudden load connection.

Matlab simulation result of uncompensated system under study.

Response to a change in wind speed.

Initially, wind speed is set at 8 m/s, then at t = 5s, wind speed increases suddenly at 12 m/s. We Start simulation and observed the signals on the "Wind Turbine" scope monitoring the wind turbine voltage, current, generated active and reactive powers, DC bus voltage and turbine speed.

At t = 5 s, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9 MW in approximately 15 s. Over that time frame the turbine speed will have increased from 0.8 pu to 1.4 pu. Initially, the pitch angle of the turbine blades is zero degree and the turbine operating point follows the red curve of the turbine power characteristics up to point D. Then the pitch angle is increased from 0 deg to 0.76 deg in order to limit the mechanical power.

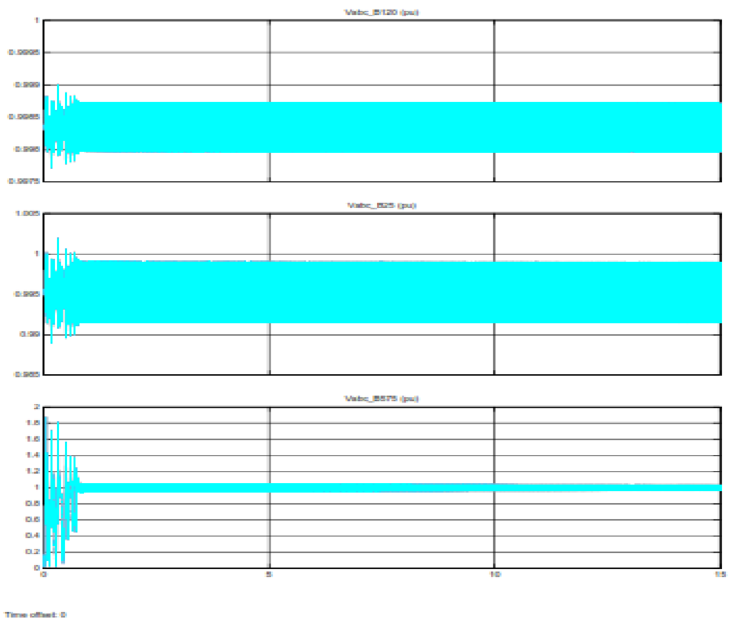


Fig. 4 Effect of change in wind speed on output Voltages at various buses with Resistive load

Response to fault on the 120-KV grid system.

We now observe impact of a single phase-to-ground fault occurring on the 120-kV line at B120 bus. Now by opening the "Fault" block menu and selecting "Phase A Fault". We check that the fault is programmed to apply a 9-cycle single-phase to ground fault at t = 5 s.

From the below two graphs we observe that when the wind turbine is in "Voltage regulation" mode, the positive-sequence voltage at wind-turbine terminals (V1_B575) drops to 0.8 pu during the fault, which is above the under voltage protection threshold (0.75 pu for a t > 0.1 s). The wind farm therefore stays in service.

The second scenario is compared with the HVRT of Indian electricity grid code as shown in Fig. 5. As can be shown in the figure, the voltage at the PCC violates Indian electricity HVRT level, which calls for the disconnection of the wind turbine from the grid to avoid any possible damages to the WTG.

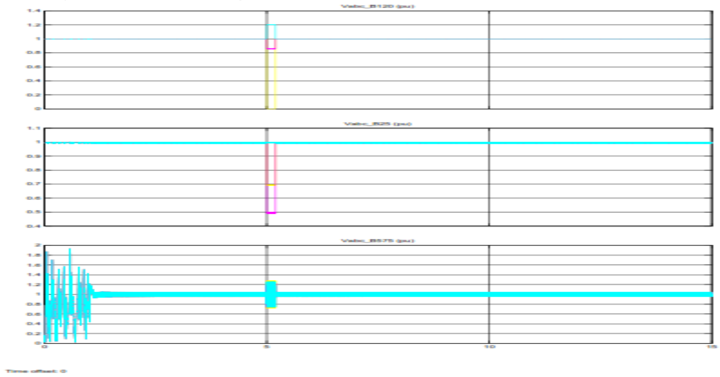


Fig. 5 Volatge at PCC for LG fault with Resistive Load.

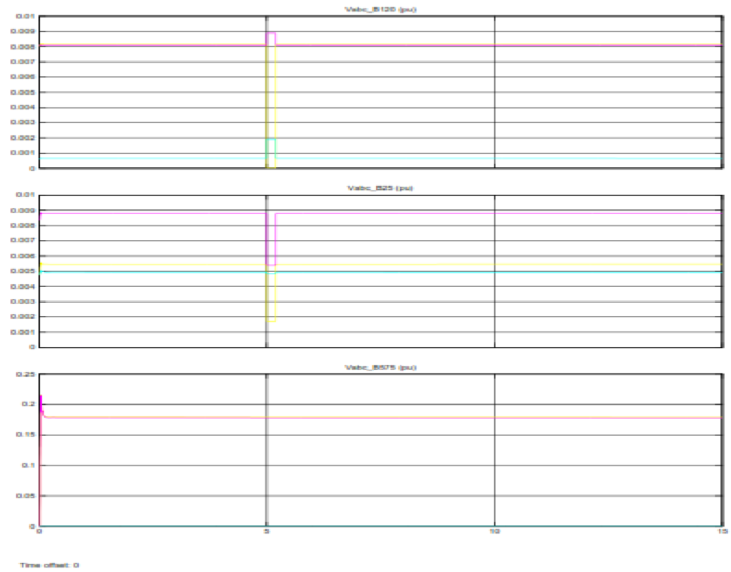


Fig. 6 Volatge at PCC for LG fault with Inductive Load.

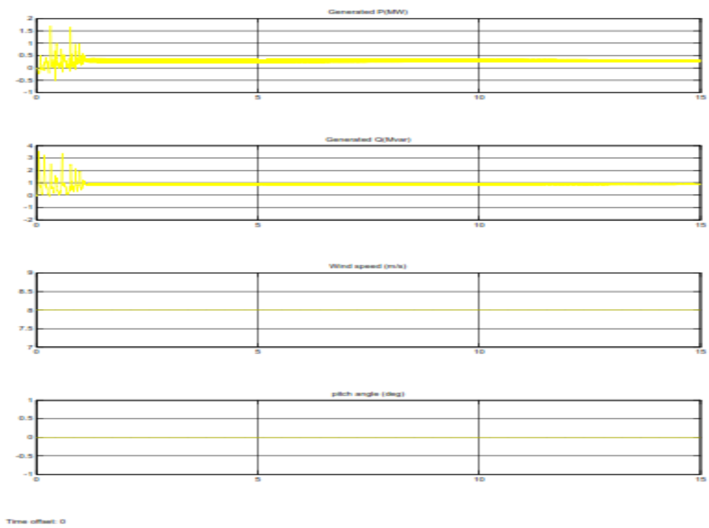


Fig. 7 Reactive power at PCC for LG fault with Resistive Load.

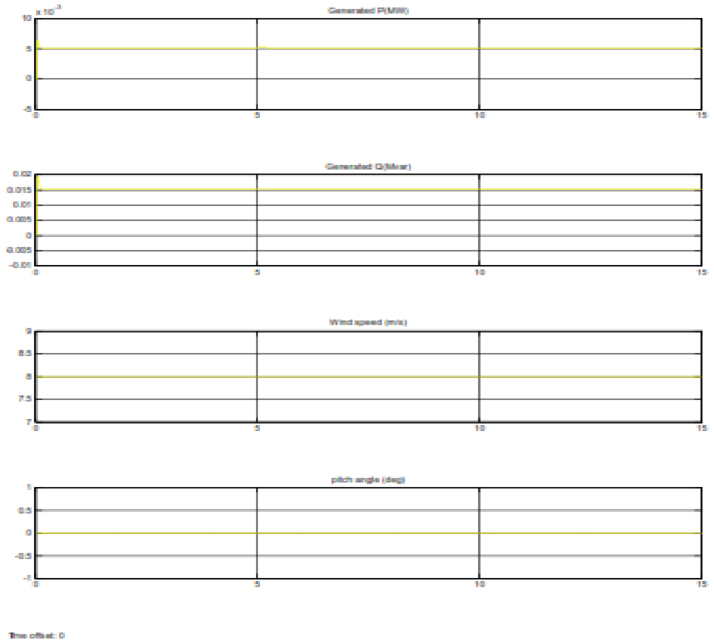
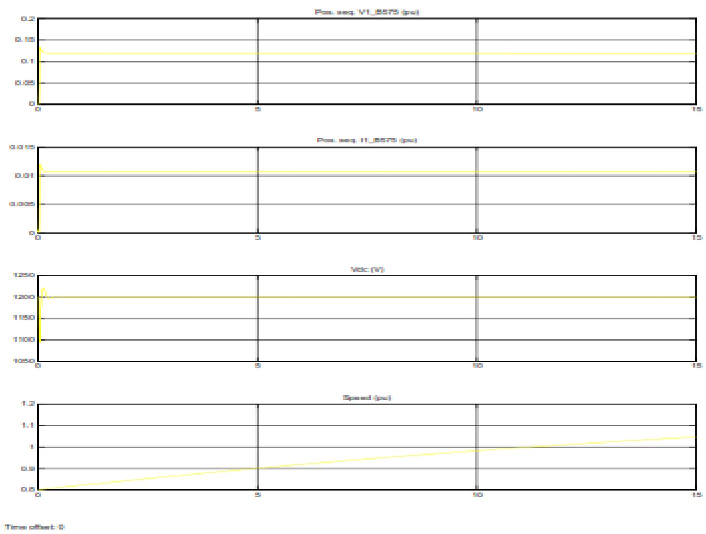


Fig. 8 Reactive power at PCC for LG fault with Inductive Load.

Fig. 9 Positive sequence Voltage for LG fault with Resistive Load



. Fig. 10 Positive sequence Voltage for LG fault with Inductive Load

However, if the "var regulation" mode is used with Q_{ref} = 0, the voltage drops under 0.7 pu and the under voltage protection trips the wind farm. We can now observe that the turbine speed increases. At t= 10 s the pitch angle starts to increase in order to limit the speed.

Matlab simulation result of compensated with upfc system under study

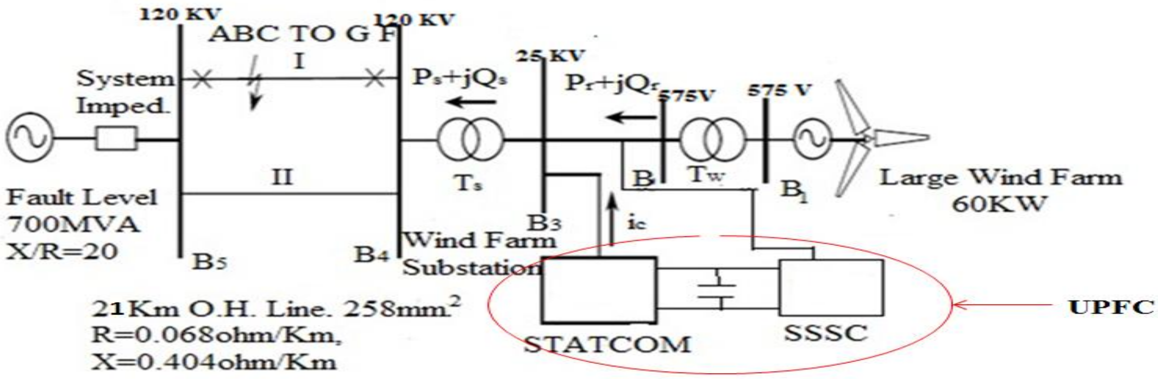


Fig. 11: Study case power system with UPFC

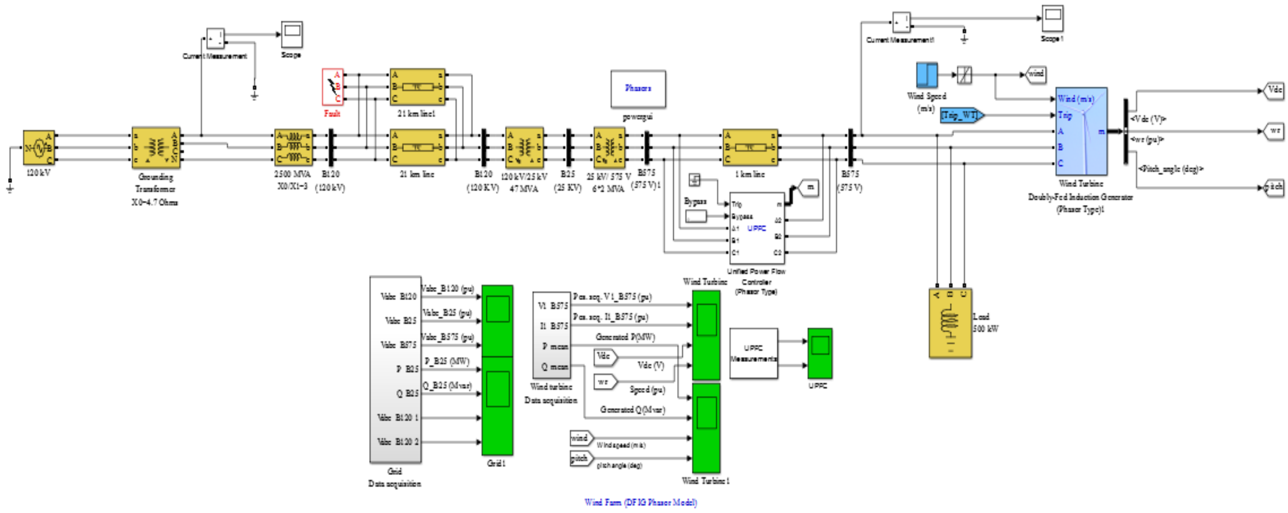


Fig.12 Simulink model of uncompensated system With UPFC

Response to fault on the 120-KV grid system.

Simulation is carried out with a fault at the grid side that causes voltage sag at the PCC bus at t= 5 s for duration of 0.6 s. The voltage performance at the point of common coupling is investigated during the fault without and with the connection of the UPFC to the PCC bus.

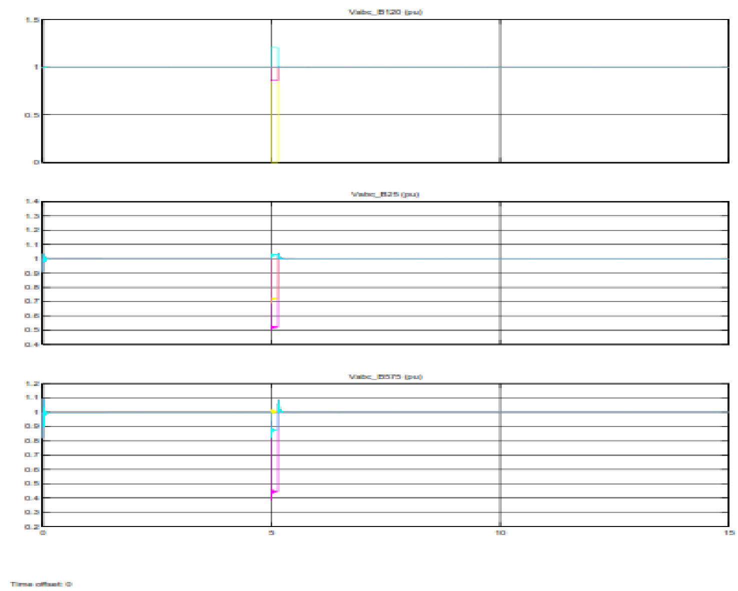


Fig. 13 Voltage at PCC for LG fault in UPFC compensated system with Resistive Load

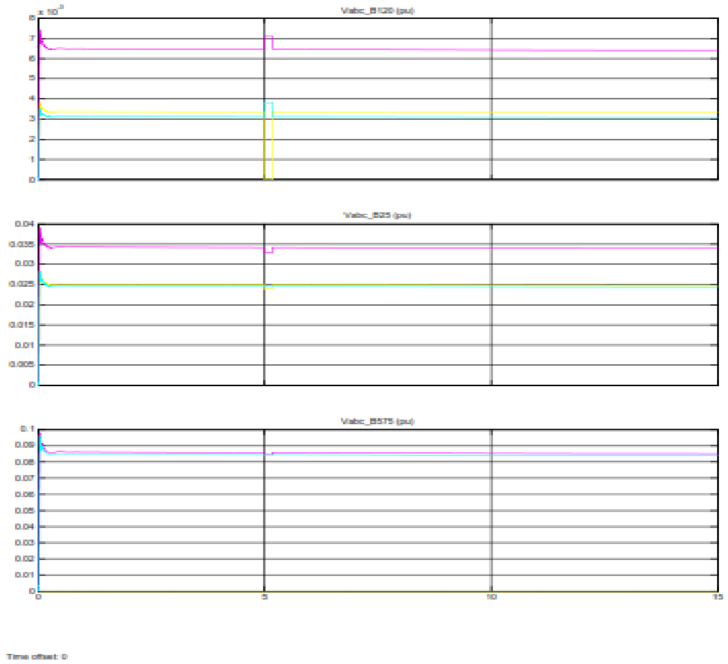


Fig. 14 Voltage at PCC for LG fault in UPFC compensated system with Inductive Load

Fig. 5 shows that the grid fault causes the voltage at the PCC to decrease to a level lower than 0.5pu. Referring to the Indian Electricity LVRT grid code the WTGs are to be disconnected from the grid as this violates its lowest permissible limit as shown in Fig. 5. However, by connecting the UPFC to the grid at the PCC bus, the amount of voltage sag reaches a safety margin of the Indian Electricity grid requirement as can be shown in Fig. 13 and hence avoiding the disconnection of WTG.

If the US grid code is applied, without UPFC, voltage sag at the PCC violates the safety margin of LVRT grid code as shown in Fig. 5.When the UPFC is connected to the system, voltage sag can be maintained at a safe level and the WTGs connection to the grid can be maintained during the fault as can be shown in Fig. 13.

Fig. 17 & Fig. 18 shows the voltage across the DC-link capacitor of the WTG (*VDC*) with and without the connection of the UPFC. With the UPFC connected to the system, the overshooting and settling time are substantially reduced compared to the system without the connection of the UPFC.

The performance of the UPFC during fault can be examined in Fig. 13 to Fig. 20. When voltage swell or sag at the PCC is applied, the UPFC controller acts to instantly exchange reactive power with the AC system (delivering in case of voltage sag and absorbing in case of voltage swell) to regulate the voltage at the PCC within a safety level. It worth to notice that during normal operating conditions, there is no reactive power exchange between the UPFC and the AC system and the reactive power generation is maintained at zero level to achieve unity power factor operation for the WTG.

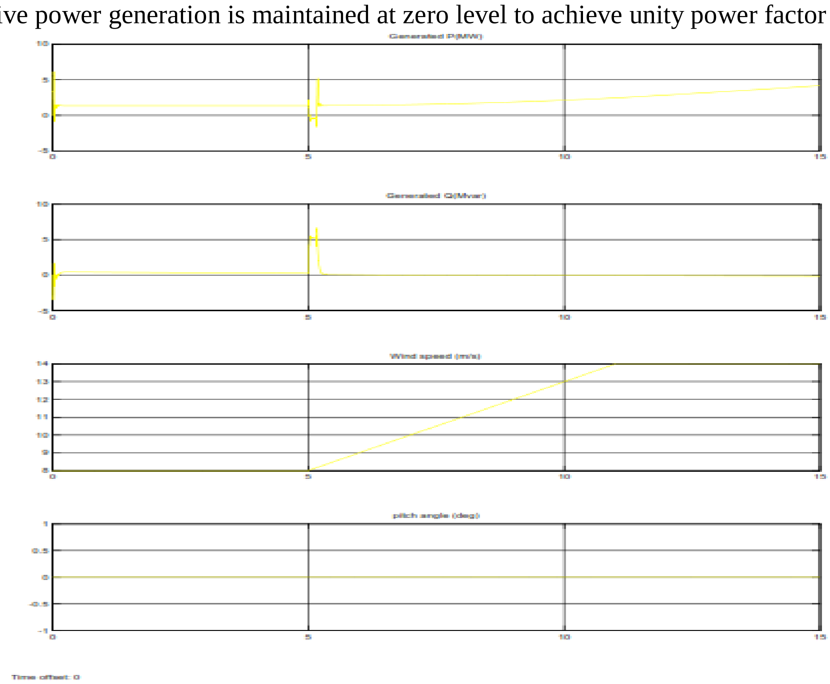


Fig. 15 Real and Reactive power at PCC for LG fault in UPFC compensated system with Resistive Load

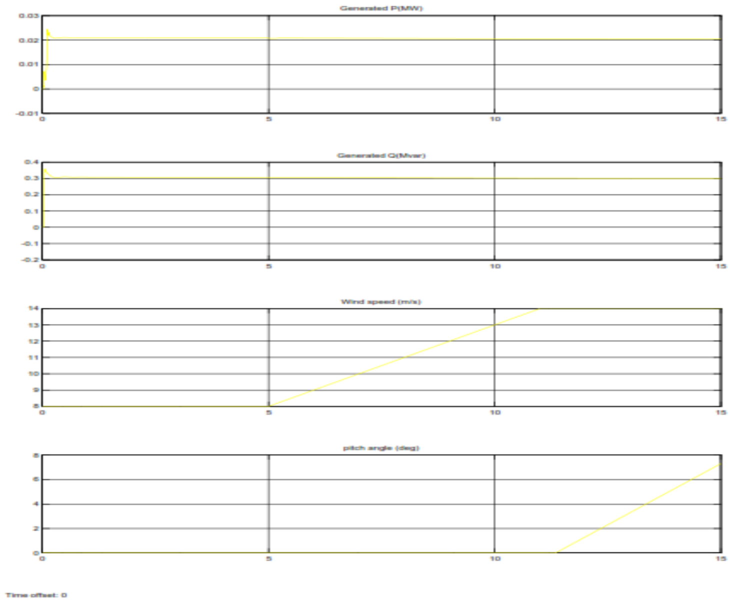


Fig. 16 Real and Reactive power at PCC for LG fault in UPFC compensated system with Inductive Load

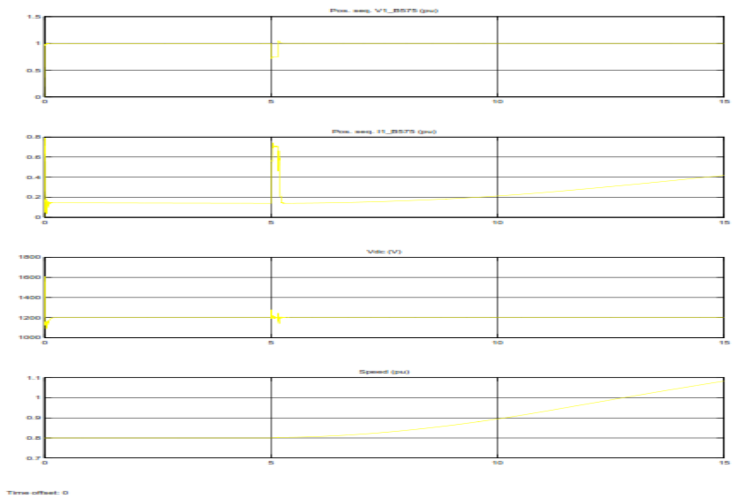


Fig. 17 Voltage across the DC-link capacitor of the WTG for LG fault in UPFC compensated system with Resistive Load

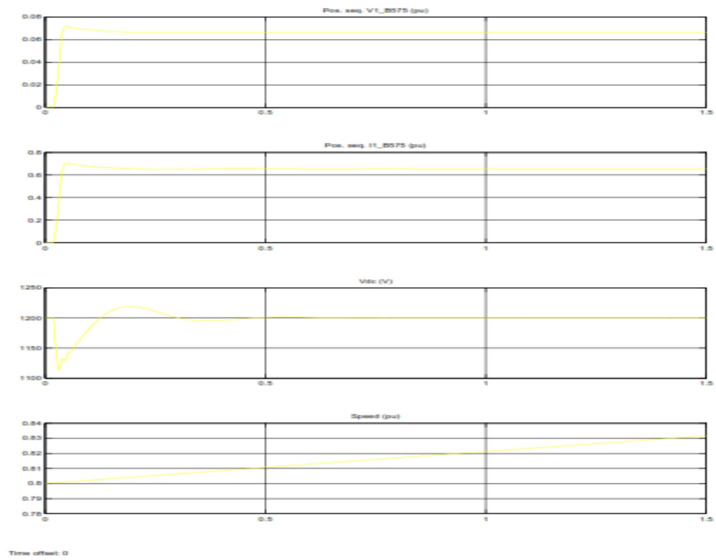


Fig. 18 Voltage across the DC-link capacitor of the WTG for LG fault in UPFC compensated system with Inductive Load

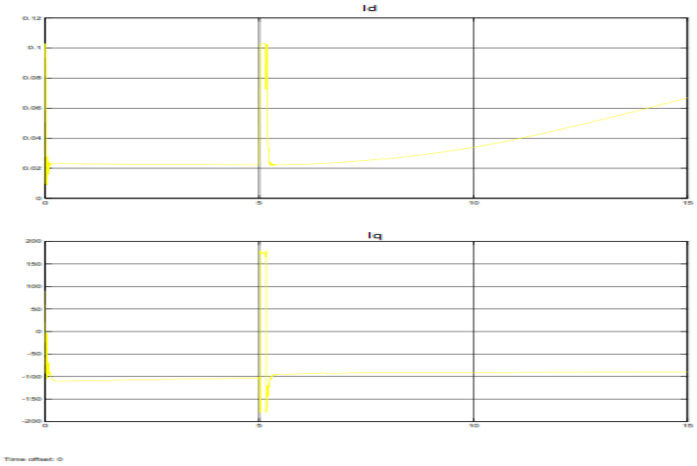


Fig. 19 Direct and Quadrature UPFC Current for LG fault with Resistive Load

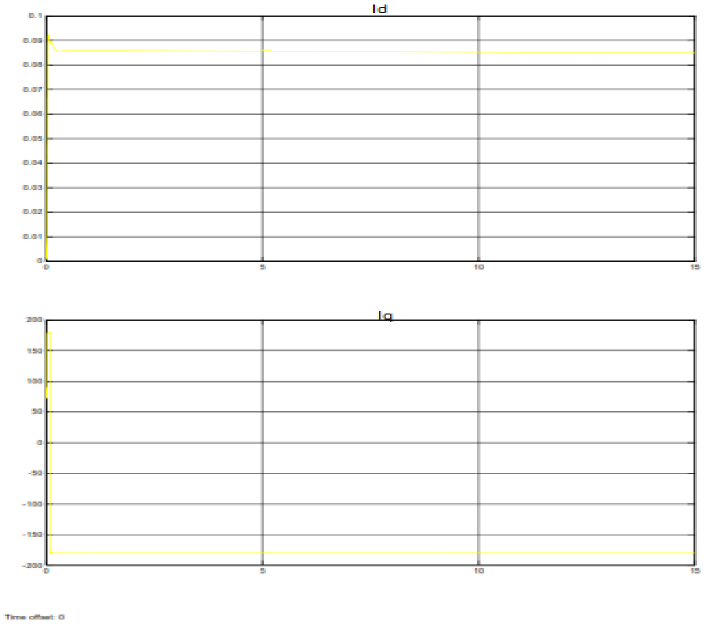


Fig. 20 Direct and Quadrature UPFC Current for LG fault with Inductive Load

The direct and quadrature currents response of the UPFC during fault are shown in Fig. 19 & Fig 20. At normal operating conditions both currents are set to zero level and there will be no power transfer between the UPFC and the system. Upon fault occurrence, Id and Iq levels change accordingly to provide reactive power support to the system during the fault. After fault clearance, both currents return to zero level.

IV. CONCLUSIONS

This paper investigates the application of UPFC to enhance the FRT of wind energy conversion system to comply with the grid codes of Indian Electricity and US. Results show that, without UPFC, WTGs must be disconnected from the grid during voltage swell or voltage sag event to avoid the turbines from being damaged, as the voltage at the PCC will violate the safety margins required for both studied grid codes. The presence of UPFC can significantly improve the FRT capability of the WTGs and hence their connection to the grid can be maintained to support the grid during fault conditions and to guarantee the continuity of its power delivery to the grid.

This paper applies and discusses the above control strategy for suppressing undesirable electromechanical oscillations in power system with an UNIFIED POWER FLOW CONTROLLER (UPFC). The paper investigates the enhancement in voltage stability margin as well as the improvement in the power transfer capability in a power system with the incorporation of UPFC.

A simple transmission line system is modeled in MATLAB/SIMULINK environment. The load flow results are first obtained for an uncompensated system, and the voltage and real and reactive power profiles are studied. All the simulations for the above work have been carried out using MATLAB (SIMULINK) software.

In circuit diagram of fact solution the connection of the UPFC to the wind\ farm to provide voltage support. The UPFC control providing voltage control and a 'ride through' solution is demonstrated in this study by a Simple model of a fixed speed wind farm with UPFC in MATLAB. The wind farm consists of 6x1.5MW fixed-speed, stall regulated wind turbines. The 'equivalent' turbine is assumed to respond in a coherent manner to the system disturbance. The short-circuit ratio at bus B575 is 10. For the simulation results it was assumed that the 120 kV network was subjected to a three-phase

fault along one of the parallel circuits, of 150 ms duration at 2 seconds. The faulty circuit is disconnected after the fault clearance. The main simulation results produced by using MATLAB.
The voltage at the high-voltage point of connection of the wind farm (B575) does not recover the pre-fault voltage value after the clearance of the fault. That is, the wind farm does not have the capability to ride through the fault. However, when the UPFC is set in operation the wind farm is able to ride through the fault as shown by the responses.
The voltage recovery of the wind farm due to the voltage support and reactive power compensation provided by the UPFC. The reactive power exchange between the wind farm and the UPFC is presented in Fig. 5 . It can be observed that the UPFC supplies some reactive power to the wind farm under normal operation. During the fault, the reactive power supplied by the UPFC is decreased an then immediately after the fault, the UPFC supplies an amount of reactive power to the wind farm and compensates its requirements for reactive power in order to recover and ride through this fault scenario.
When consumption of electrical energy is high, the demand on inductive reactive power increases usually at the same proportion. In this moment, the transmission lines (that are well loaded) introduce an extra inductive reactive power.

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