WIND ENERGY INTEGRATION IN ELECTRICAL POWER GRID: SIMULATION OF TRANSIENT FAULT BEHAVIOUR AND ANALYSIS

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Abstract: *In this paper, the effect of wind power on the transient fault behaviour of the power system is investigated. The current and future wind power situation is modelled as two cases and short circuit faults in the system are simulated. The simulations yield information on (i) how the faults impact on the wind turbines and (ii) how the response of the wind turbines influences the post-fault behaviour of the power system. Here, we attempted to compare the impact, in terms of voltages, active and reactive power, of adding wind turbines into electrical power grid.*

1 Introduction

In the recent years, due to the increasing prices and depletion of conventional energy sources, wind energy has become an important part of electrical generation in many countries and its importance is continuing to increase.

A further substantial growth in wind power generation is expected in the next two decades [1]. The size of the individual wind mills is also rapidly increasing and has already reached some MW. The enormous potential of the wind resource is also due to the possibility of building offshore wind farms. Large amounts of wind power generation (up to some hundreds of MW) are located offshore, because of offshore winds up to 20% stronger than on land, with the electrical energy brought to shore through large heavy duty underwater cables.

Since the beginning of the 20th century, numerous types of wind turbine have been tested in order to identify the most effective designs to capture the energy in the wind. Several solutions are now available, with wind turbines of different size. However, size is not the only aspect. Particularly important is also the choice of the generator. Most commercial wind turbines are operated with a horizontal hub, with four distinct technology types [2], namely, constant-speed with SEIG (Self-Excited Induction Generator), limited variable-speed with WRIG (Wound Rotor Induction Generator), variable-speed with DFIG (Doubly-Fed Induction Generator), and direct-drive with PMSG (Permanent Magnet Synchronous Generator).

There are some critical aspects related to the wind generation. One major problem is due to the uncertain nature of the wind resource. The dependence of the power produced on the wind speed makes it difficult to assess the amount of electricity a wind turbine can produce in a given time period. Furthermore, the wind energy production in European countries has already increased so rapidly to have approached or reached in some cases the limits for its possible integration into the existing transmission system. These limits are mainly due to the operation of large wind farms subject to wind speed variations that may cause stability problems in the power system.

The critical aspects concerning the electricity production from wind sources have pushed forward an intense regulatory activity, aimed at setting up suitable limits and indications for addressing the specific features of the wind systems. Such an activity has led to the formulation of *grid codes*, containing interconnection standards and guidelines, with different solutions depending on the voltage level of the interconnection [3], [4], [5]. In response to the technical problems and to grid code requirements, various models and control strategies for the wind farms have been developed, aimed at optimising the operation of the wind farms in terms of their participation in power system control of power (frequency) and reactive power (voltage), maximising the energy production, improving the power quality characteristics and limiting mechanical loads. One of the major challenges is to obtain a sufficient ride-through capability to withstand the effects of external faults [6], [7], [8].

This paper considers the mutual effects of wind power in power systems under transient fault situations. It is analyzed (i) what impact the wind turbines have on the dynamic behaviour of the system experiencing a fault and (ii) how the wind turbines behave in the system when it experiences a transient fault. If transient faults in the system lead to considerable excursions in voltage and/or frequency the wind turbines were to disconnect and to reconnect only once the system has returned to stable operation. Increasing wind power penetration leads to the problem that considerable amount of generation might disconnect in case of a transient fault in the system, causing the system to become unstable from an otherwise harmless fault situation. To prevent such situations newly installed wind turbines have to comply with new grid connection requirements that demand wind turbines to ride through transient faults. This paper presents the dynamic behaviour of the power system during transient faults, when wind energy is connected to the existing power system.

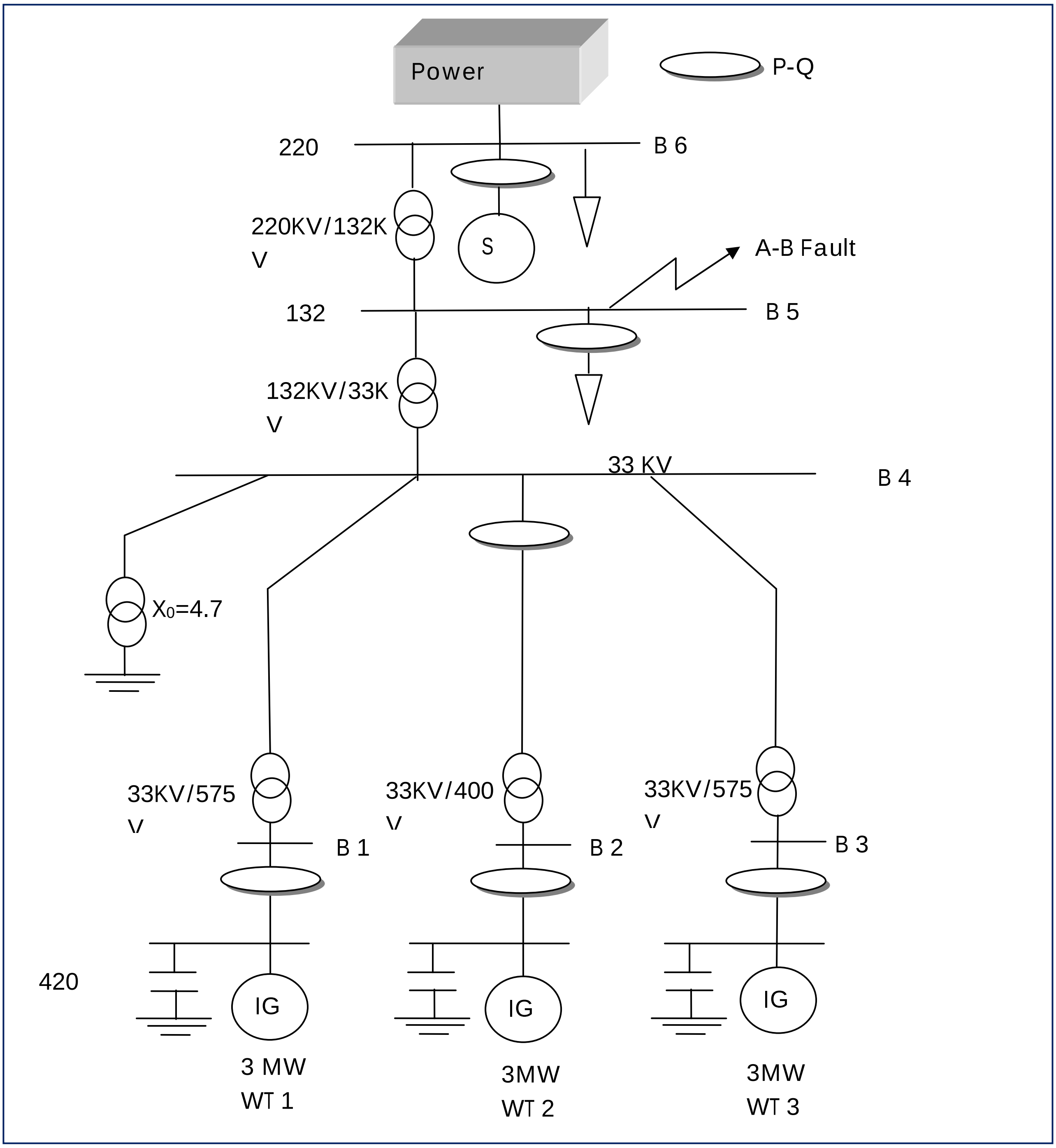


Fig.1: Grid Diagram of Power System Model Introducing the Wind Power.

2. Power System Model

A 9 MW wind farm is connected to a 33-kV distribution system exports power to a 220-kV grid. The 9-MW wind farm is simulated by three pairs of 3 MW wind-turbines. Wind turbines use squirrel-cage induction generators (IG). The stator winding is connected directly to the 50 Hz grid and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed. Fig. 1 shows the layout of the wind system with its interconnection to the transmission grid. The wind farm is composed of SEIGs with squirrel cage rotor and is modelled with its single-machine equivalent representation [9-10].

Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 KVAR for each pair of 1.5 MW turbine). Bus B1, B2 and B3 are connected to wind turbines WT1, WT2 and WT3 respectively having voltages 575V, 400V and 575 V respectively. One transformer that steps up the voltage to 33KV is connected between buses B1 and B4. Similarly transformers are connected to B2 and B3. The 132KV feeder connecting the wind turbine WT1 is assumed to be 26Km long. The connection from bus B4 to wind turbine WT2 is modelled with a 28Km long and 132KV feeder connecting the wind turbine WT3 with B4 is 30 Km.

2.1 Wind Turbine Modelling

Before discussing the application of wind turbines for the generation of electrical power, the particular aerodynamic characteristics of windmills need to be analyzed. Here the most common type of wind turbine, that is, the 'propeller' (horizontal axis) type, is considered. The modelling of wind turbine is complicated. According to the blade element theory, modelling of blade and shaft needs complicated and lengthy computations. Moreover it also needs detailed and accurate information about the rotor geometry. For that reason, considering only electrical behaviour of the system, a simplified method of modelling of wind turbine blade and shaft is normally used. The mechanical power available from a wind turbine

$$P_W = 0.5\,\rho\pi\,R^2\,V_W^3\,C_p(\lambda,\beta) \qquad (1)$$

where, P_w is the extracted power from the wind, ρ is the air density, R is the blade radius, V_ω is the wind speed. C_p is called the 'power coefficient', and is given as a nonlinear function of the parameters tip speed ratio λ and blade pitch angle β. The calculation of the performance coefficient requires the use of blade element theory [11-12]. As this requires knowledge of aerodynamics and the computations are rather complicated, numerical approximations have been developed [11]. Here the following function will be used

$$C_p = \frac{1}{2} * (\lambda - 0.022 * \beta^2 - 5.6) * e^{-0.17\lambda} \qquad (2)$$

Where,

$$\lambda = \frac{V_W}{\omega_B} \qquad (3)$$

Where, ω_B is the rotational speed of turbine. Usually Cp is approximated as,

$$C_p = \alpha\lambda + \beta\lambda^2 + \gamma\lambda^3 \qquad (4)$$

Where, α, β and γ are constructive parameters for a given turbine. Fig.3 shows typical C_p versus λ. It can be seen that C_{pmax} , the maximum value for C_p , is a constant for a given turbine. The torque developed by the windmill is

$$T_t = 0.5\,\rho\left(\frac{C_p}{\lambda}\right)V_W^{\,3}\pi R^2 \qquad (5)$$

To describe the impact of the dynamic behaviour of the wind turbine, a simple model is considered [13], where the tower bending mode and the flap-bending mode of the wind turbine are neglected. It is assumed that all the torsion movements are concentrated in the low-speed shaft, as T_{lss}. Emphasis is placed on the parts of the dynamic structure of the wind turbine, which contribute to the interaction with the grid, i.e., which influence the power. Therefore, only the drive train is considered in the first place because the other parts of the wind turbine structure have less influence on power.

The drive train model is illustrated in Fig.2. The input to the model is the aerodynamic torque. This is converted into the torque on the low-speed shaft T_{lss}, which is further scaled down through the gearbox to the torque on the high-speed shaft T_{hss}. The generator inertia is implemented as part of the generator model, not as a part of the transmission system. The output of the model is the torque on the high-speed shaft T_{hss}. The rotor is modelled by inertia I_{rot}, low-speed shaft only by a stiffness k_s (the torsion damping is neglected), while the high-speed shaft is assumed to be stiff. Thus, the transmission is described by the following equations:

$$J_{rot}\frac{d\omega_{rot}}{dt} = T_{rot} - T_{lss} \quad (6)$$

$$\frac{dT_{lss}}{dt} = k_s\left(\omega_{rot} - \frac{\omega_{gen}}{\eta_{gear}}\right) \quad (7)$$

It is also assumed that the losses in the gearbox are zero, thus, the gear transmits ideally from the low speed to high speed. The output of the model is

$$T_{hss} = \frac{T_{lss}}{\eta_{gear}} \quad (8)$$

where η_{gear} is the ratio of the gear box. Fig. 3 shows topology of wind turbine model.

As shown in Fig. 3, the wind model together with the blade pitch angle and rotor speed ω_{rot}, are inputs to the aerodynamic block [14]. The output of the aerodynamic model is the aerodynamic torque Trot, which is the input for the transmission system together with the generator speed ω_{gen}. The transmission system has as output the mechanical torque on the high-speed shaft T_{hss}, which is used as an input to the generator model. Finally, the blade angle control block models the active control loop, based on the measured power and the set point.

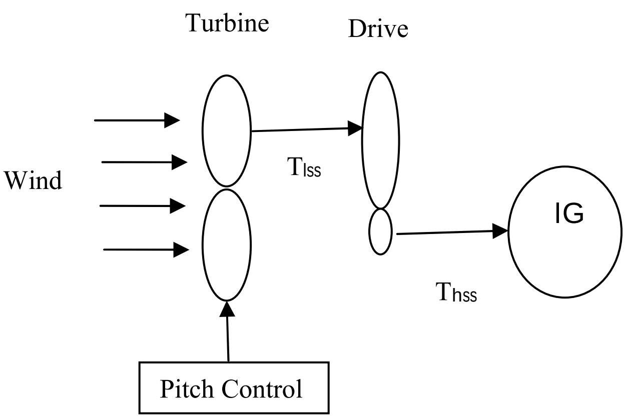


Fig.2: Drive Train Model of Wind Turbine

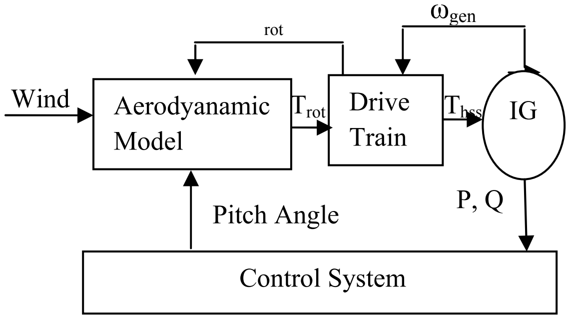


Fig.3: Wind Turbine Model

A Proportional-Integral (PI) controller [15] is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value the PI controller increases the pitch angle to bring back the measured power to its nominal value. The control system is illustrated in the Fig.4.

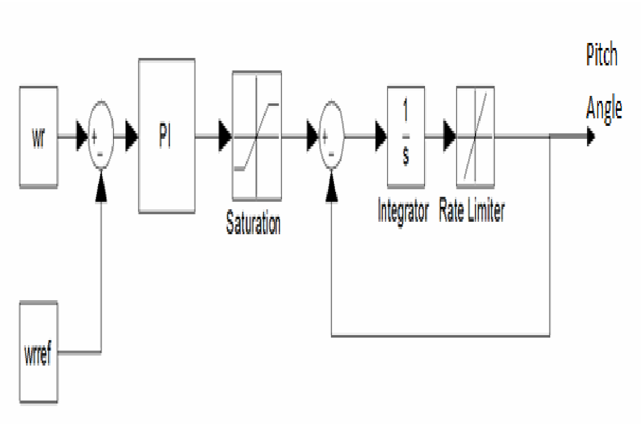


Fig.4: Pitch Angle Controller

The protection system that disconnects the turbines in case of a fault is implemented in the form of undervoltage, overspeed and overcurrent protection. The protection scheme implemented in this model disconnects the generator and its compensation unit, when

- the voltage at the generator terminals drops below 0.75 pu for 100 ms;
- the speed of the generator exceeds 105% of its rated speed (when the generator cannot export as much power as is imported through the wind, it accelerates);
- the voltage exceeds 1.1 pu for 100 ms.
- the instantaneous AC overcurrent exceeds 10 pu.
- the maximum AC current exceeds 1.1 pu.
- the maximum AC current unbalance exceeds 0.4 times maximum AC current.
- the maximum AC voltage unbalance exceeds 0.05 times maximum voltage.

The Power Coefficient Cp v/s λ Curves for Various Values of Pitch Angles are shown in Fig.5. Fig.6 shows turbine output power v/s turbine speed for pitch angle 0 deg.

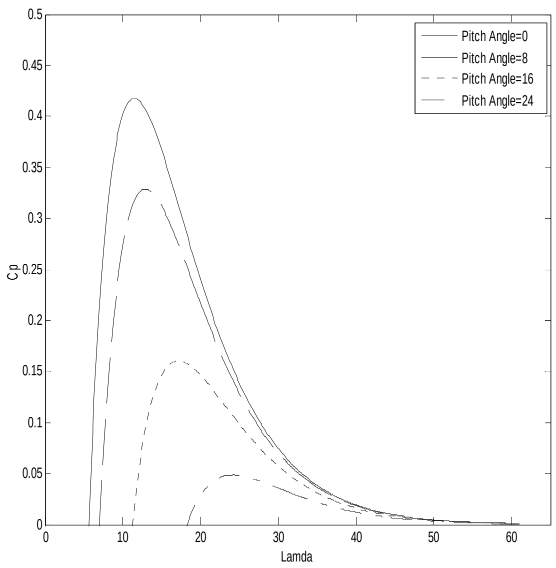


Fig.5: Power Coefficient Cp v/s λ Curves for Various Values of Pitch Angles

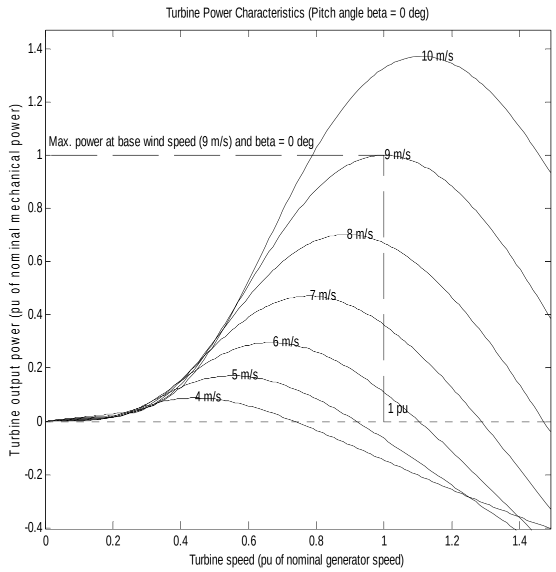


Fig.6: Wind Turbine Power Characteristics

3. Simulations, Results and Discussions

Different scenarios are simulated to assess the impact of wind power on integration with power grid. The faults simulated are 104 ms, zero impedance; phase to phase short circuits on 132KV line (see Fig.1). The fault gets cleared by permanent disconnection of the faulted line. This is a fault situation described in Elkraft's grid connection requirements for wind farms connected to the transmission system.

3.1 Case- I

The situation which is simulated here is that the wind turbines are not connected to the transmission system. A phase to phase fault is simulated on 132KV line i.e. bus B5 at t=5 sec. for 104 ms. Fig.7 shows that the voltage at busbar B5 drops to zero, as it is closest to the fault location. Bus B6 is hardly affected by this fault as it is far away from the fault. The voltage at B5 gets suppressed in the beginning of the fault and after a few ms it recovers quickly after the clearance of the fault which means that they do not consume reactive power any more. The voltage at B4 recovers also relatively quickly because of the reduced reactive power demand in the first seconds.

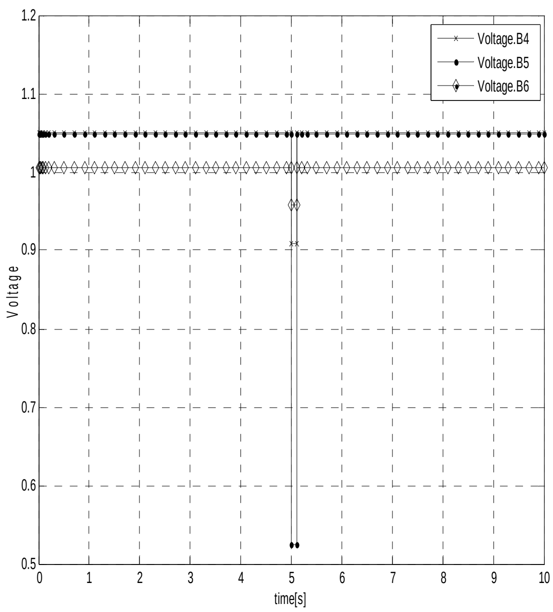


Fig.7: Voltage at Different Locations in the Power System (Case-I)

3.2 Case -II

Here the situation is simulated that 9 MW wind farm has been connected to power system. The fault conditions are kept same as before. There is substantial drop in voltage at wind turbines due to fault and wind turbine WT1 trips due to operation of protection system of turbines, which disconnects wind turbine WT1 due to AC under voltage at t=5.112 sec. After the clearance of fault, the voltage recovers to normal position in the system. Fig.8 shows voltage at different locations during present case. The fault excites the inherently flexible drive train of the wind turbines to oscillations, which in the first instances after the clearance of the fault leads to a strongly reduced active power production [16]. At the same time the compensation capacitors stay connected helping the voltage to recover. Fig.9 shows active and reactive power of wind turbines.

Wind turbine 1 is tripped due to fault and power is delivered by wind turbines 2 & 3.

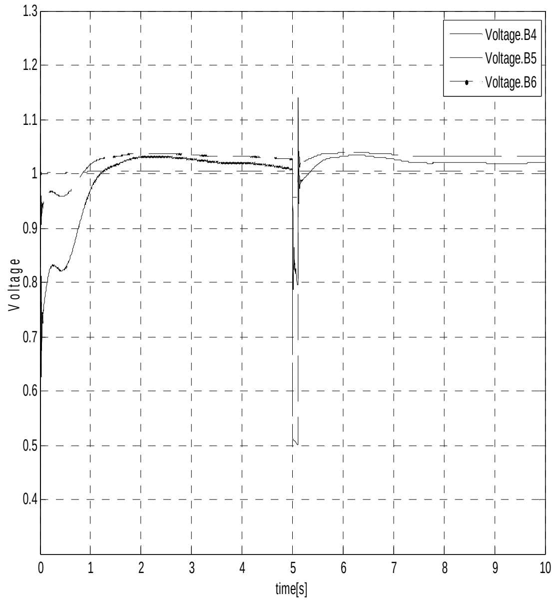
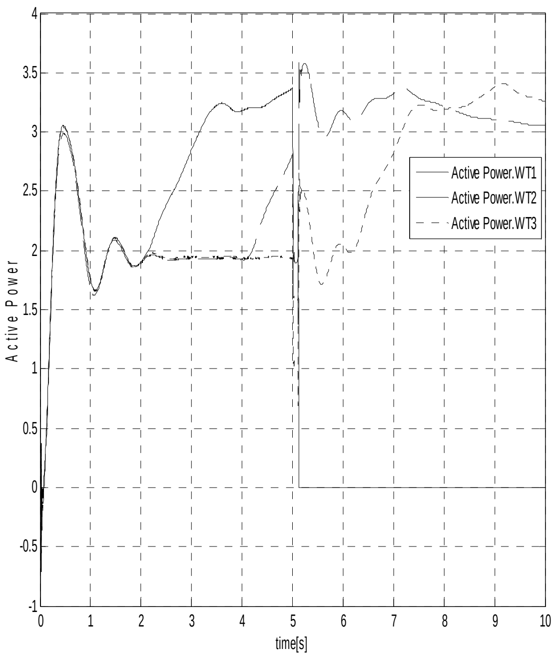


Fig. 8: Voltage at Different Locations in Power System(Case -II)



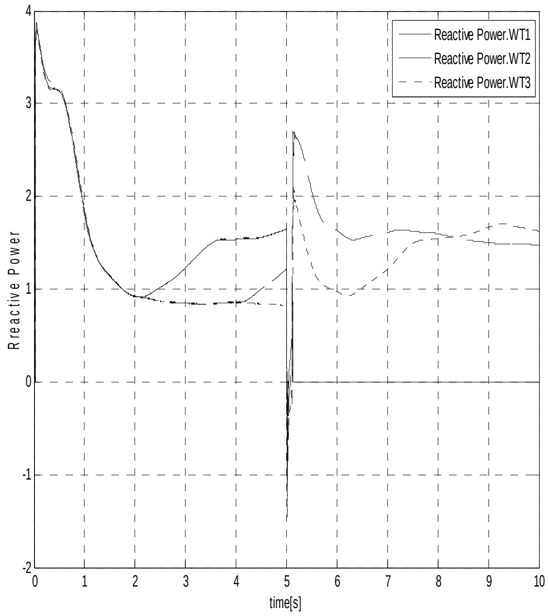


Fig. 9: Active and Reactive Powers at Wind turbines 1, 2 & 3 (Case –II)

3.3 Comparison of Cases I and II

As noted above, the voltage variations [17] caused by the faults, simulated in the different cases, has a negligible impact on the power system. The frequency and hence the active power flow [18] through the system gets affected though. An effective means of comparing the consequence of the different scenarios on the power system is comparing the active and reactive powers in the system.

Fig.10 shows the comparison of active power at buses B4, B5 and B6 for Cases-I and II. It is observed that variation in active power at buses B4, B5 and B6 for Case-I which do not include wind turbines, is very less as compared to Case-II. The variation is about -0.05 to +0.05 for buses B4 and B5 and -0.3 to 0.1 for bus B6 during phase to phase fault for Case-I and hence cannot be predicted clearly while comparing with Case-II. The active power at buses in Case-II has a dip during fault, but oscillations die out quickly in approx. 2 secs. Fig.11 shows the comparison of reactive power at buses B4, B5 and B6 for various cases. The reactive power at bus B6 is most affected during A-B fault at t=5sec, but oscillations die out quickly after the clearance of fault.

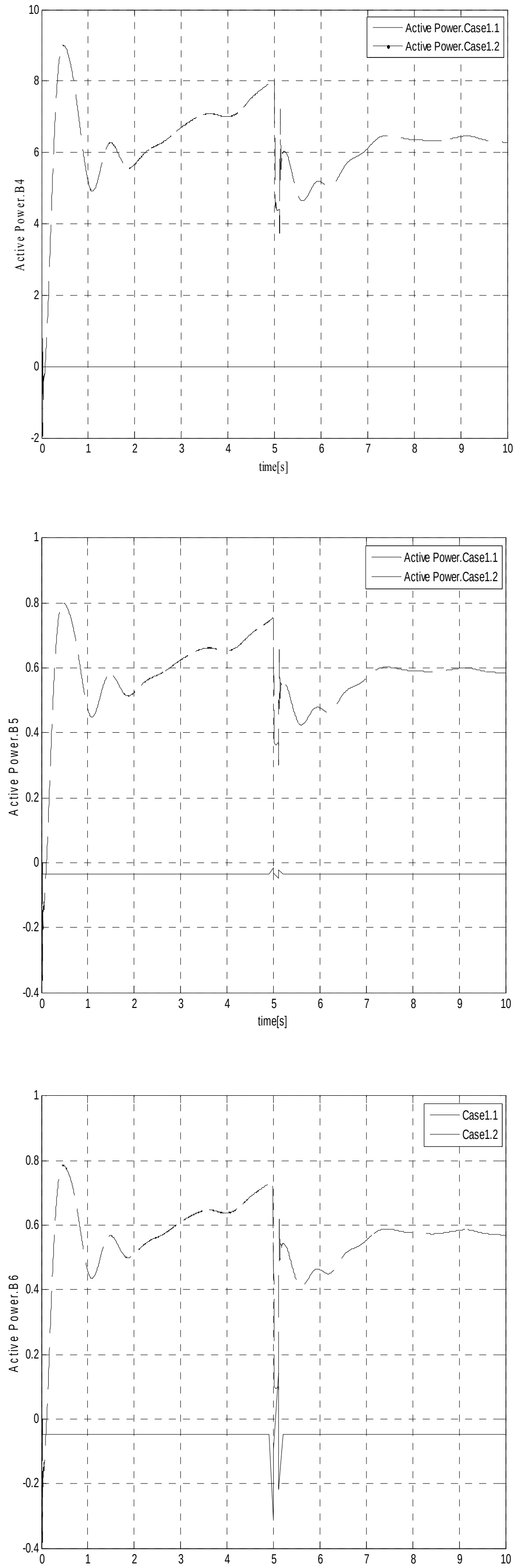


Fig.10: Active Power at Buses B4, B5 and B6 during different Cases

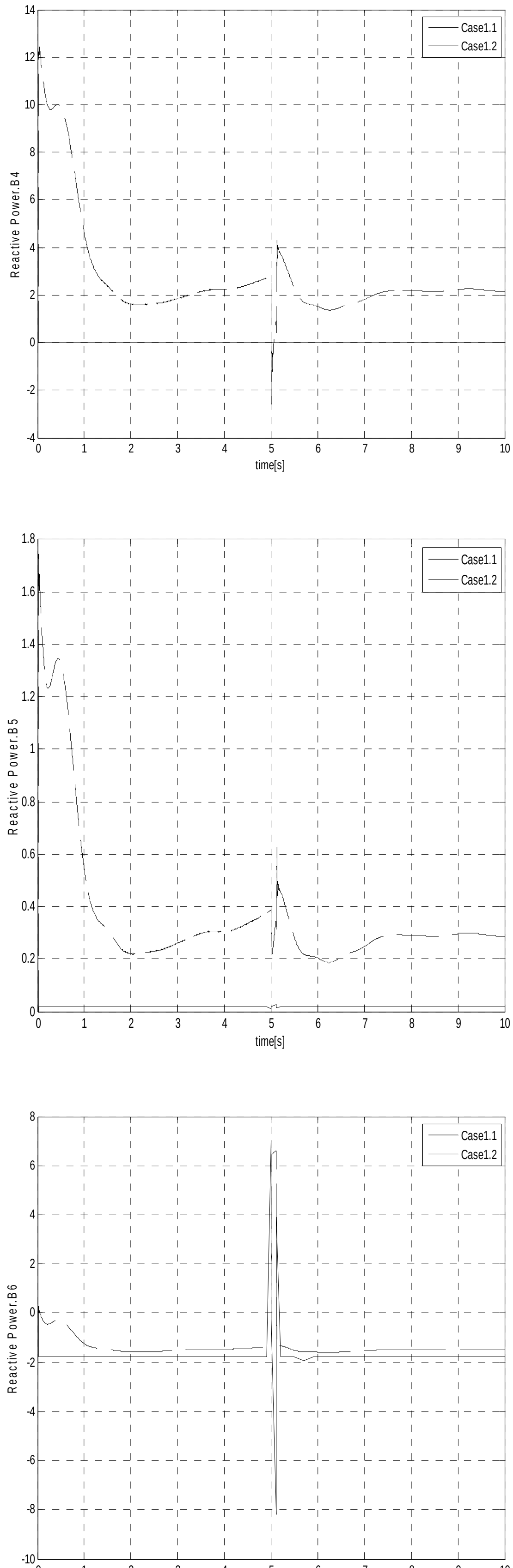


Fig.11: Reactive Power at Buses B4, B5 and B6 during Different Cases

4. Conclusions

This paper has presented the analyzed results on transients of a small wind power generation system connected to a low voltage power grid. Two different cases are considered examining the influence of adding 9 MW wind farm to the power system. A transient phase to phase fault was simulated and its impact on the system voltage, active and reactive power at different locations in power system was investigated. The local voltage depression can hardly be noticed in other parts of the transmission system. It does however upset the wind turbines in the vicinity and cause their flexible drive trains to exhibit torsional oscillations. These oscillations manifest themselves in power fluctuation. Such power fluctuations are not only local effects but propagate through the system. It has been proven that with the inclusion of wind turbines equipped with sufficient control mechanisms, the performance of power system impoves.

5. References

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