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Impact of Voltage Sag and Swell on the Power Quality of Grid Connected Wind Power Plant

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ABSTRACT

Injection of wind power into an electric grid usually affects the power quality of the system, - a parameter that is required to be within a specified voltage and frequency tolerances, and to have a pure noise-free sinusoidal wave shape so as to comply with the utility requirements. Voltage variation is the most common type of disturbance that affects the power quality and stability of grid connected wind power plants especially in weak grid or when the wind power penetration becomes relatively high. In order to ensure safety and reliability to consumers and their equipment, grid operators and wind farm vendors require a balanced three-phase a.c voltage with smooth sinusoidal shape and constant magnitude. However, the intermittency of wind, can tamper with the technical performance and reliability of the power system, hence, deteriorating the power quality. This paper investigates the two common types of voltage variations (sag and swell) that can occur when large amount of wind power is injected into the grid. A wind power plant (WPP) with doubly fed induction generator (DFIG) is simulated using Simpower Simulink in MATLAB environment. The simulated system is subjected to two types of voltage variations, namely; voltage sag and voltage swell. The simulation results show how both disturbances (sag and swell) lead to fail function, system halt as well as complete system shut down, thereby deteriorating the power quality of the net system.

Keywords*—Power quality; voltage sag; voltage swell; WT; WPP.*

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I. INTRODUCTION

Traditionally, the electrical grid has been designed to integrate different types of conventional electric power plants (hydro, thermal, diesel, gas, nuclear e.t.c) in order to meet the ever increasing demand of energy which is the basic necessity for the economic development of any country. Thus, with the increased human population and industrial development, there is more and more demand of electric power. To meet this large and ever increasing power demand, it becomes necessary to tap all the possible sources including the non-conventional ones such as wind and utilize them optimally [1]. When power from non conventional sources such as wind is injected into the grid, maintaining the power quality of the net system requires careful consideration. Power quality is of great concern to the grid operators especially when large wind power is injected into the grid. The wind power plant is therefore expected to contribute in providing the power quality required to maintain the system stability and reliability in order to satisfy the customers connected to the grid. Power quality here refers to maintaining smooth sinusoidal voltage and current waveforms at rated frequency.

Wind power generation is gaining popularity all over the world. This is partly due to its environmental friendliness – which makes it free from environmental pollution unlike fossil fuels, and partly due to the fact that it is renewable – a quality which makes it occur freely, naturally and repeatedly. Wind energy is clean and plentiful source of electrical energy; hence, it will play a predominant role in adding clean and non-polluting energy to the grid. In fact, wind power can now effectively compete with other conventional sources of energy in the electricity market [2]. Thus, as argued by D. Mary et al [3], wind energy is beginning to compete with other conventional sources of energy and will in the nearby future becomes the undisputed number one choice form of renewable source of energy. Harnessing clean energy source like wind to produce electricity decreases the dependency on fossil fuels. This enables electrical power generation with minimum pollution.

Wind power generation has been in use since nineteenth century with the development of wind machines for charging batteries [4]. However, the improved understanding by the aviation technology of the forces acting on blades moving through the air results in rapid development in wind power generation yielding to the development of two and three bladed wind turbines in the early decades of nineteenth century [5]. Wind infrastructure is now one of the most cost effective methods of electrical power generation.

Unfortunately, wind power is stochastic in nature and intermittent resulting in fluctuating power being injected into the grid – this can lead to several operational problems, thereby affecting the power quality of the net-system. Similarly, effects such as wind turbulence, wind shear, tower shadow and the operation of the control system (like capacitor switching for power factor correction and transformer tap changing) can also lead to pulsations in the output power. Results from recent research [6] reveal that the higher the wind power penetration, the larger will be its impact on the power quality and system stability. Therefore, voltage at the point of common coupling (PCC) must be kept within a certain limit in order to maintain the power quality required by consumers.

II. CLASSIFICATION OF WIND POWER PLANTS (WPP)

A. Constant Speed WPP

In the constant speed WPP, the generator is locked electrically to the grid to which its stator is connected. The generator will always run at constant speed regardless of how fast the wind blows. The constant speed of the rotor is fixed by the grid frequency and the number of pole-pairs of the generator and also on the gear ratio. In this setup, the rotor does not turn faster than the synchronous speed. Constant speed wind turbines (CSWT) are generally stall regulated and use induction generators for power generation. The three-phase rotor windings of the generator are directly connected to the grid, while the stator windings provide the excitation to the generator. The synchronous speed of rotation, n_s can be expressed in terms of the supply frequency and the number of pole-pairs for which the stator winding is connected [7].

$$n_s = \frac{120f}{p} \qquad (1)$$

Where f = frequency of the supply, and $p =$ number of pole-pairs

Another parameter used in the analysis of induction generator is the per-unit slip which is defined as the difference between the synchronous speed and rotor speed expressed as a percentage of the synchronous speed [8]. The per-unit slip, s is given as:

$$s = \frac{n_s - n_r}{n_s}\ x\ 100 \qquad (2)$$

Where $n_s =$ synchronous speed, and $n_r =$ rotor speed

The slip is positive for motoring mode and negative for generating mode [9]. Thus, a wind power plant with induction generator can only supply power to the grid when the speed of the generator, n_r exceeds that of the rotating magnetic field (synchronous speed), n_s.

B. Variable Speed WPP

In variable speed WPP, the generator is allowed to be driven at varying speed, in line with the wind. In this design, a power electronic converter (PEC), is employed to convert the a.c output of the generator to d.c and finally to grid friendly a.c. Variable speed wind turbines (VSWT) can be stall, pitch or active-stall regulated. In stall regulated WPP, the blades of the wind turbine (WT) are firmly fixed to the hub at a particular angle while in pitch regulated type, the blade's angle of attack is modified in order to limit the torque. This can be achieved by varying the orientation, or pitch, of the blade, thus, altering its aerodynamic efficiency. However, in active-stall WPP, the rotation of the turbine's rotor is achieved by pitching the blades back into a deeper stall. Emergency stopping and start-up can be achieved by flexible coupling of the blades to the hub.

When the wind speed is below cut-in value, the generator operates at sub-synchronous speed, in which case, the PEC may have to borrow 30% power from the grid leaving the line with 100% power. The 30% power will be passed to the stator to enable it supply 130% power to the grid. Thus, in sub-synchronous mode, power flow from the grid to the rotor via the bi-directional PEC. When the wind speed reaches the turbine's cut-in wind speed, the generator will operate in the super synchronous mode, so that electrical power is generated and delivered to the grid directly by the stator. The turbine reaches its rated power when the wind speed reaches the rated value; then the flow of power is from the rotor to the grid via the bi-directional PEC. When the wind speed exceeds the rated value and reaches cut-out value, the excess power is spilled away by pitching the turbine's rotor blades out of the wind.

The PEC usually consists of two converters; the rotor side converter, and the grid side converter which are controlled independently of each other. The rotor side converter controls the active and reactive power by controlling the current component, while the grid side converter controls the DC-link voltage and ensures that the generator operates at unity power factor and supply the reactive power when needed.

The DC-link capacitor is serving as energy buffer to minimize the voltage variations in the DC-link voltage.

III. VOLTAGE VARIATIONS IN GRID-CONNECTED WIND POWER PLANTS

Voltage variations are defined as the changes in the root mean square (rms) value of the supply voltage during a short period of time ranging from micro seconds to a few minutes [10]. In grid-connected WPP, voltage variations can be in the following forms of sagging (voltage sag / voltage dip), swelling (voltage swell / voltage rise), transient, flicker or harmonic distortion.

Considering Fig. 1 which represents a WPP connected to the utility grid through impedance, Z.

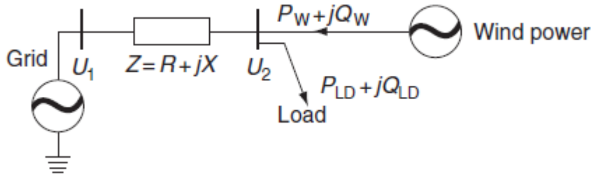

Fig. 1: Single line diagram of a Grid Connected WPP

Where U_1 = Grid side voltage; U_2 = Voltage at the WPP connection point; P_w= Active power injected into the grid by the WT; Q_w= Reactive power injected into the grid by the WT; and Z= Impedance of the transmission line, cable and transformer in the feeding grid.

Application of Kirchhoff's Voltage Law to Fig. 1 gives:

$$U_1 = U_2 + \sqrt{3}I(R + jX) \qquad (3)$$

When the WT generates the power required to meet the load demand, no current will be drawn from the grid. Under that condition, U_1 will be equal to U_2. Hence, equation 3 becomes: $U_1 = U_2$

However, when the WT produces more power than demanded, then, $U_1 < U_2$ (i.e U_1 will be less than U_2)

Similarly, when the WT generates lower power than that demanded, then, the difference between the load and the turbine's generated power will be supplied to the grid and the current drawn from the grid will pass through the impedance, Z so that $U_1 > U_2$ (grid side voltage will be greater than that at the PCC.

The short circuit power, S_k, in the wind connection point (bus 2) can be expressed as;

$$S_k = \frac{U_1^2}{Z} \qquad (4)$$

Equation (4) implies that the short circuit power which represents the fault level at the wind connection point is inversely proportional to the impedance, Z between the source and the load. Thus, a low value of Z will results in high fault level making the grid strong. However, a large value of Z will results in low fault level, so will the short circuit ratio too, and the grid will then be considered as weak. It is therefore clear that in weak grid, there is a high tendency of voltage variations because any sudden change in the output power of the WT will creates a current flow through the impedance.

The voltage variation at the point of interconnection (POI) of the WT, ΔU can be expressed in terms of active and reactive power, grid impedance and the nominal phase to neutral voltage of the grid [11].

$$\Delta U = \frac{(RP - XQ)}{U_n} \qquad (5)$$

Where $U_n =$ nominal phase to neutral voltage of the grid, $P =$ magnitude of in-fed active power, $Q =$ magnitude of in-fed reactive power, $R =$ resistance of the grid, $X =$ reactance of the grid

Among all forms of voltage variations, voltage sag and voltage swell are more common and are the main focus of this paper.

A. Voltage Sag / Voltage Dip

Voltage sag refers to the sudden reduction in the potential of electric grid usually between 10% and 90% of its nominal value followed by a rapid return to its normal value [12]. Voltage sag usually lasts for duration of 10ms to 60s [13]. It usually occur when large wind turbines are started up together – in which case, the current drawn from the electric grid will rise to a high value for a duration of milliseconds. Voltage dip can also occur as a result of the start up of large motors or when there is grid short circuit. The occurrence of voltage dip can be identified when lights begin to go on and off momentarily.

The decrease of nominal voltage change (voltage dip), ΔU_d at the POI of the WT can be expressed in terms of the voltage change factor, K_u the rated power of the WT, S_n and the short circuit apparent power of the grid, S_k [14].

$$\Delta U_d = 100K_u(\varphi_k)\frac{S_n}{S_k} \qquad (6)$$

The acceptable voltage dip limiting value is ≤ 3% [15].

Voltage dip can leads to the disconnection of sensitive loads and fail function of equipment. To overcome the impact of voltage dip, WT's starting has to be properly arranged. Alternatively, the current and acceleration of the WTs can be reduced by aerodynamic blade pitching.

B. Voltage Swell

Voltage swell refers to the rapid increase in the nominal value of the a.c voltage for a duration of less than one minute. The threshold limit for voltage swells is 1.1 to 1.8 p.u and the minimum duration is 10ms [16]. Voltage swell usually lasts between 30 to 60 seconds [17]. In grid connected WPP, voltage swell can occur due to the inrush currents of the WPPs or during shut down of large capacity WTs. Other origins of voltage swell include grid lightning strikes, earth fault on another phase and incorrect settings of substations.

Voltage swell, ΔU_s at the wind POI is defined as a function of the turbine's maximum apparent power, resistance and reactance of the grid and the nominal phase to neutral voltage of the grid [18].

$$\Delta U_s = \frac{S_{max}\ (R cos\varphi - X sin\varphi\ )}{{U_n}^2} \qquad (7)$$

Where S_{max} = Maximum apparent power of the WT
The limiting voltage rise value is < 2% [19].

Voltage swell can leads to the disconnection of equipment, aging of insulation, and harm to equipment with inadequate design margins. One way to prevent the occurrence of voltage swell is by the use of a soft starter – which will provide smooth grid connection so that the high inrush current during starts up will be reduced. Other means of overcoming voltage swell include the application of transformer with tap changer and connection of large loads at the point of common coupling.

IV. EXPERIMENTAL SET UP

The system is simulated in simulink environment of MATLAB. The system (as shown in Fig. 2) is a 9MW WPP of DFIG type. It consists of six 1.5MW WTs that are connected to a 25kV distribution system which exports power to a 120kV grid network through a 30km 25kV feeder. At bus B25 of the same feeder, a plant of 2MVA, 2300V, with motor load (1.68MW induction at a lagging power factor of 0.93) and resistive load of 200kW is connected. Another resistive load of 500kW is also connected on the 575V bus of the system. A protection system is incorporated to both the wind turbine and the motor loads that monitors the system parameters, namely; voltage, current and machine speed.

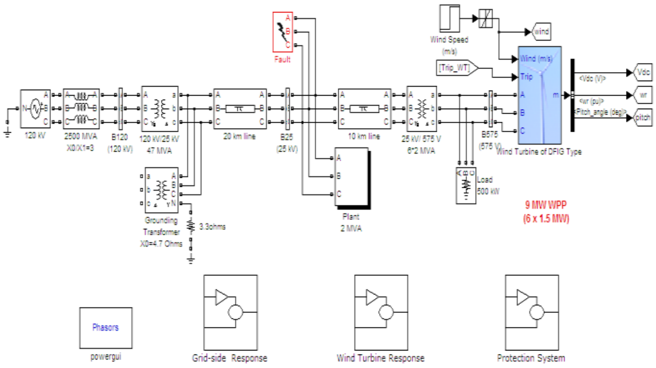

Fig. 2: Simulink Diagram of a 9MW WPP of DFIG Type

V. SIMULATION RESULTS AND DISCUSSION

A. Simulation of Voltage Sag in VAR Regulation Mode

With the control parameters of the WPP set to VAR regulation mode and at constant wind speed of 9m/s, a remote fault is applied to the 120kV grid, such that a 0.17pu voltage drop lasting 0.5 seconds is set in the grid network to occur at the 8th second of the simulation time. The results shown in Fig. 4 were obtained.

In Fig. 3a, voltage sag is recorded for duration of 0.5s in which case, the system voltage falls below 0.9pu for the given duration. Fig. 3b shows the positive sequence component of the plant current in which the protection system trips the plant at t = 8.22s because of the detection of an under voltage that lasts more than 0.2s. The motor speed (Fig. 3c) decreases gradually as soon as the protection system trips the plant. Fig. 5d shows that the WPP keeps on generating active power of 1.9MW. However, at bus B25, 1.37MW active power is exported to the grid after the plant has tripped (Fig. 3e).

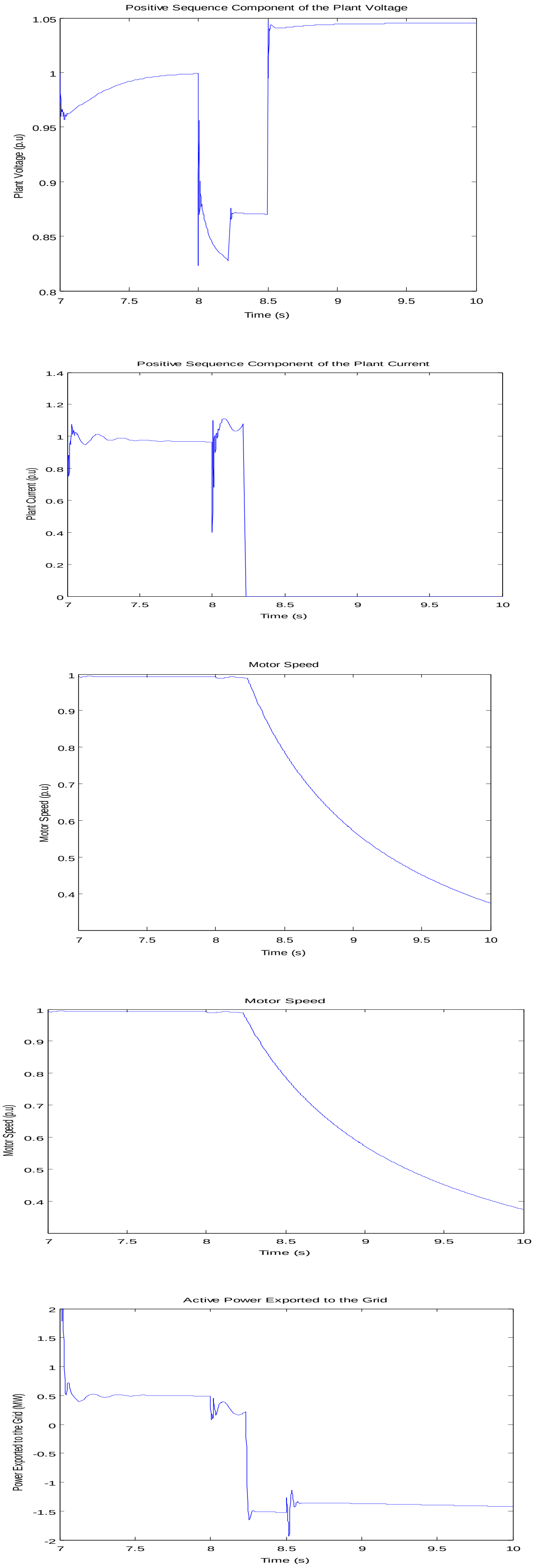

Fig. 3a-e: Voltage Sag in VAR Regulation Mode

B. Simulation of Voltage Sag in Voltage Regulation Mode

However, when the control parameters of the WPP were changed to voltage regulation mode, the results shown in Fig. 5 were obtained.

Fig. 4a shows the applied voltage sag for a duration of 0.5s in which the plant voltage falls below 1pu but above the 0.9pu protection threshold. The plant current (Fig. 4b) didn't trip because of the voltage support provided by the WT's control parameters during the disturbance. The motor (Fig. 4c) is only disturbed during the sagging period.

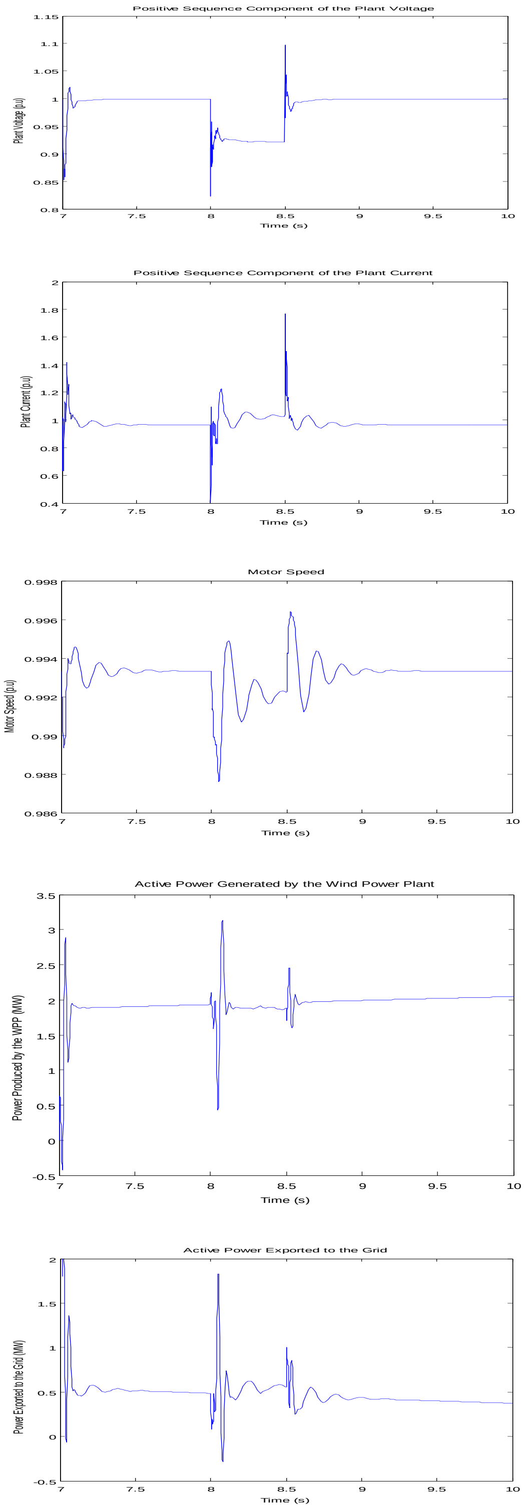

Fig. 4a-e: Voltage Sag in Voltage Regulation Mode

C. Simulation of Voltage Swell in VAR Regulation Mode

In this case, a 0.17pu voltage rise lasting 0.5 seconds is set in the 120kV grid network to occur at the 8th second of the simulation time with the control parameter of the WPP set to VAR regulation mode. The results shown in Fig. 5 were obtained at a constant wind speed of 9m/s.

It can be seen from Fig. 5a through 6e that a voltage rise for a duration of 0.5s exceeding the maximum threshold limit trips the plant 0.2s after it is sensed. At that instant, the motor speed starts reducing gradually.

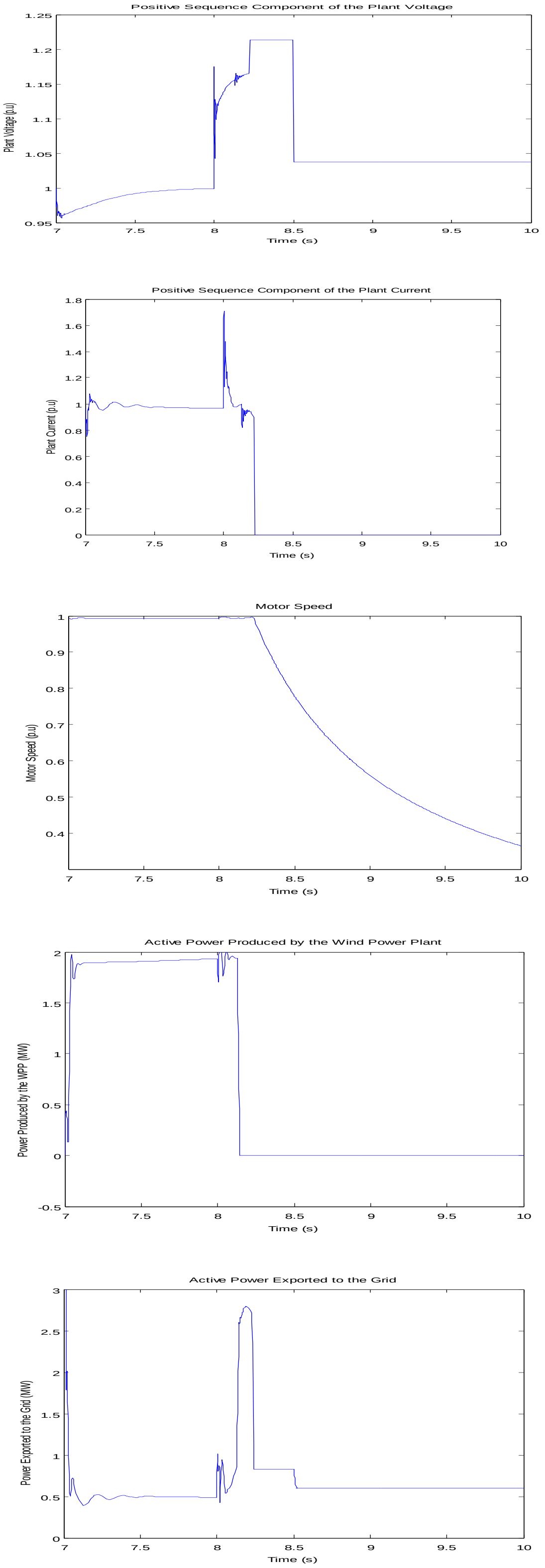

Fig 5-e:Voltage Swell in VAR Regulation Mode

D. Simulation of Voltage Swell in Voltage Regulation Mode

The simulation is repeated with the WT's control parameter changed to voltage regulation mode. It can be seen from the simulation results (Fig. 6a-e) that the plant does not trip because of the voltage support provided by the reactive power generated by the wind turbines during the voltage sag which keeps the voltage above the protection threshold value of 0.9.

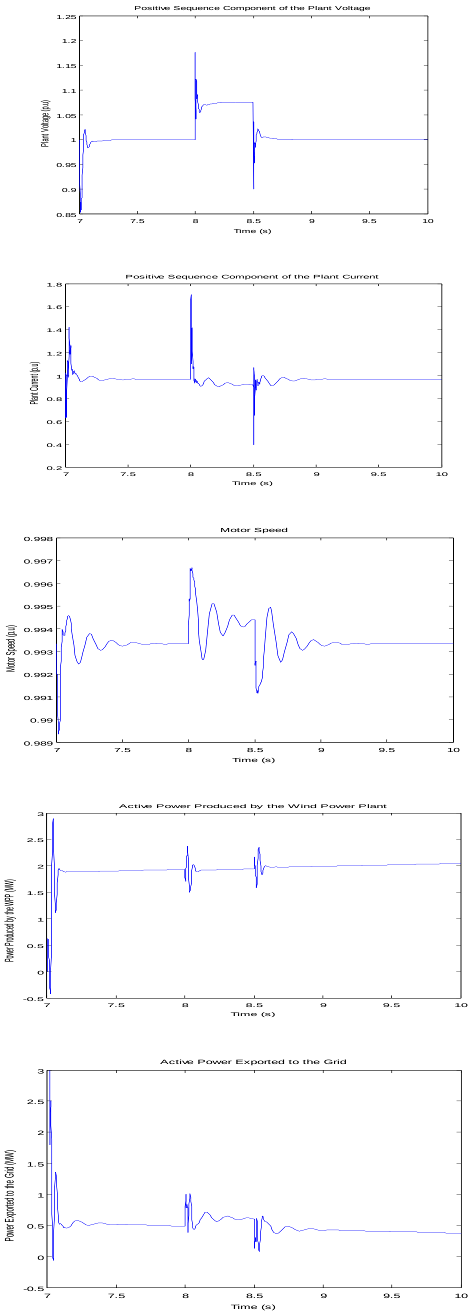

Fig 6-e:Voltage Swell in Voltage Regulation Mode

VI. CONCLUSION

The paper has investigated the impact of voltage sag and voltage swell on the power quality of grid connected WPP. The simulation results shows that the main impacts of voltage sag include disconnection of sensitive loads, fail functions, system halt, loss of data, and complete system shutdown. Voltage swell on the other hand can leads to disconnection of equipment, nuisance tripping and equipment damage / reduced life. Since the behavior of WPP is different from that of other conventional sources, its grid integration therefore requires proper planning in order to strengthen the grid network. A grid connected WPP is expected to comply with certain grid codes; namely; fault ride through (FRT) or low voltage ride through (LVRT) capability, power quality control, frequency control, voltage control, active and reactive power control at the POI with the grid network. A WPP with FRT or LVRT capability can withstand an electrical, disturbance on the transmission line. In other words, it will remain connected to the grid network during electrical disturbances.

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