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Evaluation of Open Circuit Fault of a Wind Farm Consisting of Fixed Speed Wind Turbines

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Abstract-In this paper, the effects of open circuit fault on the grid parameters such as active power, reactive power, voltage and the compensator rating of a fixed speed wind farm are investigated. To evaluate effects of open circuit fault, a wind farm that consists of six fixed speed wind turbines connected to capacitor banks, transformers and transmission lines is simulated using MATLAB/SIMULINK Toolbox and Aerospace/Environment and Power System Block-sets. The results reveal that after occurrence of single phase open circuit fault, the grid remains stable but the power quality is reduced because of voltage fluctuations.

Keywords- *Open circuit fault, Wind Farm, compensator, reactive power, active power*

I. INTRODUCTION

The use of the wind has a history of thousands of years. Since ancient times, wind power has been used for different purposes, varying from agricultural activities, like grain milling and water pumping to, nowadays, electricity production. Since the early 1970s oil crisis, wind power technology has experienced an important development, moving – in just two decades – from a low level, experimental technology used mainly for batteries charging to a mainstream power technology. Today, wind power is by far the fastest-growing renewable energy source [1].

The power produced by wind worldwide reached, at the end of 2004, 48 GW, representing 0.57% of the total world electricity supply. The figure might not seem impressive, but when compared to other renewable energy technologies, it becomes clear that wind power is the most promising one. As an example, wind power is still a small electricity player on the European market, producing 2.4% of its total electricity production. This will change as the European Union has decided to make wind power a major electricity source, with a 12% market share in 2020 and 20% in 2030 [2].

The development of various wind turbine concepts in the last decade has been very dynamic. The main differences in wind turbine concepts are in the electrical design and control [11][12].

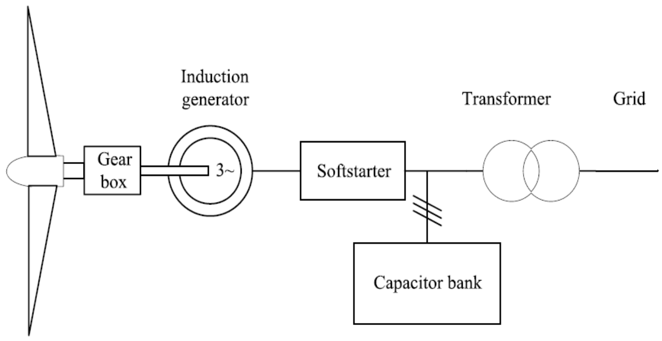


Figure 1. General structure of a fixed-speed WECS

Thus, wind energy conversion system (WECS) can be classified according to speed control and power control ability, leading to wind turbine classes differentiated by the generating system (speed control) and the method employed for limiting the aerodynamic efficiency above the rated power (power control). The speed-control criterion leads to two types of WECS: fixed-speed and variable-speed wind turbines, while the power control ability divides WECS into three categories: stall-controlled, pitch-controlled and active-stall-controlled wind turbines. Fixed-speed wind turbines are the pioneers of the wind turbine industry. They are simple, reliable and use low-cost electrical parts. They use induction generators and they are connected directly to the grid, giving them an almost constant rotor speed stuck to the grid frequency, regardless of the wind speed [1][2].

Induction generators are more attractive than synchronous generators for wind turbines due to their robust construction, low cost, low maintenance, long life (more than 50 years) and low power to weight ratio [2][9]. However the reactive power management is a major concern, not only to compensate for the reactive power requirements of the wind farm itself but also to support the system voltage in particular for wind farms based on fixed speed induction generators [8].

While a short circuit is the usual fault mode of power semiconductors, an open circuit is another thinkable fault that can occur. Open circuits can be caused by the rupture of the connections [3].

In this paper, the effects of open circuit fault on the grid parameters and the compensator rating of a fixed speed wind farm are investigated. The study was carried out by means of simulation using the software package MATLAB/SIMULINK and the results presented.

II. Fixed Speed Wind Turbine

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Fig. 1 [2].

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed.

As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important. SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed [2]. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection. SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed.

Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency. An evolution of the fixed-speed SCIG-based WECS are the limited variable speed WECS [7]. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% over the synchronous speed [1][2].

III. Wind Turbine Performance

The performance of a wind turbine is primarily characterized by the manner in which the main indicator – power – varies with wind speed. Besides that, other indicators like torque and thrust are important when the performances of a wind turbine are assessed. The generally accepted way to characterize the performances of a wind turbine is by expressing them by means of non-dimensional characteristic performance curves [2].

The tip speed ratio of a wind turbine is a variable expressing the ratio between the peripheral blade speed and the wind speed. It is denoted by λ and computed as

$$\lambda = \frac{R.\Omega_l}{v} \tag{1}$$

Where R is the blade length, Ωl is the rotor speed (the low-speed shaft rotational speed) and v is the wind speed [2]. It characterizes the power conversion efficiency and it is also used to define the acoustic noise levels. The power coefficient, Cp , describes the power extraction efficiency of a wind turbine. The aerodynamic performance of a wind turbine is usually characterized by the variation of the non-dimensional Cp vs. λ curve. The power extracted by a wind turbine whose blade length, R is expressed as

$$P_{wt} = \frac{1}{2}.\rho.\pi R^2.v^3.C_p(\lambda) \tag{2}$$

Therefore, the Cp(λ) performance curve gives information about the power efficiency of a wind turbine. The torque coefficient, denoted by C_Γ , characterizes the rotor output (wind) torque, Γ_{wt}[2] . It is derived from the power coefficient simply by dividing it by the tip speed ratio [2]:

$$C_\Gamma(\lambda) = \frac{C_p(\lambda)}{\lambda} \tag{3}$$

The tip speed ratio curve, compared to the power coefficient curve, does not give any additional information about the wind turbine performance but it is useful for torque assessment and for control purposes (e.g., assisted start-up process). $C_\Gamma(\lambda)$ gives the rotor mechanical characteristic allure, $\Gamma_{wt} - \Omega_l$, for a fixed wind velocity. for a fixed-pitch (β) wind turbine, this torque depends on the low-speed shaft rotational speed and on the wind speed [2]:

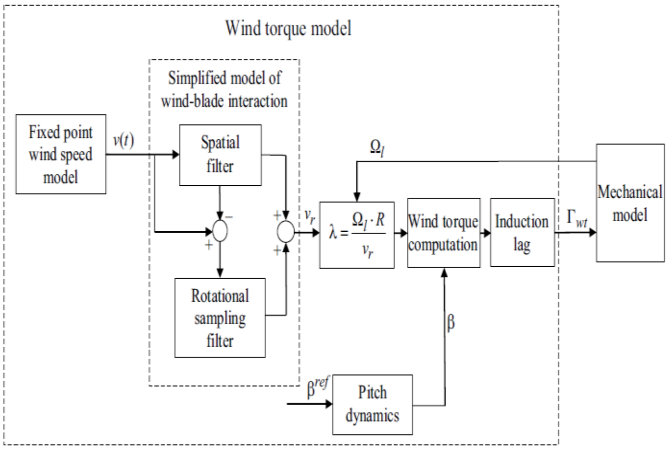
$$\Gamma_{wt} = \Gamma_{wt}(\Omega_l, l)|_{\beta=constant} \tag{4}$$

According to Equation 2, one obtains

$$\Gamma_{wt} = \frac{P_{wt}}{\Omega_l} = \frac{1}{2} \cdot \rho \cdot \pi v^2 \cdot R^3 \cdot C_\Gamma(\lambda) \quad (5)$$

Where $C_\Gamma = {C_p}/{\lambda}$ is the torque coefficient (introduced by Equation 3).

More detailed aerodynamic models can be developed, emphasizing the rotational sampling, spatial filtering or induction lag, leading to a more complex expression of the developed aerodynamic torque, Γ_{wt} . Furthermore, the power coefficient characteristic should take into account the effects due to Reynolds number and air density variations. For low-power wind turbines, these effects, together with the structural dynamics, can be neglected, and simplified models are preferred [2]. The spatial filter performs the averaging of



the wind speed's variations across the area swept by the rotor.

The fixed-point spectrum is modified in such a way that a spectral representation of the average wind speed across the rotor is obtained. The filter's transfer function is

$$H_{sf}(s) = \frac{\sqrt{2} + b_{sf} \cdot s}{\left(\sqrt{2} + b_{sf}\sqrt{a_{sf}} \cdot s\right) \cdot \left[1 + \frac{b_{sf}}{\sqrt{a_{sf}}} \cdot s\right]} \quad (6)$$

Whereas f is an empirical factor (a_{sf} =0…55) and b_{sf} is a parameter describing the intercorrelation between wind speed evolutions in different points across the rotor, which can be expressed as

$$b_{sf} = \gamma_{sf} \cdot \frac{R}{v_s} \quad (7)$$

with $\gamma_{sf} = 1.3$, R being the blade length and vs being the average wind speed experienced by the hub [2].

The rotational sampling filter includes a number of effects, among which are the ones mentioned above, that induce deterministic changes of the wind torque. Thus, the rotational sampling effect is due to blades' rotating motion inside the turbulence field of the fixed-point wind speed [2].

IV. Open Circuit Fault

A fault in an electrical power system is the unintentional and undesirable creation of a conducting path (a short circuit) or a blockage of current (an open circuit) [3]. The causes of faults include lightning, wind damage, trees falling across lines, vehicles colliding with towers or poles, birds shorting out lines, aircraft colliding with lines, vandalism, small animals entering switchgear, and line breaks due to excessive ice loading.

While a short circuit is the usual fault mode of power semiconductors, an open circuit is another thinkable fault that can occur. Open circuits can be caused by the rupture of the connections. In this paper, the effect of open circuit fault on the grid parameters and the compensator rating of a fixed speed wind farm are investigated.

V. System Description

Fixed speed wind turbines basically consist of squirrel cage induction generators which are directly connected to the grid via a step-up transformer. In order to study the effect of single phase open circuit fault on the grid parameters and fixed speed wind farm, the system shown in Fig. 4 was studied.

The network consists of a 9MW wind farm, a 25 km overhead transmission line, 132/11 kV (80MVA) transformer, STATCOM, 11/0.4 kV (80MVA) transformer and capacitor bank. The wind farm consists of 6 fixed speed wind turbines, each with its own 0.4/11 kV transformer.

Traditionally, the required reactive power for the machine excitation is provided by the capacitor banks installed at its terminals. However, capacitor banks cannot provide dynamic compensation for events such as the sudden drop of voltage [4]. Dynamic compensation devices such as static VAr compensator SVC, or static synchronous compensator (STATCOM) can provide a suitable compensation for fixed speed wind farms [5].

Each wind turbine drives a 1.5MW induction generator, the parameters of which are shown in Table 1. In the studies reported in this paper, a STATCOM was used to provide the reactive power required by a 9MW fixed speed wind farm.

Table I. The 1.5 MW Induction Machine Parameters

Rating	**1.5 MW**
Stator voltage (L-L, RMS)	**0.4 kV**
Number of pair pole	**3**
Stator resistance	**0.004843(pu)**
Stator inductance	**0.1248(pu)**
Mutual inductance	**0.0027(pu)**
Rotor resistance	**0.004377(pu)**
Rotor inductance	**0.1791(pu)**
Combined inertia constant of the generator and the turbine	**5.04 s**

The induction machine model used in this study is based on a fourth-order state-space model. This model is a built-in model in the SIMPOWER-SYSTEM library in MATLAB/SIMULINK.

All the parameters of the 1.5MW induction generator are given in p.u..

The 25 km transmission line connecting buses B5 and B4 shown in Fig. 4. The line between the buses B3 and B2 in Fig. 4 represents the lines which connect the 0.4/11 kV transformers of each wind generator to the central 11 kV bus bar. The parameters of the two transformers and the transmission lines are shown in Table II and Table III, respectively.

TABLE II. TRANSFORMER DATA

Wind farm transformer data (0.4/11kv)	
Rating	4 MVA
Vsecondary (L-L, RMS)	0.4 kV
Vprimary (L-L, RMS)	11 kV
L	0.025 (pu)
Grid side transformer data (11/132kv)	
Rating	48 MVA
Vsecondary (L-L, RMS)	11 kV
Vprimary (L-L, RMS)	132 kV
L	0.08 (pu)

Transmission line parameters

Resistance	0.1153 Ω/km
Inductance	1.05 mH/km

VI. SIMULATION

Fig. 3 shows the whole system consisting of wind farm, STATCOM, transition lines and transformers. The simulation results are shown in figures (4-13).

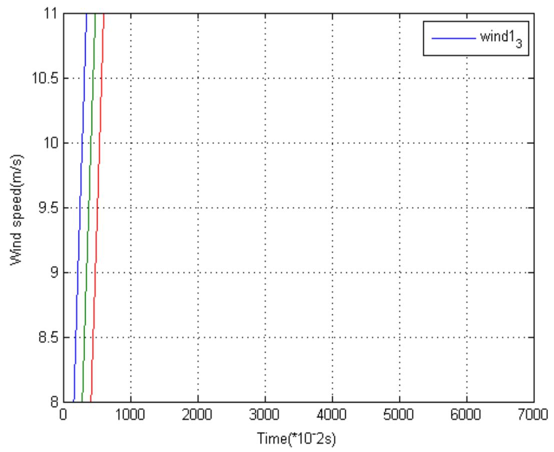


Figure 2. Wind speed of pair wind turbines (No. 1-3)

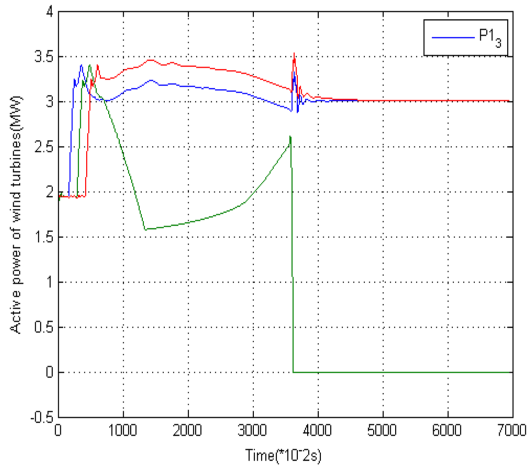


Figure 3. Active power of pair wind turbines (No. 1-3) Whole Power System

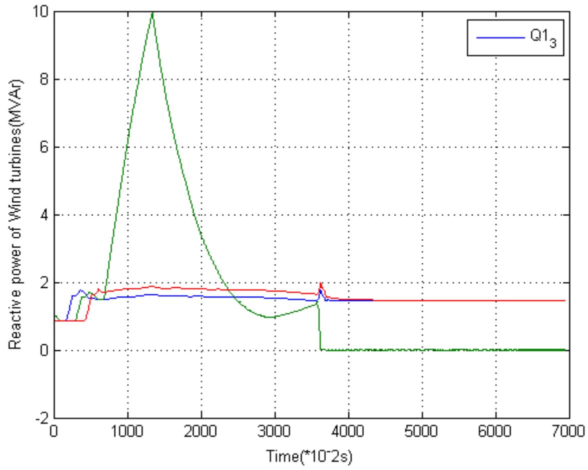


Figure 4. Reactive power of pair wind turbines (No. 1-3)

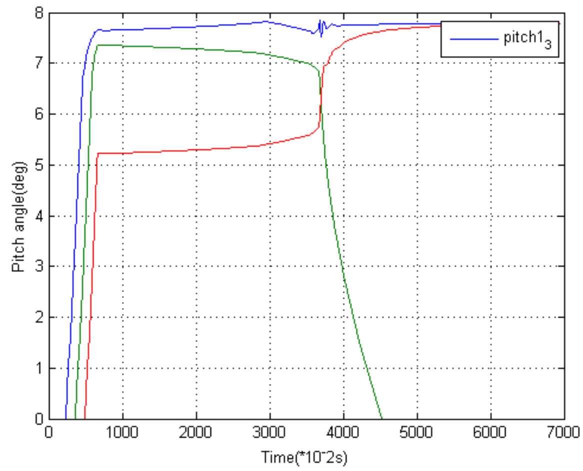


Figure 5. Pitch angles of pair wind turbines (No. 1-3)

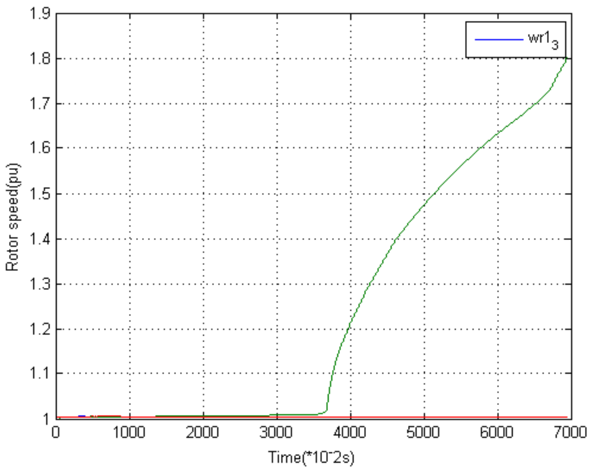


Figure 6. Rotor speed of pair wind turbines (No. 1-3)

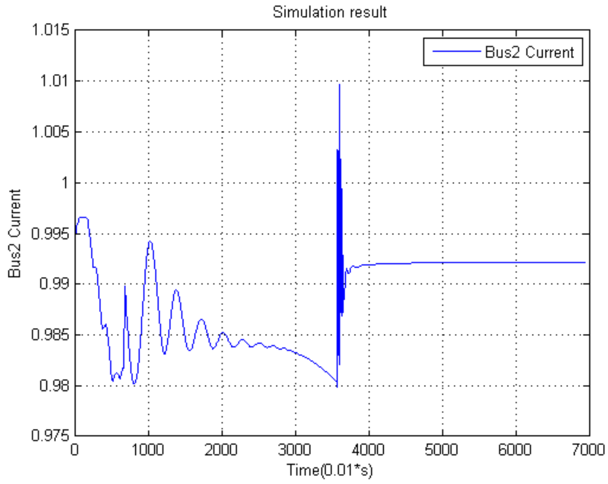


Figure 9. Current of Bus 2

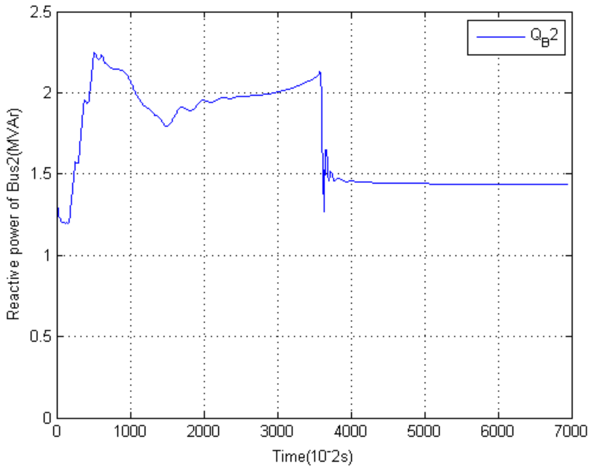


Figure 7. Reactive power of Bus 2

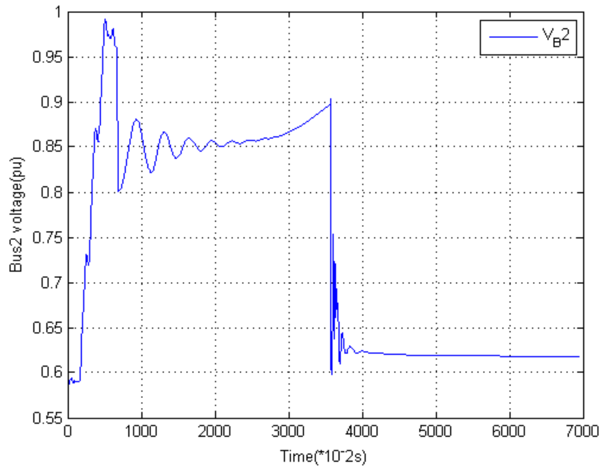


Figure 10. Voltage of Bus 2

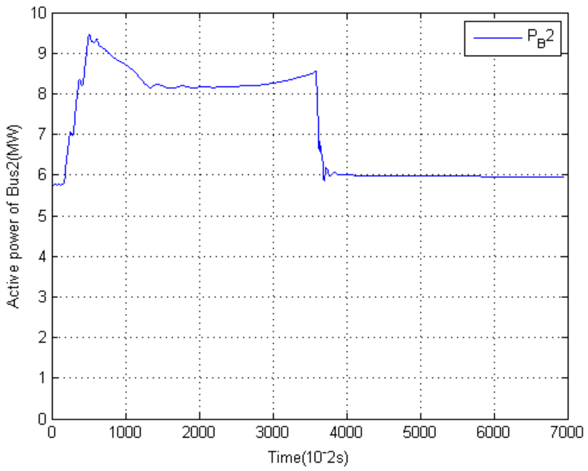


Figure 8. Active power of Bus 2

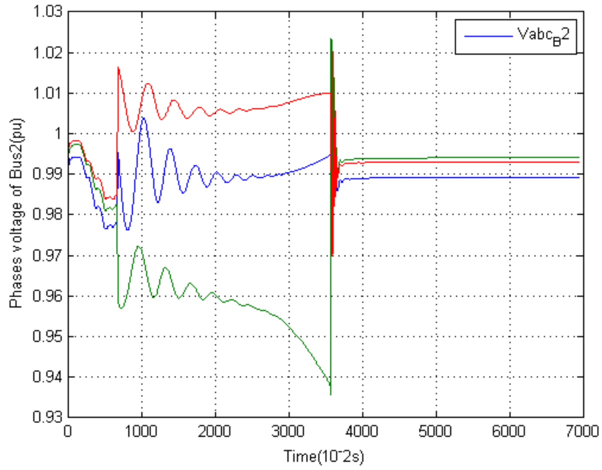


Figure 11. Phases voltage of Bus 2(pu)

In order to simplify the simulation, the whole wind farm was modeled as three pair of wind turbines. Each pair consisted of two 1.5MW wind turbines. Fig. 2 shows wind speeds that blew to blades of couple wind turbines with a delay. Also, the open circuit fault occurred at t=7s (700*10^-2s). Fig. 3 shows active power of couple wind turbines. The green lines in all figures are relevant to faulty couple wind turbines (open circuit fault). Fig. 5 presents the reactive power of couple wind turbines. Also Fig. 6 shows the pitch angles of couple wind turbines. Fig. 7 shows the rotor speed of wind turbines and it can be seen that after occurrence of open circuit fault, the rotor speed of faulty couple wind turbines (green line) increase violently. Fig. 8 presents reactive power of bus 2. Also Fig. 9 shows active power of bus 2. Fig. 10 and Fig. 11 show current and voltage of bus 2 respectively. Also Fig. 12 shows phases voltage of bus 2 in per unit.

VII. Conclusion

In this paper, the effect of single phase open circuit fault on the grid and wind farm parameters is investigated. The study was carried out by means of simulation using the software package MATLAB/SIMULINK.

The results reveal that after occurrence of single phase open circuit fault the grid remains stable but the power quality is reduced because of voltage fluctuations. So the wind farms must have a high protection system to tolerant the faults and damp the voltage fluctuations in short periods.

References

[1] V. Nelson, “Wind energy renewable energy and the enviroment”, CRC Press, 2009.

[2] I. Muhteanu, A.I. Bratcu, “Optimal control of wind energy systems”, Springer, 2008.

[3] L.L. Grigsby, “Electric power engineering handbook”, CRC Press, 2007.

[4] H.M. El-Helw, S.B. Tennakoon, “Evaluation of the suitability of a fixed speed wind turbine for large scale wind farms considering the new UK grid code”, Scinece direct, 2008.

[5] S. Saoud, M.L. Lisboa, “Application of STATCOMs to wind farms”, IEE Proc Generation Transmission Distribution, 1998.

[6] T Burton, D Sharpe, N Jenkins, E Bossanyi, “Wind energy handbook”, John Wiley & Sons, New-York, 2001.

[7] AD, Hansen, P Sørensen, F Iov, F Blaabjerg, “Control of variable speed wind turbines with double-fed induction generators”, Wind Engineering, 2004

[8] F.D. Kanellos, S.A. Papathanassiou, “Dynamic analysis of a variable speed wind turbine equipped with a voltage source AC/DC/AC converter interface and a reactive control loop”, 10th Electrotechnical Conference, MELECON, August 2000

[9] F. khalifa, A. Eliwa, M. Abdelrahman, W. Sabry, “Classical and modern control systems of self excited induction generator”, 19th International Conference of Electricity Distribution, Vienna, May 2007

[10] P.V. Jreng, A. D. Diop, “New approach for regulating the voltage of an off grid wind turbine eqquiped with a self excited induction generator without storage”, International conference wind energy and remote region, Island, Oct 2005

[11] M. Sadeghizadeh, A. Rezazadeh, “Adaptive PID controller based on reinforcement learning for wind turbine control”, Proceedings of world academy of science, engineering and technology, Feb. 2008

[12] [12] J. Wang, B. G. Kao, “Neural network PID control of a distributed power generation system based on renewable energy”, Journal of