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Operation and Protection of Grid Connected Wind Farm

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Abstract:

In modern power systems, wind energy shares significant amount in electricity generation. Accordingly, the grid performance could be affected due to the natural behavior of the connected wind farms. The main challenge is to fulfill the voltage ride through (FRT) requirements and fast fault detection as well as reactive power coordination using FACTs devices such as STATCOM. Fulfilling these requirements will minimize the loss of wind energy generation due to emerged disconnection of the wind turbines from the grid.

This paper presents fast and efficient over current and under voltage protections against faults on both grid high voltage line and on medium voltage feeders connecting the wind turbines to the point of common coupling (PCC). The proposed protection scheme based on measuring the voltage and current signals at PCC bus, evaluating and analyzing these signals for fault detection. Thereby, the main objective is to keep wind turbines connected to the grid and to regulate the reactive power and voltage level during grid-transmission line faults using STATCOM. Under voltage, relay time delay settings is proposed to fulfill the Fault Ride-Through (FRT) requirement. Moreover, over current relay settings is presented to isolate the wind farm from the grid during the internal wind farm feeder faults.

1. INTRODUCTION

Self-excited squirrel cage induction generators tend to drain large amount of reactive power from the grid in their steady state operation for excitation. In case of short circuit fault condition, these generators absorb more extreme reactive power, which may result in voltage instability [1]. Such requirements had known as fault ride though capability code. Voltage control and reactive power capability became important technical constraints for wind power plants. The minimum amount of reactive power is specified in these grid codes to reduce the risk of the grid voltage collapse during system contingencies [2]. Therefore, the induction generators need external supporting device to avoid their tripping during voltage sags such as static VAR compensator SVC or STATCOM. STATCOM is capable to inject a controllable reactive current independently on the grid voltage and thus the compensating current is not reduced as the voltage drops [3-5]. Therefore, in this paper, an efficient STATCOM is proposed to enhance the system performance and provide low voltage ride through of the studied wind farm with induction generators. This requires intensive simulations to understand the behavior of wind power plant regarding voltage and system stability under normal and fault conditions.

Generally, the protection scheme requires continuous measuring and analyzing of current and voltage signals. If the voltage or current amplitudes are in the permissible standard range, no tripping actions are taken, when electrical grid faults are detected then the connecting high voltage line is tripped leaving the wind farm in stand-alone mode of operation. On the other side, if the defined limit values of the turbine feeder protection are exceeded, the wind turbine is shut down. As soon as the voltage and frequency return to their permissible range, wind turbines are, being started up again to reduce the farm shut down times.

In this paper, two-protection relay settings are proposed based on measuring the current and voltage signals at the point of common coupling (PCC) bus. Firstly, under voltage protection-scheme at the PCC to avoid wind farm isolation during the faults on the high voltage transmission lines is applied according to the fault right through FRT requirements. Secondly, the transmission lines are protected using overcurrent relays against faults on both the high voltage transmission lines connecting wind to the grid with 220 kV voltage level and on the medium voltage feeders, which connecting the wind farm to the PCC with 22 kV voltage level. The paper is organized in the following way: After the introduction, section 2 describes the studied grid-connected wind farm including the STATCOM modeling and control; section 3 addresses the proposed overcurrent and under voltage protection algorithms; section 4 displays the simulation results and finally the conclusions are given in section 5.

2. DESCRIPTION OF STUDY CASE:

The schematic diagram of grid connected wind farm is shown in Fig.1. The studied wind farm represents a part of an existing system in Suez Gulf area, Egypt with typical manufacturer turbines; technical data and the associated feeders and lines electrical parameters. It consists of 22 kV network, four 660 kW wind turbines. The medium voltage grid of wind farm consists of four 22 kV feeders. Wind turbine has a step up transformer with 800 KVA capacity and voltage ratio of 690V/22kV. The average wind speed is 9 m/sec. The turbines are coupled to induction generators with fixed capacitors. The wind farm is connected to the grid at PCC which is integrated to the grid via15 MVA and 22/220kV substation. A local load of 9 MW is being connected at PCC. This substation is connected to the public grid of capacity 300MVA through 200 km transmission line. STATCOM with a rating of 15 MVA is connected at PCC bus to enhance system performance.

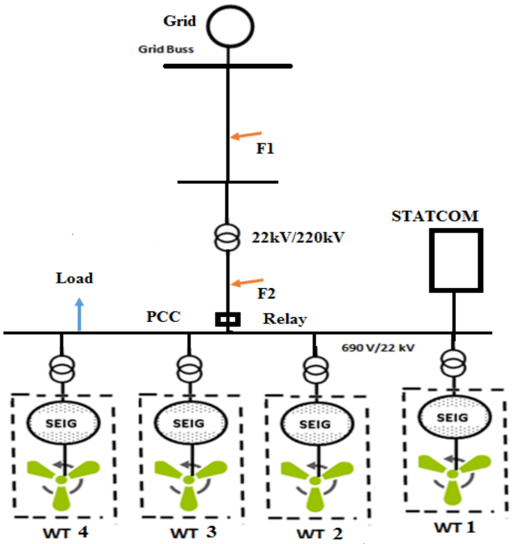

Fig.1: Schematic diagram of power system under study

A. *Induction Generator Model:*

Induction generator with fixed shunt capacitor is modeled according to [5, 6] by the following equations:

$$\varphi'_{ds}=w_b(V_{ds}+r_s i_{ds})+w_s\varphi_{qs} \qquad (1)$$

$$\varphi'_{qs}=w_b(V_{qs}+r_s i_{qs})-w_s\varphi_{ds} \qquad (2)$$

$$\varphi'_{dr}=w_b(V_{dr}+r_r i_{dr})+(w_s-w_r)\varphi_{qr} \qquad (3)$$

$$\varphi'_{qr}=w_b(V_{qr}+r_r i_{qr})-(w_s-w_r)\varphi_{dr} \qquad (4)$$

The electromechanical torque in per unit can be written in terms of stator flux linkages and currents as:

$$T_e=\varphi_{ds}i_{qs}-\varphi_{qs}i_{ds} \qquad (5)$$

The per unit rotor acceleration is given by

$$\dot{w}_r=\frac{1}{2H_T}(T_e-T_m-D_T w_r) \qquad (6)$$

B. *Wind turbine model:*

The mechanical power output of a wind turbine P_m can be written as ;

$$P_m=0.5\rho A C_p V^3 \qquad (7)$$

Where ρ is the air mass density, V is the wind speed, A is the rotor swept area, and Cp is a power coefficient representing the fraction of power extracted from the aerodynamic power in the wind by a practical wind turbine.

C.STATCOM Model:

The basic STATCOM model consists of a step-down transformer with leakage reactance X, a three-phase GTO VSI, and a dc side capacitor. The ac voltage difference across this transformer leakage reactance produces reactive power exchange between the STATCOM and the power system at PCC. In addition to voltage regulation, a secondary damping function can be added to the STATCOM to enhance power system dynamic stability. The STATCOM‘s main function is to regulate the voltage magnitude at PCC by dynamically absorbing or delivering reactive power to the ac grid network. This reactive power transfer is done by adjusting the secondary transformer voltage to be in phase with the primary voltage (network side). This voltage is provided by a voltage-source PWM inverter and is always in quadrature to the STATCOM current [3, 7-9]. The instantaneous power at the AC- and DC-terminals of the inverter is equal by neglecting losses of inverter, giving the following power balance equation:

$$2V_{dc}I_{dc}=3E_a I_a\cos(\emptyset) \qquad (8)$$

$$V_{dc}=\frac{1}{2C\,V_{dc}}\int(3\,Ea\,Ia\,\cos(\emptyset))\,dt \qquad (9)$$

Changing d-q frame to ABC equations by using park’s transformation, the full model equations can be summarized in d-q frame as fellow:

$$\begin{bmatrix}\frac{di_d}{dt}\\ \frac{di_q}{dt}\\ \frac{dv_{dc}}{dt}\end{bmatrix}=\begin{bmatrix}-\frac{Rs}{Ls} & -w\\ w & -\frac{Rs}{Ls}\\ \frac{3\,m\cos(\alpha)}{2C} & \frac{3\,m\sin(\alpha)}{2C}\end{bmatrix}\begin{bmatrix}id\\ iq\end{bmatrix}+\frac{1}{Ls}\begin{bmatrix}Ed-Vsd\\ Eq-Vsq\end{bmatrix} \qquad (10)$$

Then, active and reactive power of STATCOM at the inverter bus can be calculated as

$$P=\frac{3}{2}(V_{od}I_d+V_{oq}I_q) \qquad (11)$$

$$Q=\frac{3}{2}(V_{oq}I_d-V_{od}I_q) \qquad (12)$$

Under light load conditions, the STATCOM controller is used to minimize or completely diminish line over voltage; on the other hand, it can be also used to maintain certain voltage level at PCC under heavy loading conditions. The reactive power exchange between STATCOM and ac system at the PCC can be controlled by the phase angle α between ac system bus and the fundamental inverter voltage as follows:

$$P_{stat}=\frac{3V_a V_{ref}}{X}\sin(\alpha) \qquad (13)$$

$$Q_{stat}=\frac{3\,V_{ref}}{X}(V_a\cos(\alpha)-V_{ref}) \qquad (14)$$

Where; V_{ref} is the reference voltage at the PCC and V_a is the three level inverter output. The angle α is small (couple of degrees in steady state) due to the fact that the real power exchange between the voltage-sourced converter and the AC system is of small amount. The main function of the STATCOM is to absorb or inject the reactive power at the PCC according to its mode of operation either leading or lagging. When the induction generator operates at no load or light load conditions, the slip is very small near to zero and the reactive power absorbed by the generator is at its lowest value. The rotor slip and the reactive power absorption will increase as long as the power generation is increased. In the wind farms the reactive power is mainly compensated, when the power output is increased, by increasing the STATCOM current at the PCC.

3. PROPOSED PROTECTION SCHEME:

Line protection at high voltage level or above is provided primarily with over current protection. The over current protective relays use local and remote end current measurements. The protection scheme is adaptive and based on the use of smart relays, where their settings can be changed on-line by means of externally generated signals or control action [10, 11]. In cases of line short circuits, the fault resistances are small and in general, they do not exceed a few ohms. However, they may become much higher during ground faults owing to the tower footing and arc resistance. In general, the effective generator reactance vary rapidly from synchronous to sub-transient values after fault inception. Consequently, the fault current contains varying amplitude and high frequency oscillations after fault inception. The medium voltage network in wind farm has been protected against short-circuit faults with overcurrent relays. In island operation, these relays may fail to detect fault conditions due to drastically voltage drop and reduced short-circuit current [12, 13].

In this paper, to study the under voltage behavior at the relay location, three-phase faults had applied at different locations along the 220kV high voltage transmission line, F1. The fault incidence is at time of 2 sec and cleared after 200 msec. The measured instantaneous values with sampling time of 50E-6 sec. are smoothed by movable window of half cycle (2000 samples). The proposed under voltage relay action, during HV line faults, must have a delay time before disconnection by applying the FRT Characteristics as demonstrated in Figure (2). The proposed under voltage relay sag time matched with FRT requirements are given in Table (1) depending on the bus voltage level.

Similarly for studying the over current behavior at the relay location, different three-phase faults had applied at different locations along the 22 kV voltage feeder such as F2. The values of the fault currents are used to check the performance of the proposed over current protective relays. The over current protection relay setting is summarized in Table 2.

From the analysis of the fault cases at both HV transmission lines and MV feeders, it should be noted that the current at the PCC is extremely increasing in case of faults on medium voltage feeder more than the case of HV grid transmission line faults. While under voltage, protection has to be checked for HV transmission line faults according to the delay time displayed in Table (1) before any trip action. That means the FRT voltage conditions has to be checked before the proposed overcurrent relay disconnecting the wind farm.

Table 1: Proposed under voltage protection relay setting

Relay setting	**Voltage sag (pu)**	**time delay (s)**
1	V<0.2	Instantaneously
2	0.2<V<0.5	0.5
3	0.5<V<0.85	0.75
4	0.85<V<0.9	1
5	0.9<V	3

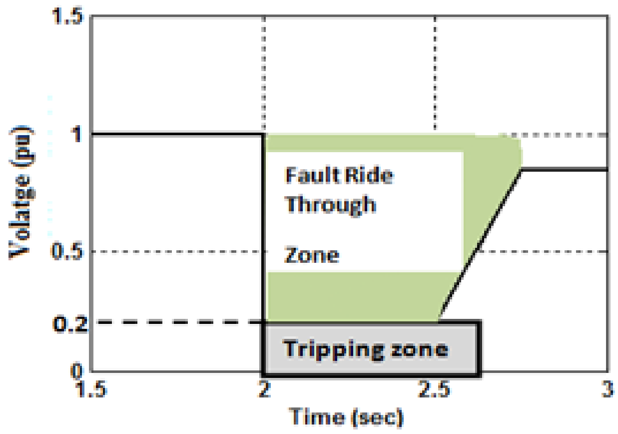

Fig. (2): FRT capability for wind farm

Table 2: Proposed overcurrent protection relay setting

Relay setting	**I (pu)**	**Relay trip time (s)**
1	I≥8	Instantaneously
2	6<I<8	0.5
3	4<I<6	0.75
4	3<I<4	1
5	1.5<I<3	2.5
6	1<I<1.5	5

The next section demonstrates two faulty cases from the studied cases to demonstrate the behavior of under voltage and over current protection relays under faulty conditions. Firstly, a fault case is selected at the 220 kV HV transmission line. Moreover, during this case, the STATCOM performance to regulate the voltage of the wind farm- bus has introduced. Second fault case deals with the fault location at 22 kV MV feeder. Both These two cases are used to validate and check the performance of the proposed protection schemes.

4. SIMULATION RESULTS

The described grid connected wind farm is simulated using MATLAB/Simulink to study its behavior under variable wind speed in normal and faulted conditions.

A. Voltage regulation using STATCOM

In this simulation, actual variable wind speed for farm site is applied to the different wind turbines as shown in Fig. (3). Each wind turbine works at mechanical power of 0.95 from its rating.

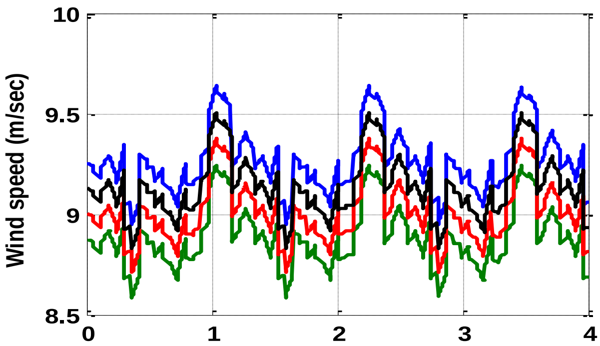

Fig. (3): Wind speed

To keep the wind turbine connected to the grid after fault inception, STATCOM is designed to enhance the system performance under such abnormal conditions. Three-phase fault is initiated on the high voltage line at time of 2 s and cleared after 200 ms. The STATCOM voltage and current are displayed in Fig. (4). STATCOM active and reactive power is presented in Fig.(5) which shows no change in the active power while the reactive power is going up during the fault period to compensate the drop in the voltage.

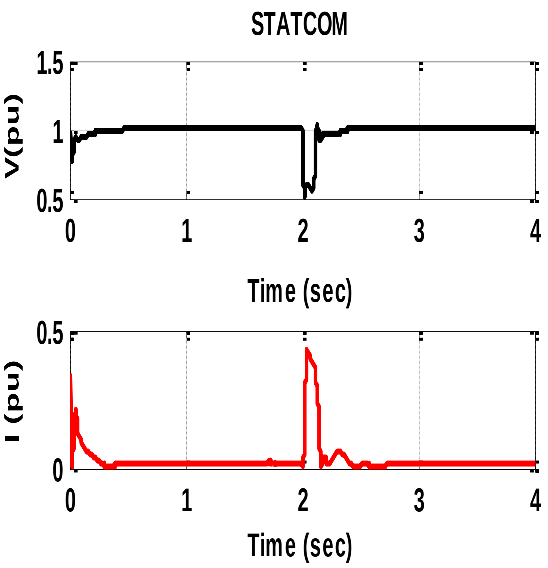

Fig. (4) Current and voltage response of the STATCOM

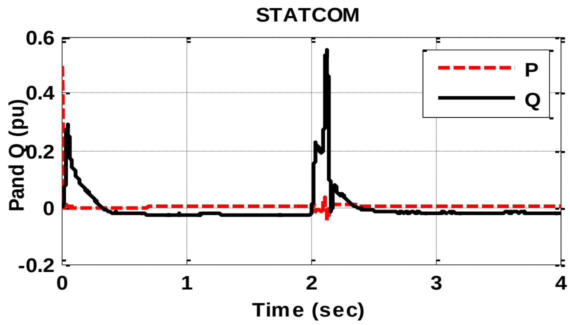

Fig. (5)Reactive and Active power of STATCOM

B. Under voltage protection

For studying the voltage behavior at the relay location, three-phase faults had applied at F1, located on the 220kV high voltage transmission The simulation results indicate that, the generating units are hardly affected by short circuit fault due to voltage instability, which can leads to complete shutdown of the generating units in case of no managment during the faulty conditions. Figure (6) shows the rotor speed of the turbines after inception of the 3-phase fault with a clearing time of 200 ms. It is seen that, the rotor speed returns to its initial value after fault clearing. Figures (7) show voltage variation at PCC under fault condition. The magnitude of this voltage is decreased instantaneously to 0.5 pu. Comparing the voltage variation with the FRT code indicted that the wind turbines could continue to operate as the voltage at PCC remains above the FRT curve. It should be noted that, the wind farm would be tripped instantaneously if the under voltage magnitude is lower than the minimum value of 0.2 pu..

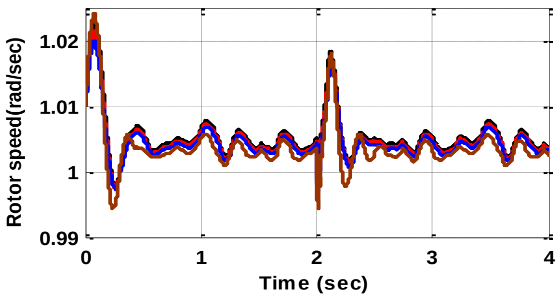

Fig. (6) Rotor speed of the different wind turbines

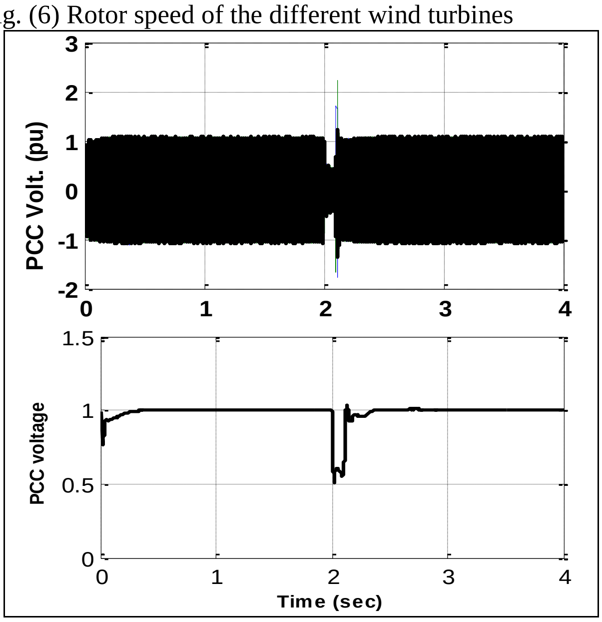

Fig. (7) PCC Voltage in time domain and RMS value

C. Over current protection

In this case, three-phase fault is applied at F2, which located on the MV transmission line 22 kV, between grid and PCC. Figures (8) illustrate the simulated current signal at the relay location at one of studied fault cases where a three phase short circuit is at midpoint of 22 Kv Transmission line. These signals are then smoothed for a window of half cycle with 2000 samples to eliminate their high frequency components, as shown in Fig. (9). The PCC current is rapidly increased at fault occurance to 6 times and returned to its nominal value after fault clearance. These figures indicated that the used smoothing approach is efficient for eliminating the transients after fault occurrence.

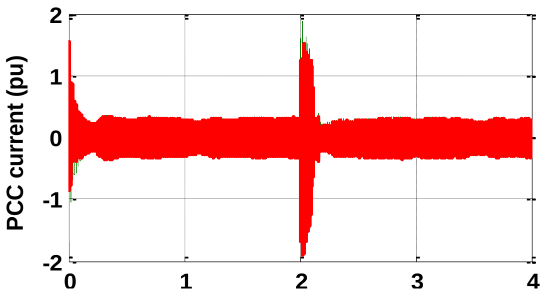

Fig. (8) PCC current at HV line fault case

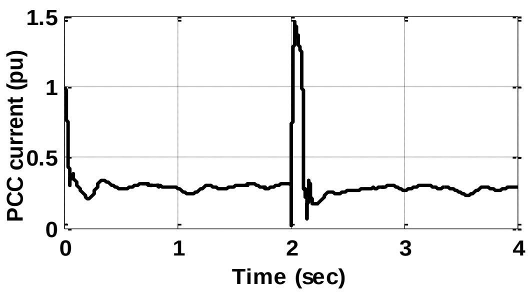

Fig. (9) PCC smoothed relay current at HV line fault case

Figure (10) illustrates the measured instantaneous current by the overcurrent relay at the PCC for the case of 3-phase fault on the medium voltage feeders connecting the wind farm to the PCC. As shown from Fig.(11), the current is rapidly increased to a value of 3 pu after fault occurrence that means 12 times its nominal value. The fault current is smoothed over a window of half cycle with 2000 samples to eliminate their high frequency components. Figure (12) shows the smoothed voltage at PCC under this fault condition. The voltage is decreased rapidly to a level of 0.3 pu less than in the case of the HV line fault. This is attributed to the high current supplied by the wind generator and justified by the high rotor speed as shown in Fig. (13), where its values are going up to 1.06 pu during fault compared to its corresponding value of 1.02 pu for faults in the high voltage lines in the previous case.

From the above results, the overcurrent relay during internal fault locations has to have a fast action to disconnect the wind farm from the grid. Thereby, the grid has to be protected against any wind farm internal disturbances.

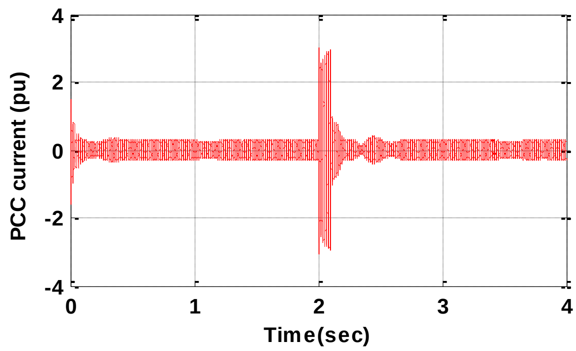

Fig. (10)PCC current during fault at the MV feeder.

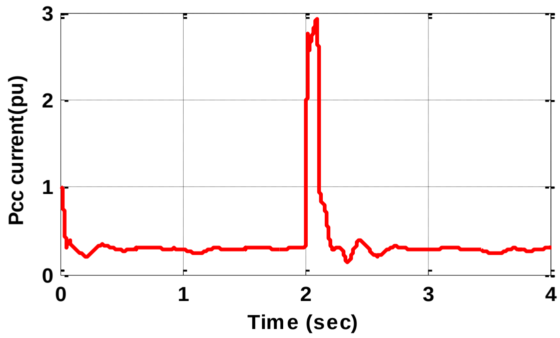

Fig (11) PCC smoothed relay current at MV feeder faults.

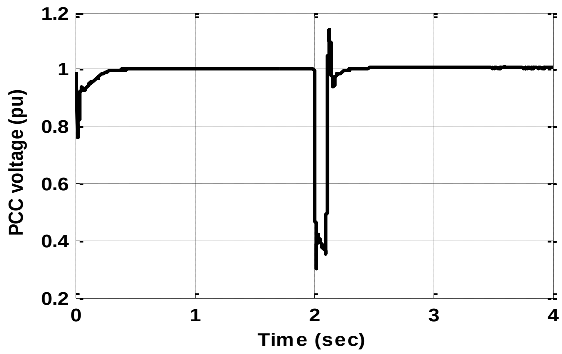

Fig (12) PCC smoothed relay voltage at MV feeder faults.

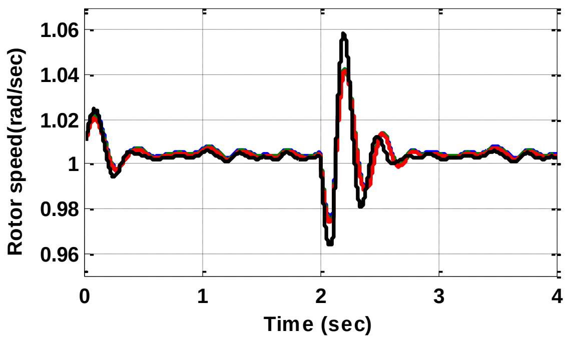

Fig. (13) Rotor speed of the different wind turbines

The proposed protection scheme is applied on the above two cases of the simulation results to evaluate its reliability for fast and efficient fault tripping. At case 1, during the fault location at HV Transmission line, the current at the relay location is 1.5 pu while the voltage is 0.4 pu. Therefore, by checking the characteristics of Tables 1 and 2, the relay action is under voltage trip after 0.5 sec from the fault occurrences. While for case 2, where the fault location at MV feeders, the current at the relay location is 3 pu while the voltage is 0.3 pu.

Therefore, the proposed scheme action is also under voltage trip after 0.5 sec from the fault occurrences.

5. CONCLUSIONS

Nowadays, the sharing of wind energy with significant amount to the power system is continuously increasing as a renewable clean energy source. The integration of these wind farms to the public grid presents many new operation challenges regarding reactive power control, voltage regulation as well as grid protection. Implementation of STATCOM is proposed in this paper as an efficient reactive power source to regulate the voltage levels in the grid within their acceptable limits, during normal and faulty conditions. To fulfill the farm operation and protection requirements, intensive simulations are carried out. Based on the simulation results, the proposed STATCOM can efficiently regulate the PCC voltage, enhance the system stability and decrease the shutdown time of the wind farm.

A simple and efficient protection scheme has been developed for the studied system and numerically tested during high voltage lines and medium voltage feeder faults utilizing the measured voltage and current signals at lines and feeders end busses. The obtained results of the proposed protection scheme show that the wind farm has been efficiently protected against short circuit faults using overcurrent relay as primary protective device and under-voltage relay as pack up protection.

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