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Wind Gust Protection Algorithm for Non-Pitched Control Wind Farm

Mohamed M. A. Mahfouz[1], Mohamed A. H. El-Sayed[2]

[1] Electrical Power and Machines Dept., Helwan University, Cairo, Egypt
[2] Electrical Dept., College of Engineering and Petroleum, Kuwait University, Kuwait
E-mail: mohamed.mahfouz@yahoo.co.uk, elsmah@hotmail.com

Abstract: A significant capacity of wind energy has been recently interconnected into the public grids to utilize this clean energy for electricity generation. The efficient utilization of wind-converted energy requires stable operation of wind farms under wind gust conditions. This paper focuses firstly on defining the critical wind speed together with the corresponding critical voltage and current of the wind generators to keep the farm in its stable region. Secondly, an over speed protection scheme is proposed to trip out the wind farm before reaching its unstable region. Thereby, the critical clearing time for the proposed over speed relay is determined in coordination with the wind gust speed and the corresponding critical voltage and current. The simulation results indicate that the proposed over speed turbine protection improves significantly the grid connected wind farm system performance under wind gust conditions.

Key words

Wind Energy, Wind Gust, Turbine Modeling, Over speed protection.

1. Introduction

Wind power, as a clean energy resource with a continuously reduced cost, gained an intensive research due to its increased projection in the future electricity generation [1]. On the other side, the wind speed has a wide range of variations and can be gusty with high rates. Consequently, the behavior of wind farms has stricken the attention to rotor over-speed protection during the wind gusts [2].

Currently, fixed-speed induction-generators wind turbines are commonly used with grid connected wind farms, as they are cheap, reliable, and readily available in a wide capacity range from fractional horsepower to few megawatts [3]. Under abnormal conditions, such as wind gusts, the grid has to supply the reactive power required for the voltage recovery. If the voltage has recovered without the generator is over-speeded, torque could be restored and the wind turbine returns to its normal operation condition. Otherwise, the rotor speed would continue to increase and the reactive power consumption will significantly increase, resulting in a further drop in the terminal voltage. If the rotor speed exceeds its critical value the system becomes unstable and then the turbine must be tripped out by over speed protection relays [4-5]. A natural question is whether the transients caused by wind gust in each individual wind turbine generator (WTG), can adversely affect its dynamic behavior [6-9].

In most of the previous researches, the wind turbine model has developed for steady state analysis based on constant torque for a particular wind speed [10]. It should be noted that this assumption is not true, as the torque-speed characteristic of a wind turbine depends mainly not only on the wind speed but also on the slip of the induction generator. Therefore, the wind turbine and the grid connected induction generator must accurately be modeled [11]. As wind fluctuations can cause significant shaft oscillations, their interaction effects have been taken into consideration using two-mass shaft model with a fifth-order model for the induction generator [12].

The dynamic behavior of the studied system has examined by extensive simulation cases using MATLAB/ SIMULINK under different speeds of wind gust. Thereby, the generator voltage, current and rotor speed have been monitored in order to define critical speed for the stable operation region. The over speed critical cleaning times (CCT) are determined in coordination with the different speeds of wind gust.

This paper is organized as follows; after this introduction, the second section will describe the studied power system including medium voltage and high voltage transmission network. Moreover, the induction generator, shaft system and turbine aerodynamic are modelled in section 3. The fourth section will handle the proposed over speed protection algorithm and followed by presenting the simulation results at wind gust conditions. Finally, the evaluation of the proposed protection algorithm and conclusions will been introduced.

2. Studied Wind Farm

The studied wind farm represents a real system with typical manufacturer turbines technical data with the electrical parameters of the associated feeders as shown in Figure (1). It consists of three subsystems and each subsystem contains sixteen 660 kW wind turbines. The medium voltage grid of the considered subsystem consists of four 22 kV feeders, and each feeder has four series turbines. The step up transformer is located in a separate compartment to the rear of the nacelle. The transformer is a three-phase dry-type cast resin with capacity 15 MVA and voltage ratio of 690V/22kV.

The windings are delta connected on the medium voltage side and in a star on the low-voltage-side, where the star point is connected to ground. Surge arresters are mounted on the medium voltage (primary) side of the transformer. The average wind speed in the site is 9 m/s measured at a level of 40 m above ground. The wind turbines are located in four rows and the wind speed for each row is recorded. The turbines are coupled to induction generators with fixed capacitors. The wind farm is connected to the grid at PCC through 75 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 150 km parallel transmission line.

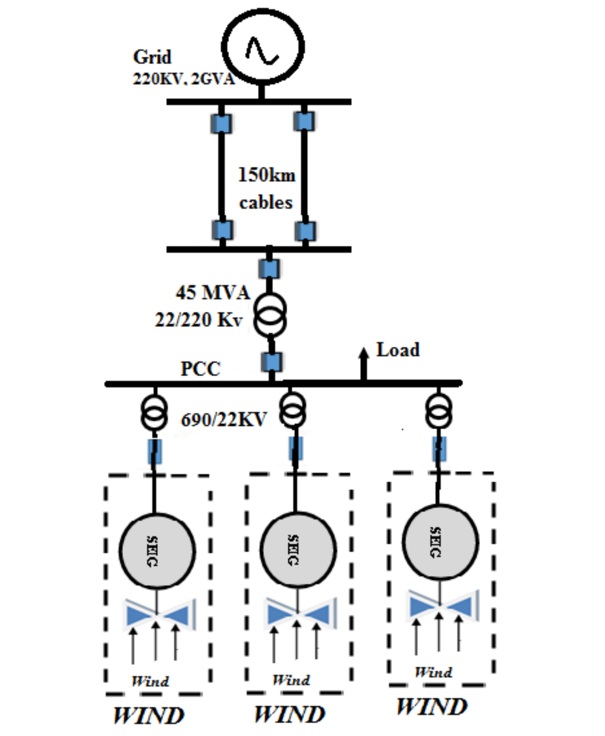

Fig. 1: Studied wind farm grid connected system

3. Dynamic Modeling of Wind Farm

A. Induction Generator

The induction generator represented by fifth-order model [2, 3, and 12]. The set of per unit voltage equations in rotating frame is described by:

$$V_{Ds} = R_s I_{Ds} - \omega_s \Psi_{QS} + \frac{d\Psi_{DS}}{dt} \quad (1)$$

$$V_{Qs} = R_s I_{Qs} + \omega_s \Psi_{DS} + \frac{d\Psi_{QS}}{dt} \quad (2)$$

$$V_{DR} = R_R I_{DR} - S\omega_s \Psi_{QR} + \frac{d\Psi_{DS}}{dt} \quad (3)$$

$$V_{QR} = R_R I_{QR} + S\omega_s \Psi_{DR} + \frac{d\Psi_{QS}}{dt} \quad (4)$$

$$T_E = \Psi_{DS} I_{QS} - \Psi_{QS} I_{DS} \quad (5)$$

Where;

$V_s = (V_{Ds}, V_{Qs})$ Stator voltage of wind generator

$I_s = (I_{Ds}, I_{Qs})$ Stator current of wind generator

$\Psi_S = (\Psi_{DS}, \Psi_{QS})$ Stator flux of wind generator

$I_R = (I_{DR}, I_{QR})$ Rotor current of wind generator

$\Psi_R = (\Psi_{DR}, \Psi_{QR})$ Stator flux of wind generator

S : Rotor slip

Ψ_S : Synchronous speed rotating flux

T_E : Electric torque

R_S, R_R : Stator and rotor resístanles

$V_R = (V_{DR}, V_{QR})$: The rotor volatge and it equals zero when rotor is shorted.

B. Mechanical Shaft System Margins

In order to study the electro-mechanical interactions of the wind farm, the shaft system is represented by lumped two-mass model. These interactions are expressed by the voltage and current signals of the induction generator as well as rotor speed. The model equations in per unit are given by [1-3]:

$$2H_L \frac{d\omega_L}{dt} = T_M - T_E - F_L \omega_L \quad (6)$$

$$2H_M \frac{d\omega_M}{dt} = T_M - K_S \theta_s - F_M \omega_M \quad (7)$$

$$2H_G \frac{d\omega_G}{dt} = K_S \theta_s - T_E - -F_G \omega_G \quad (8)$$

$$\frac{d\theta_s}{dt} = \omega_0 (\omega_M - \omega_G) \quad (9)$$

Where:

H_L : Total lumped inertia constant

F_L : Total damping coefficient

ω_L : Total system speed

ω_M : Wind turbine rotor speed

ω_G : Generator rotor speed

K_S : Shaft stiffness

F_G : Damping coefficient of the generator rotor

F_M : Damping coefficient of the turbine rotor

H_G : Lumped inertia constant of the generator rotor

H_M : Lumped inertia constant of the turbine rotor

θ_s : Torsional twist

ω_0 : Electrical system speed.

C. *Aerodynamic model of the turbine rotor*

The wind turbine continuously extracts kinetic energy from the wind by decelerating the air mass and feeds it to the generator as mechanical power. Therefore, the aerodynamic model of the wind turbine represents the coupling between the wind speed and the mechanical torque produced by the wind speed. The mechanical power (P_M) produced by the wind turbine rotor is defined by [2-3]:

$$P_M = 0.5\, \rho_{air}\, V^3\, A\, C_p \quad (10)$$

$$T_m = \frac{P_m}{\omega_g} \quad (11)$$

Where:

A :swept area of the wind turbine rotor

C_P :performance coefficient of the wind turbine;

P_M :wind power available in the rotor swept area;

v :wind speed

ρ_{air} :air density

In order to avoid wind turbine damage at wind gust, the aerodynamic forces on the rotor can be controlled to limit the power captured. The aerodynamic control systems using variable-pitch blades or trailing-edge devices, are costly, complex and become even more as turbines capacity becomes larger. For wind gust conditions, the pitch control has no effect on system operation and pitch angle reaches its maximum, while the excess wind power accelerates the turbine rotor.

In this paper, wind turbines without pitch control are being used with over speed protection, which eliminates the need for ancillary aerodynamic control systems. The potential benefit of such configuration is a lower cost of energy resulting from lower capital cost, improved reliability and reduced maintenance expense [13].

The discrete gust can be used singly or in multiples to assess airplane response to large wind disturbances. The mathematical Matlab representation of the discrete gust is

$$V_{wind} = \begin{cases} 0 & x < 0 \\ \dfrac{V_m}{2}\left(1 - \cos\left(\dfrac{\pi x}{d_m}\right)\right) & 0 \le x \le d_m \\ V_m & x > d_m \end{cases}$$

Where; V_m is the gust amplitude, d_m is the gust length, x is the distance traveled, and V_{wind} is the resultant wind velocity in the body axis frame.

4. Proposed Over Speed Protection Algorithm

The proposed over speed protecting algorithm is illustrated in Figure (2) with the following sequential steps:
Based on the extensive simulation results of the studied wind farm system at different wind gust speeds and durations, the critical generator parameters are defined such as critical wind speed, current and voltage. For the studied wind farm, the critical wind speed is identified as (1.2 pu). In addition, the critical current is (1.5) pu and the voltage is not less than is (0.6 pu). The measured wind speed should be compared with the critical wind speed setting value (1.2 pu) and this comparison results in the following conditions:

- If the wind speed is less than the set value, the system is stable, and the over speed relay is blocked.
- Otherwise, if the wind speed is greater than its critical value, an unstable system state is detected due to wind gust and the proposed over speed protection should be activated to avoid the turbine damage and the over speed relay trips out the turbine.
- For emergency conditions where the wind speed signal is interrupted due to high wind gust or communication failed, both current and voltage signals are used as back up for the over speed protection algorithm.
- If the wind speed is unavailable and the current is greater than its critical value of (1.5) pu and the generator voltage is greater than (0.6 pu,) the system is unstable and the over speed proposed protection should be activated to avoid the turbine damage due to wind gust and the farm is instantaneously tripped out.
- Otherwise, if the current and voltage are less than the set values, the system is stable and the over speed relay is blocked.

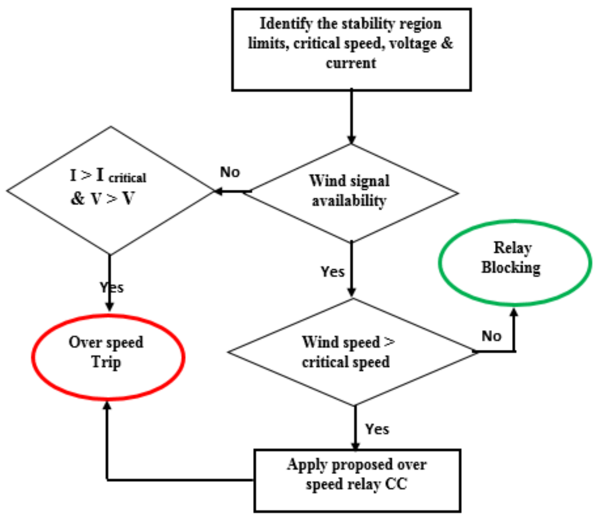

Fig. 2: Proposed over speed protection algorithm

5. Simulation Results

A. Case 1;Stable region:

In this case, the generator stability and performance are tested at different levels of sinusoidal wind gusts between one pu and the critical wind speed at the stable state of the system. Each wind gust starts at 1.6 seconds of the simulation period and with variable durations. This identify the critical stable wind speed and the corresponding critical generator current and voltage.

After extensive simulation cases, the critical wind speed to keep the studied power system in its stable state is determined equal to 1.2 pu.
Figure (3) demonstrates the wind generator response and performance at the critical wind speed for (1.2 pu). Consequently, the wind speed amplitude is sinusoidal increased from 1 to 1.2 pu and the rotor speed varies around 1.015 pu at full load.

Figure (3c) shows that the current signal suffers from small oscillations during wind change and returns to its stable value with value of 0.75 pu equal to the generator nominal current. Similarly, the voltage is slightly effected and it’s magnitude decreased to 0.88 pu during gust and returns to its final value of 1.05 pu as shown in Fig. (3d).

The test results indicate that the farm is stable during the whole simulation period for a wind gust speed less than or equal 1.2 pu which is the critical speed to keep the stability of the farm while the corresponding critical current is 1.5 pu and the voltage is decreased and reaches value of 0.88 pu.

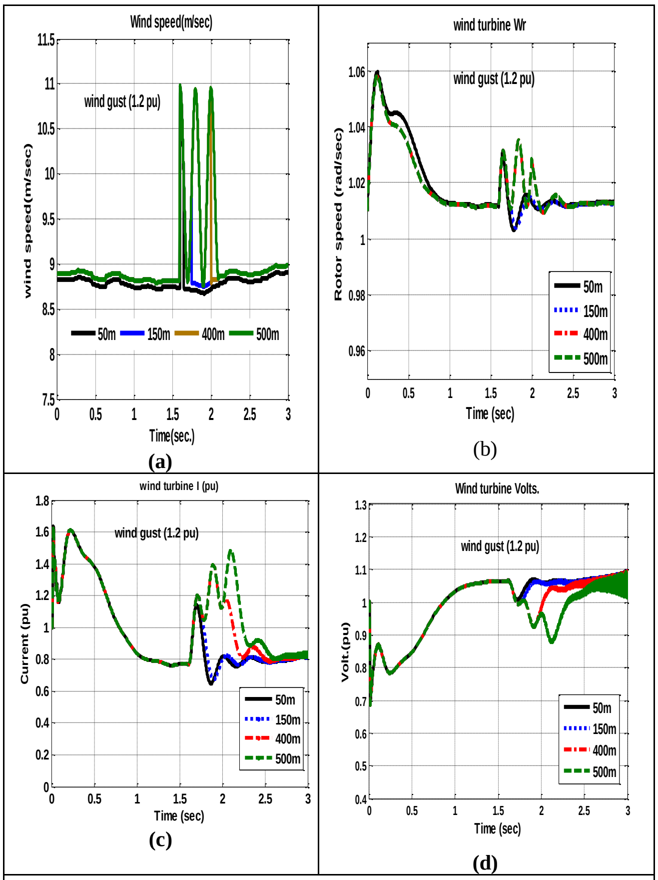

Fig.3: Simulation results for wind gust 1.2 pu a) wind speed , b) rotor speed, c) wind turbine current and d) wind feeder volt

B. Case 2: unstable region:

This section illustrates the effect of high-level wind speed gust above the critical wind speed on the wind farm performance. Similarly, the wind gust is applied at 1.6 s for different durations. In the case of a severe wind gust, the generator operates at high speed, which can affect the system stability and the turbines need to be shut down. The system will be stable only if the rotor speed does not go beyond the critical speed at which the turbine will return to its equilibrium point. In order to determine the relationship between the critical tripping out time and the wind gust, the speed has changed from 1.25 pu and 2 pu. When wind gust occurs, the turbine power is converted to kinetic energy, and the generator rotor accelerates. Consequently, the more wind speed is, the less stable is the wind turbine.
Figure (4) demonstrates the effect of 1.5 pu wind speed gust with different durations on the system response. The corresponding variation of the wind speed is displayed in Fig. (4a). The rotor speed of the generator at a wind speed gust of 1.5 pu is given in Fig. (4b). It is clearly shown from this figure that the rotor speed of the generators are firstly increasing to 1.06 pu due to the gust. Secondly, the rotor speed returns to its stable value depending on the duration of the wind gust. That means the farm is stable as long as the wind gust duration is less or equal 200 ms. On the other side, the corresponding generator currents are represented in Fig. (4c), which shows that its values are increased between 1.65 to 2.0 at different wind gust duration and back to its nominal value if this duration is less than the CCT of 200 ms ; that means the system returns to its stable state. The voltage magnitude at the point of common coupling (PCC) is also constant at 1.05 pu except for a maximum drop to 0.75 pu during the unstable system state for wind gust with 210 ms duration. The drop in voltage magnitude can be attributed to the reactive power absorption by the induction generator for compensation as illustrated at in Fig (4d).

Similarly, the system under wind gust speed of 1.9 pu is simulated. The corresponding simulation results are shown in Fig. (5). These results indicate that, the CCT is 120 ms, the currents is 2 pu, while the voltage decreased to the value of 0.60.

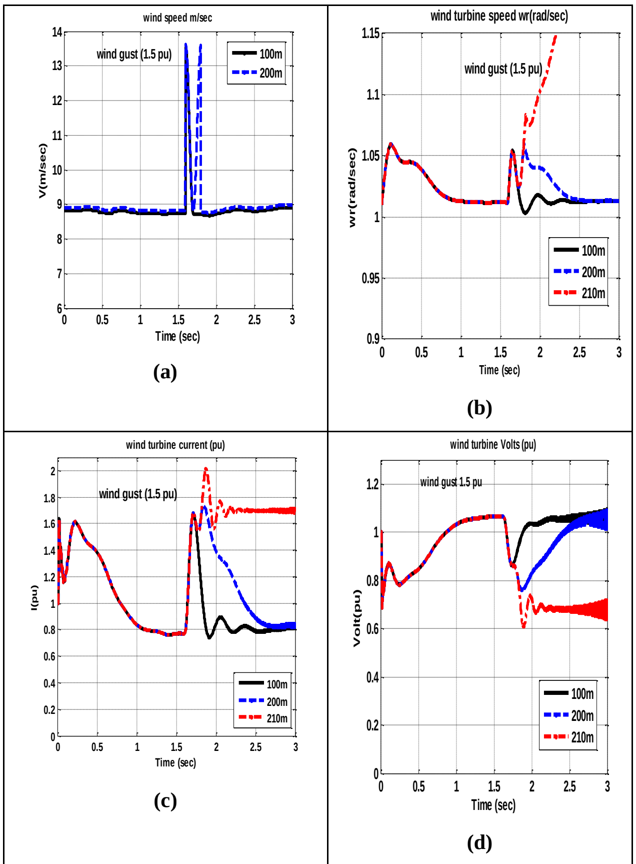

Fig.4: Simulation results for wind gust of 1.5 pu a) wind speed , b) rotor speed, c) wind turbine current and e) wind feeder volt .

Table (1) summarizes the obtained results for different wind gust indicating the critical clearing time that ensures system stability. In addition, the corresponding mechanical power, maximum normalized current of the farm and the voltage magnitude are also displayed.

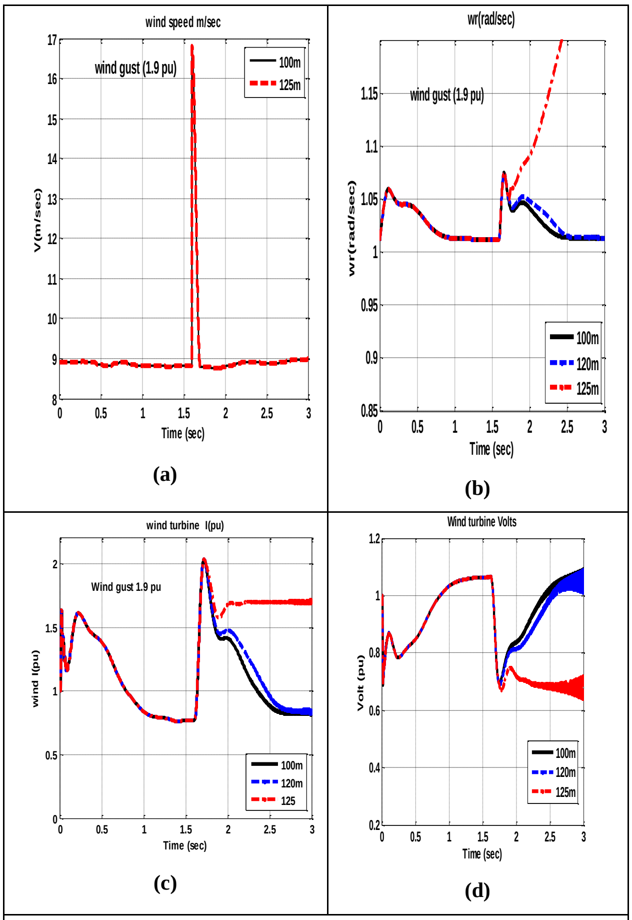

Fig.5: Simulation results for wind gust of 1.9 pu a) wind speed, b) rotor speed, c) wind turbine current and d) wind feeder volt.

Table (1) Summary of the system parameters under different wind gust

SPEED (PU)	*P_{MECH}(PU)*	*I (PU)*	*V(PU)*	*CCT (MSEC.)*
1.2	2	1.5	0.88	NA
1.4	2.73	1.58	0.80	300
1.5	2.86	1.65	0.75	200
1.6	3	1.75	0.72	180
1.9	3.4	2	0.63	120
2	3.6	2.5	0.60	Instantons

Figure (6) demonstrates the concluded results of Table 1 at different wind gust speed including the variation of the mechanical power, generator current, voltage and the CCT. Figure (6a) presents the increase in mechanical power during stepping up the wind speed as the aerodynamic power during wind gust affects directly the mechanical power of the turbine. Fig. (6b) shows the increase in generator current, which is always more than 1.5 pu (critical stable current). On the other side, the corresponding voltage magnitude is decreased to a minimum value of 0.6 pu as shown in Fig. (6c). From the displayed results, the over speed protection is necessary to avoid any mechanical damage of the farm at high levels of wind gust. The CCT of the over speed protection is displayed in Fig. (6d).

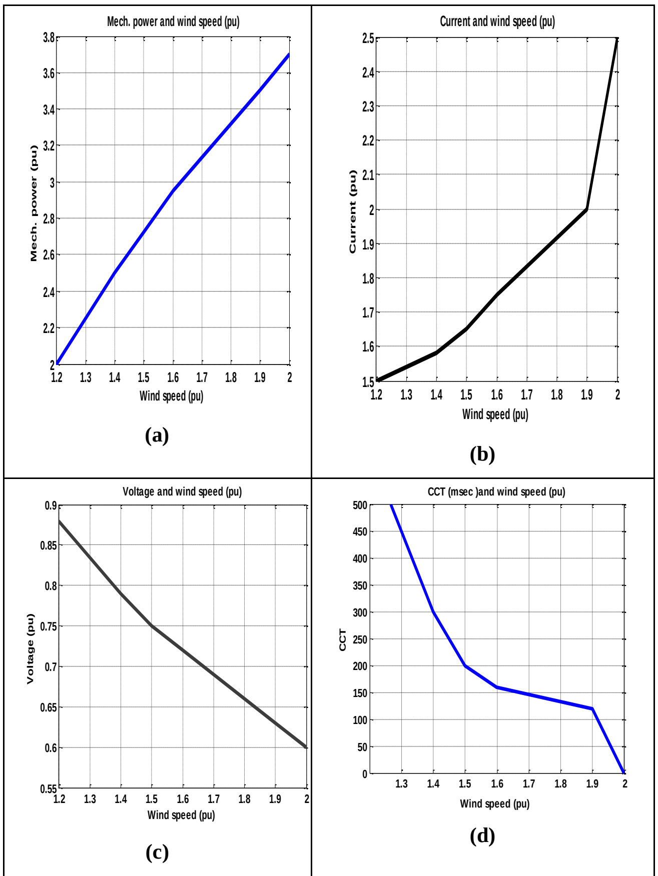

Fig.6: Proposed over speed protection relay settings a) Mechanical power, b) Current, c) Voltage and d) clearing time.

6. Conclusions

This paper has presented modeling and simulation of a wind farm connected to the public grid. The models for different studied power system components are developed using Matlab/Simulink to study the wind turbines voltage, current and power at PCC as well as the rotor speed during different wind gust conditions. Different study cases were considered to examine the effect of wind gust level and duration on the system performance and stability. The proposed protection algorithm depends mainly on the availability of wind speed signal. The current and voltage signals are required as backup signals in case that the wind speed signal is interrupted during high wind gust or loss of communication. The effect of wind gust on the CCT was studied to ensure stable and secure operation of the wind farm generators. The simulation results indicated that the rotor speed approximately fluctuating around a value of 1.05 pu in the stable region with the maximum limit wind speed of 1.2pu. In addition, above 1.2 pu, wind speed, the CCT is inversely proportional to the wind speed magnitudes.

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