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Effect of Rotor Current Control for Wound Rotor Induction Generator on the Wind Turbine Performance

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ABSTRACT

The developed torque of the wind turbine fluctuates with the change of wind speed which provides more fatigue on the turbine blades and overloads on the electric machine. This paper presents the effect of rotor current control of wound rotor induction generator driven by wind turbine during different operation modes when varying the rotor resistance. The rotor current is measured and controlled to provide constant torque from the turbine on the machine. The studied modes are wind speed variations, starting especially at high wind speed. Moreover, the effect of the proposed control on short circuit and critical fault clearing time is investigated. This technique will reliefs pitch regulator duties, will provide soft starting of the machine and reduces torque and power fluctuations.

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1. INTRODUCTION

Wind energy became one of the most important renewable energy resources, it has a great share in total power generation all over the world and its environmental is friendly. There are many types of wind turbines mainly as follow:

a) Fixed speed wind turbine stalls effect
b) Fixed speed wind turbine pitch regulation
c) Variable speed pitch regulation (Optimal Pitch-Optimal Slip)
d) Doubly Fed Induction Generator (DFIG)
e) Direct Drive Synchronous Generator

The optimal pitch optimal slip is one of the most attractive aspects economically and technically, therefore, it has been studied from different points of view in the last few years. Several studies have been proposed in the literature and might be suitable for particular applications. A brief description of the widely known studies is given as follows:

- The proposed study in [1] which is based on modeling the different control techniques of variable speed induction generators during small disturbances such as wind speed variation. The output response from constant torque, constant equivalent circuit was compared against constant rotor current control techniques. Furthermore, the results have been verified by hardware implementation for the constant equivalent circuit method.
- The method presented in [2] which account for the different linearization methods for the wound rotor induction machine in the form of fifth, third and second order transfer function. Such methods enable to design the suitable rotor current controller and compare it against proportional, proportional plus integral

and double integral controllers response without considering large wind speed variation especially in case of wind gust. Moreover, the pitch controller has been ignored with providing complicated calculations of control parameters such as the cut off frequency of the filter.

- The comparative study presented in [3] between stall effect squirrel cage induction generator and optimal slip rotor current control wound rotor induction generator. The study was carried out under wind gust operation and during short circuit conditions. The results did not indicate the effects of the stability such as the critical fault clearing time improvement and the optimal value of the added rotor resistance estimation method.
- The model discussed in [4] for all wind power generation system components including mechanical wind turbines, electrical generators, transformers, transmission lines, cables and electrical grid. Such models are employed for the comparison between optimal slip optimal pitch and double feed induction generator wind turbines in different operation conditions. This method did not give any indication about the control system sampling frequency determination and the optimal added rotor resistance value estimation method.

This paper presents a comparative study between squirrel cage pitch controlled and variable speed slip and pitch control wind turbines under the following conditions :

- Wind speed variation.
- Very sharp wind gust from blow to above rated speed.
- Three phase grounded short circuit on generator terminals.

This has been done with estimating the optimal added rotor resistance, controller parameters and critical fault clearing time in each case in order to study the improvements of rotor current control modules. This technique is used actual in a wind farm in Egypt is Called ZAFARANA Site which has squirrel cage and wound rotor induction machine. In this study the external rotor resistance is used as a soft starter as a new technique.

2. SYSTEM MODELING

The components of wind power generation system to be modeled comprise the wind turbine, gear box, induction generator, transformer, cables, and grid. The system modeling procedure is divided into three sections as follow:

2.1 Wind turbine with pitch regulator model:

The wind turbine is the system which converts the wind available energy into mechanical energy, therefore the equations used to model wind turbine are related directly to air flow equations as follow:

$$P = 0.5\,\rho\,A\,V^3 Cp(\lambda,\beta) \quad (1)$$

$$\lambda = r * \omega / V \quad (2)$$

$$Cp(\lambda,\beta) = C1\left(\frac{C2}{\lambda i} - C3\beta - C4\right)e^{-\frac{C5}{\lambda i}} + C6\lambda \quad (3)$$

$$\lambda i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1} \quad (4)$$

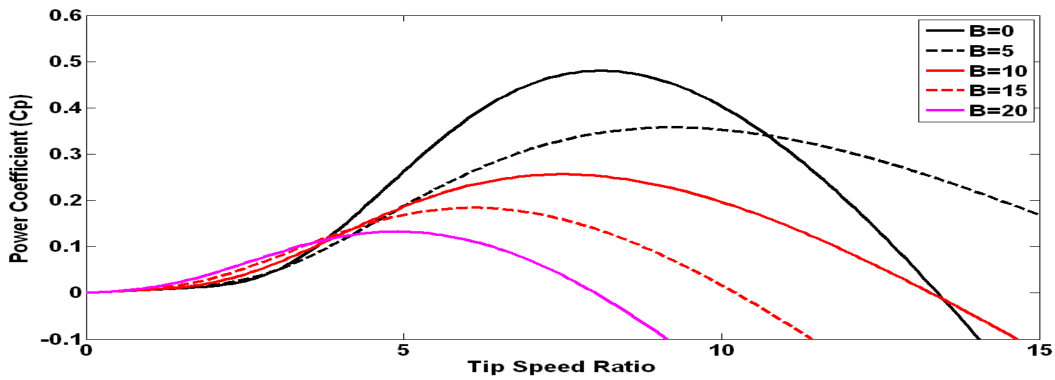


Figure 1. Wind Turbine Characteristics

Plotting Eqn. (3) gives the relationship between the power coefficient and tip speed ratio of wind turbine at different pitch angles as displayed in Fig. (1). Therefore, each turbine must have pitch controller or pitch regulator representing the main component in the turbine mechanical system to be used to vary the blade pitch angle at high wind speed in order to provide constant rated output from wind turbine and avoid overloading of electrical and mechanical parts.

The actual pitch regulator consists of some parts such as position sensor, controller and actuator. The proposed model in this study is simplified as a PI controller as shown in Fig. (2) Where the values of K_p and K_i constants of the controller are calculated as in [5]. Eqns. (1) – (4) are modeled in MATLAB/ SIMULINK power tool library with parameters given in [7].

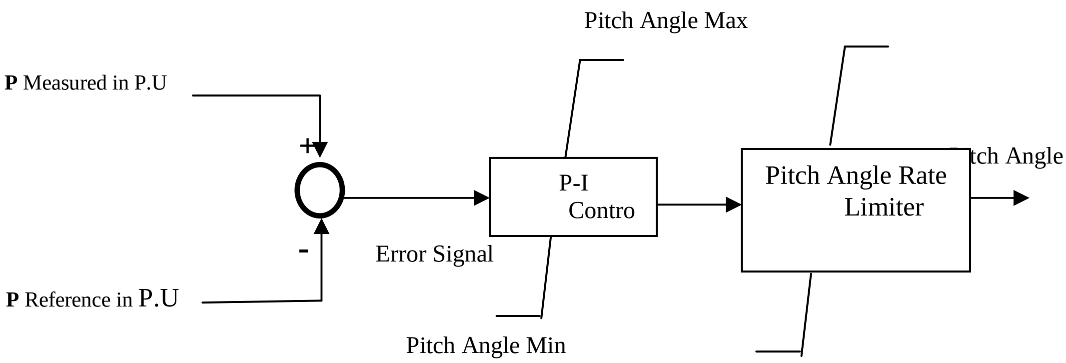


Figure 2. Pitch Angle Controller

2.2. Induction generator model:

The induction generator is modeled using park's equations transformed into the d-q axis as follow:

$$V_{qs} = R_s\, i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega\, \varphi_{ds} \tag{5}$$
$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega\, \varphi_{qs} \tag{6}$$
$$V'_{qr} = R'_r\, i'_{qr} + \frac{d}{dt}\varphi'_{qr} + (\omega - \omega_r)\varphi'_{dr} \tag{7}$$
$$V'_{dr} = R'_r\, i'_{dr} + \frac{d}{dt}\varphi'_{dr} - (\omega - \omega_r)\, \varphi'_{qr} \tag{8}$$
$$T_e = 1.5\, p\, \left(\varphi_{ds}\, i_{qs} - \varphi_{qs}\, i_{ds} \right) \tag{9}$$
$$\varphi_{qs} = L_s\, i_{qs} + L_m\, i'_{qr} \tag{10}$$
$$\varphi_{ds} = L_s\, i_{ds} + L_m\, i'_{dr} \tag{11}$$
$$\varphi'_{qr} = L'_r\, i'_{qr} + L_m i_{qs} \tag{12}$$
$$\varphi'_{dr} = L'_r id'_{dr} + L_m\, i_{ds} \tag{13}$$
$$L_s = L_{ls} + L_m \tag{14}$$
$$\mathrm{L}'_\mathrm{r} = \mathrm{L}'_\mathrm{lr} + \mathrm{L}_\mathrm{m} \tag{15}$$

The mechanical motion for generator and wind turbine tied by gear box is described as follow:

$$\frac{d}{dt}\omega_m = \frac{1}{2H}\left(T_e - F\omega_m - T'_m\right) \tag{16}$$
$$\frac{d}{dt}\theta_m = \omega_m \tag{17}$$

The steady state equation of induction machine is as shown in equation. (18).

$$T_{em} = \frac{3\, V_{th}^2 (\frac{r'_r}{s})}{\omega_s [\left(r_{th} + \frac{r'_r}{s}\right)^2 + \left(X_{th} + X'_{lr}\right)^2]} \tag{18}$$

The characteristic of the induction machine will be changed by varying its rotor resistance as shown in figure. (3). The above Eqns. are modeled in MATLAB/SIMULINK library while the other electrical components in the system such as transformers, cables and grid are used directly from SIMULINK power tool library with parameters given in the appendix [6].

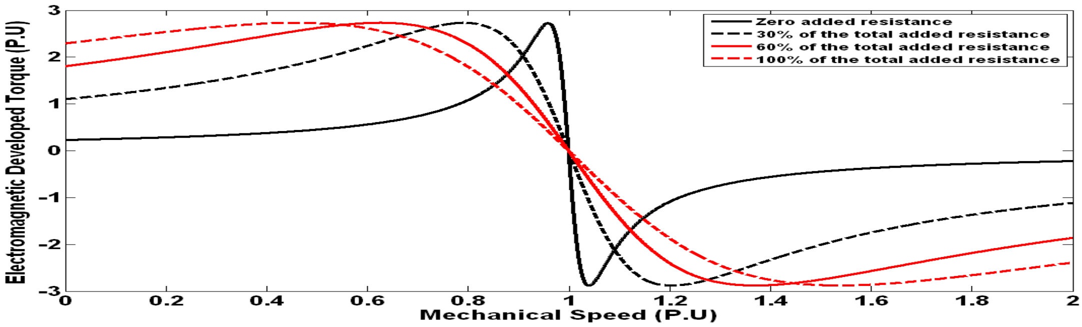


Figure 3. Induction Machine Torque-Speed Characteristics

2.3. Rotor current control module model:

The module consists of three phase star connected resistances which are parallel-connected with a power electronics switch to the induction generator rotor windings. By varying the duty ratio of the switch, the added rotor resistance will be varied to provide constant rotor current, therefore, it must have at least two current sensing elements as displayed in Fig. (4). This technique is used in actual wind turbine of VESTAS company (V47-660).

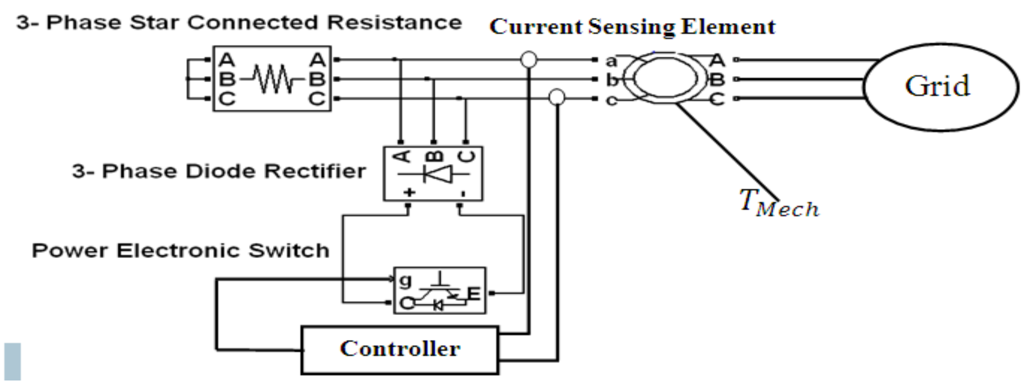


Figure 4. Induction Generator with RCC

The value of the added resistance is estimated by the torque speed characteristic of induction machine of equation. (18) to provide nominal torque at slip value 10% or speed of 1.1 of synchronous speed. While by varying the rotor resistance, the generator speed can be changed up to 110% of synchronous speed with minimum converter losses. This module with its resistance, power electronic circuit and controller can be located on the machine shaft without any slip rings in the machine. So this technique is simple, economic and need less maintenance over than other techniques which use stator power in control. The module has a PI controller as shown in Fig. (5) Which is employed to vary switch duty ratio when the rotor current deviates away from the reference value. The values of the controller parameters are tuned using Ziegler and Nichols method [1].

This method can be modified by modern optimization methods like genetic or swarm. Also the scheme of the controller can be modified to a Fuzzy control. The duty of the module and its effect on the system performance will be discussed below.

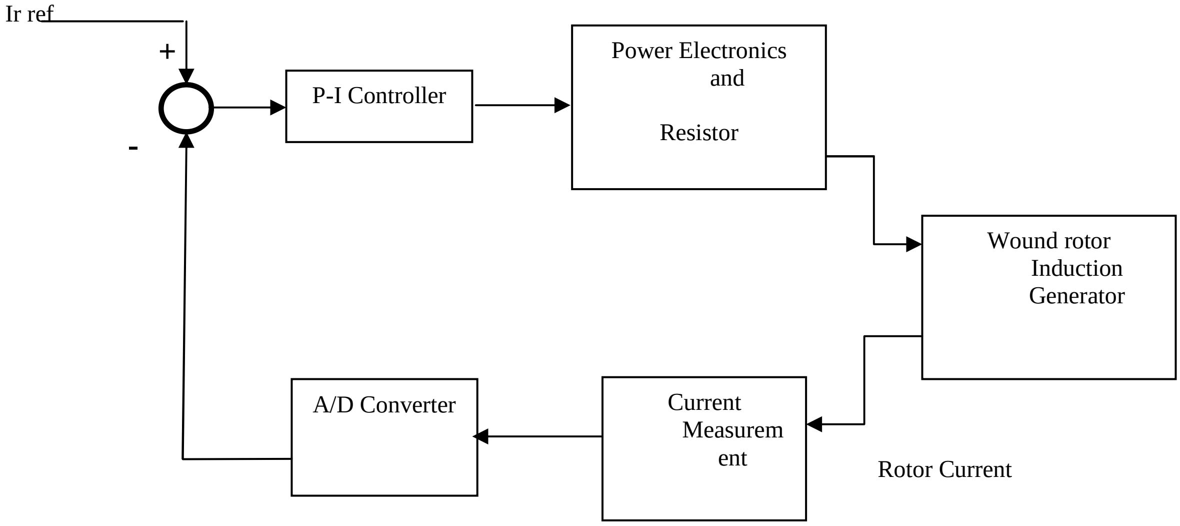


Figure 5. Rotor Current Controller

3. RESULTS AND ANALYSIS

This section presents the investigation of the effect of optimal slip or rotor current control on the wind turbine performance. This is done by comparing the performance of a wind turbine with squirrel cage induction generator pitch regulated against the rotor current control of a wound rotor induction generator. The waveforms of wind speed variation in the studied cases are recommended in many references [9]. The considered study conditions are as follows:

3.1. High wind speed starting

In case of high wind speed starting of wind turbine without added rotor resistance, the power in-rushed and decayed to zero. This phenomenon can be clarified by single phase steady state equivalent circuit displayed in Fig. (6). When starting with high wind speed the generator accelerates increasing both rotational speed and slip. In addition, the variable resistance (R_2/s) will be too small nearly causing short circuit on the magnetizing inductance (Xm) which leads to decaying the magnetizing current and the developed electric torque will decay while the mechanical input torque is constant causing more and more acceleration due to equation (16). For that the machine will be out of step and must be isolated from the grid.

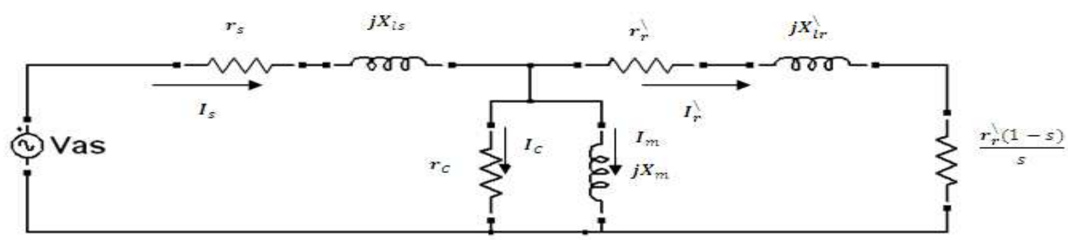
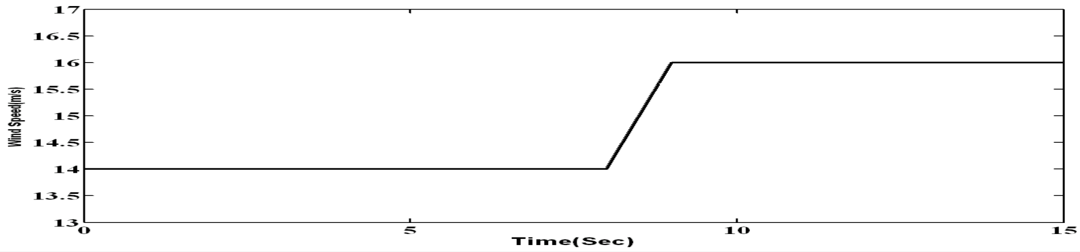
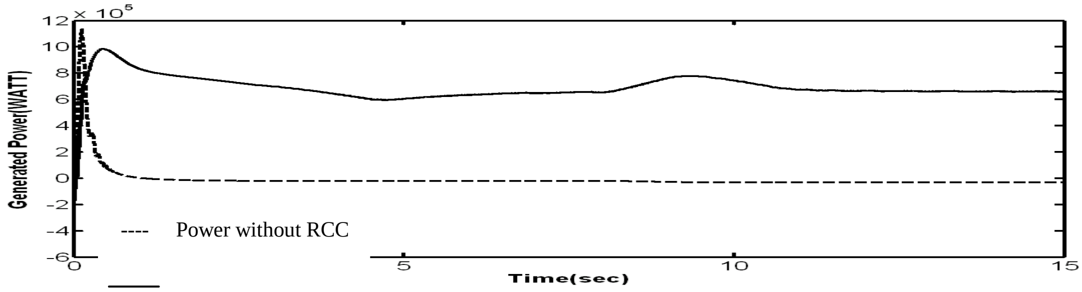


Figure 6. Induction Generator Single phase Equivalent Circuit

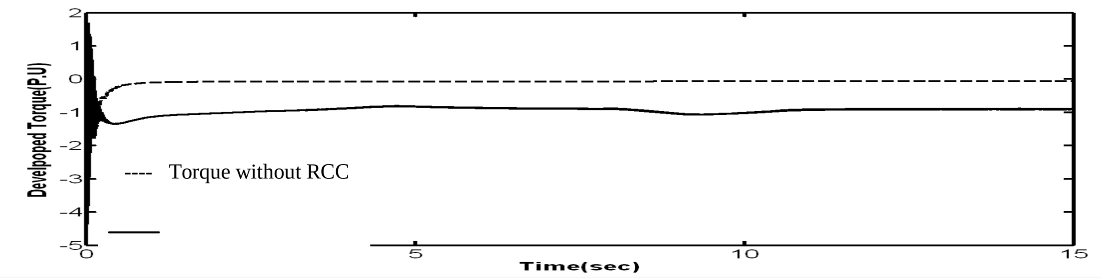
Therefore, by adding a rotor resistance will damp the system keeping the generator rotational speed within the range and allowing the magnetic field building up [3] as shown in Figs. (7.a), (7.b), (7.c), (7.d) and (7.5). Furthermore, at wind speed variation instant at time of 9 sec the developed torque of Fig. (7.c) will be nearly constant which displays that the main function of the rotor current control module is to reduce the torque and power fluctuations during the wind speed variation.



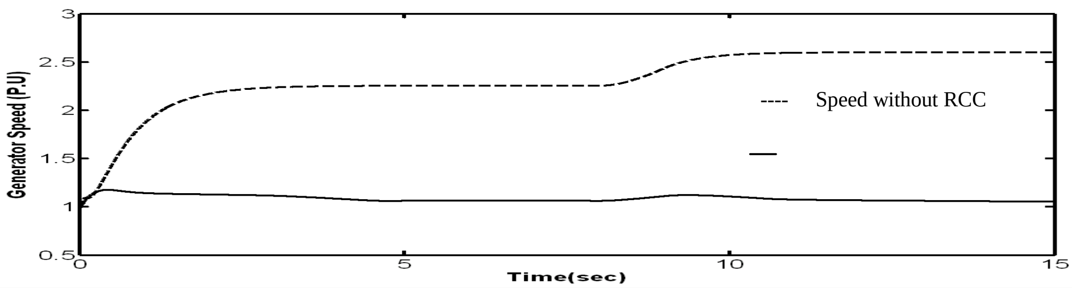
a. Wind Speed Variation



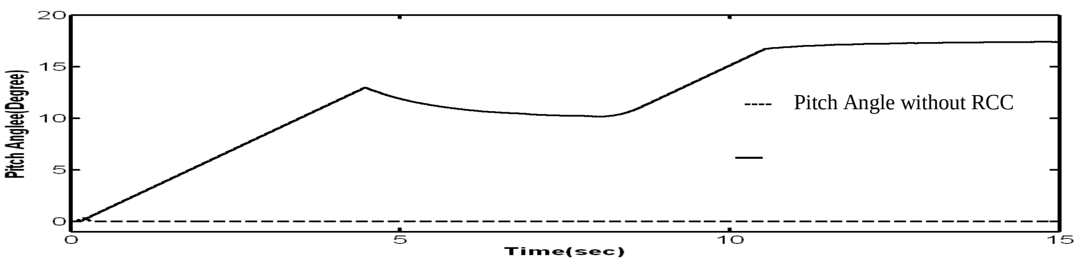
b. Generated Powers (WATT)



c. Electro Magnetic Torque in P.U



d. Generator Speed in P.U

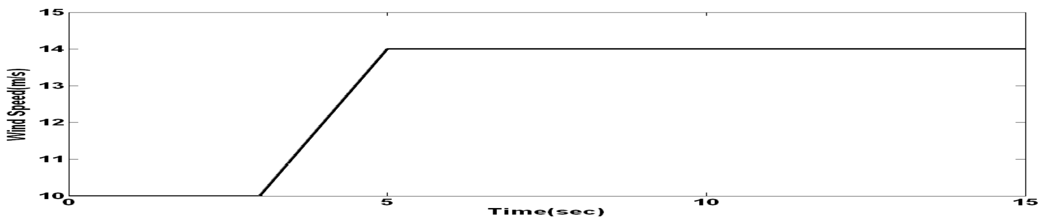


e. Pitch Angle in Degree

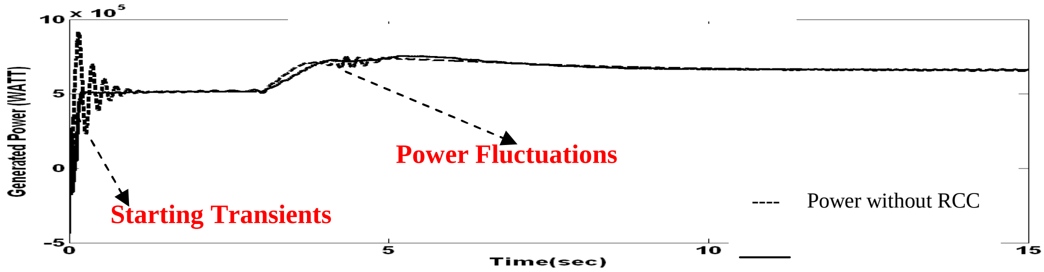
Figure 7. generator rotational speed within the range and allowing the magnetic field building up

3.2. Sharp wind gust

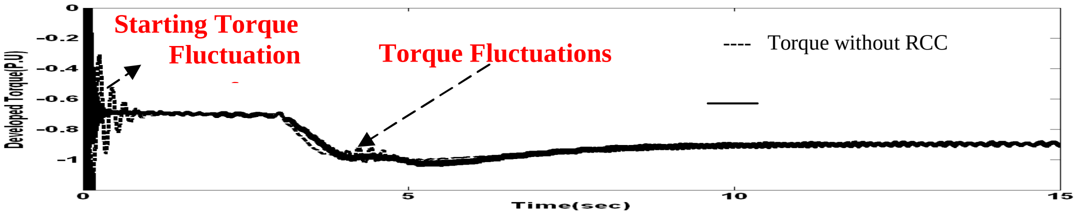
Figures (8.a), (8.b) and (8.c) displays clearly that adding rotor resistance and rotor current controller reduces the power and torque flicker where such flickers provide more stress and fatigue on wind turbine blades and more power distortions on electric power network which is refused by the grid utility.



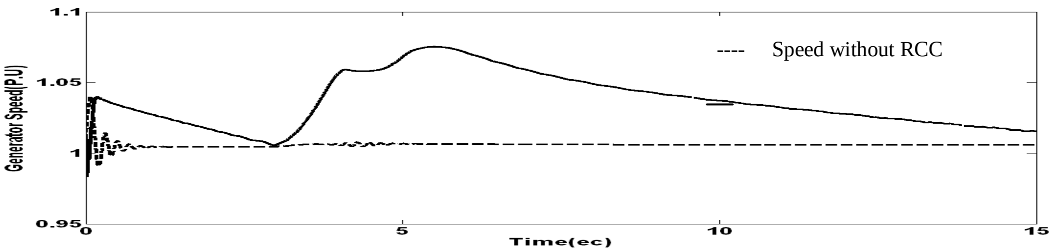
a. Sharp Wind Gust Simulation



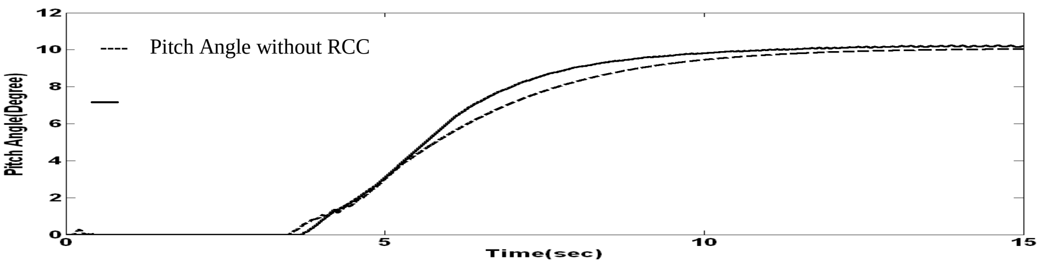
b. Generated Powers (WATT)



c. Electro Magnetic Torque in P.U



d. Generator Speed in P.U



e. Pitch Angle in Degree

Figure 8. Effect of adding rotor resistance and rotor current controller reduces the power and torque flicker

Also, the rotor current control (RCC) system takes nearly 7 sec to be stable while the squirrel cage takes nearly 5 sec to achieve the rotor resistance performance as a damping system to reduce the over shoot of the system. At the instant of starting with RCC the torque reaches the steady state value without any over shoots or fluctuations just as the squirrel cage system which reduces the soft starting module duties.

3.3. Three Phase to ground generator terminals fault

The critical fault clearing time of the studied squirrel cage wind power generation system was estimated to be 0.16 sec as illustrated in Fig (9). So, in case of applying three phases grounded short circuit at the generator terminals at instant of 11 sec for period of 0.16 sec .the power continued to zero after fault clearing while the RCC system improved the transient stability of the system and reduced the protection system duties.

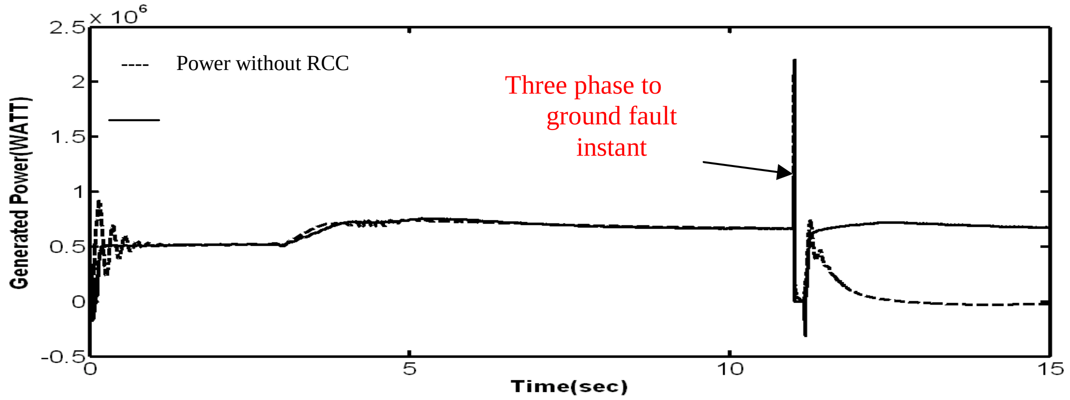


Figure 9. Generated Powers in WATT

4. CONCLUSION

From the proposed case studies in this paper, one can say that the rotor current control or the rotor resistance control system for low power wind turbines is very economical and simple control technique. It improves the transient response of the system during starting; reduce the torque and the power flickers during wind gusts and variations which provide long life time of wind turbine. It also reduces the short circuit current with increasing the critical clearing fault time which means lowest braking capacity with long clearing time for protection systems.

Appendix

- Wind turbine
- Rotor diameter = 47 m, Air Density = 1.225 Kg/m3, Inertia=22000 Kg/m2, Rated Power = 660 KW, Base wind speed = 10 m/s, Rated wind speed = 13 m/s
- Electric Generator Power = 660 KW, P.F= 0.91, Line Voltage= 690 V, Rs= 0.0064 P.U, Xs=0.0049 P.U, Rr =0.006 P.U, Xr=0.0589 P.U, Xm= 2.88 P.U, Jg= 29 Kg/m2, H=0.5 s.
- Pitch Controller Kp=5, Ki=25, Max Pitch angle= 45 degree, Min Pitch Angle= 0 degree, Pitch Angle Rate= 3 degree/s
- Rotor Current Controller External resistance (in Model) = 0.06932 ohm, Switching Frequency = 3 KHZ, Kp=0.003, Ki= 0.001, Maxi slip =10 %, Min slip = 1%,
- Compensating Capacitor (690 V, 250 KVAR)
- Turbine Transformer (0.69/20 KV, 800 KVA, X=4%)
- Grid Transformer (20/132KV, 30 MVA, X=12 %)
- Grid (132 KV, Ssc= 450 MV)

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