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Analysis of Transient Voltage Stability of a Variable Speed Wind Turbine with Doubly Fed Induction Generator Affected by Different Electrical Parameters of Induction Generator

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Abstract: This study depicted the effect of electrical parameters of the induction generator on the transient voltage stability of a variable speed wind turbine. The dynamic behavior of a variable speed wind turbine connected to a simple network is tested and evaluated. The model of the variable speed wind turbine with doubly fed induction generator which has been developed as a compact block in the simulation tool MATLAB/SIMULINK, is used in this study for studding the dynamic behavior of the wind turbine. The simulation includes the induction generator, the aerodynamic model of the wind turbine rotor, the model of the convertor and the pitch control system. Using this model, a three phase fault is applied at the terminal of the wind turbine. The effect of the induction generator on the voltage stability of this simple case is evaluated and discussed. The considered parameters are the rotor resistance, the stator resistance, the leakage stator and rotor inductances and the mutual inductance. For each parameter, the terminal voltage, the generator rotor speed and the DC voltage of the converter are drawn. The results will be helpful to illustrate the transient stability phenomena in wind farms.

Key words: Wind energy, wind turbine, Doubly Fed Induction Generator (DFIG), induction generator parameter

INTRODUCTION

The worldwide concern about environmental pollution and the possible energy shortage has led to increasing interest in generation of renewable electrical energy. Wind energy generation is one way of electrical generation from renewable sources that uses wind turbine generators to convert the energy contained in flowing wind into electrical energy. Many different types of wind turbines exist in the electricity networks all over the world specially the variable speed types (Melício and Mendes, 2004; Sandra *et al.*, 2008; Dusonchet *et al.*, 2008; Yi and Ula, 2008; Slootweg *et al.*, 2002). Although, fixed speed wind turbines are cheaper and simpler than the variable speed wind turbines (Dusonchet *et al.*, 2008) but the ability of adaption the rotor speed to the actual wind speed in order to maximize energy production causes increasing interest in variable speed wind turbines specially in Doubly Fed Induction Generator Wind Turbine (DFIGWT). In recent years (Melício and Mendes, 2004). As a result of this, in the next future, these kinds of wind turbines may start to

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influence the behavior of electric power systems by interacting with conventional generation and loads. Voltage stability is one of the important subjects in power system stability studies (Kundur, 1994; Petru and Thiringer, 2002; Slootweg *et al*., 2001) and many trials have been made in this field to make the power system less sensitive to different electrical parameters in order to keep the power system stable after different faults occurred (Kundur, 1994; Heier, 1998; Dusonchet *et al*., 2008; Slootweg *et al*., 2002). In order to investigate the impact of wind turbine on power system dynamics, adequate simulation models are essential. This study describes the effect of electrical parameters of the induction generator on the transient voltage stability of a variable speed Wind Turbine with Doubly Fed Induction Generator (WTDFIG) connected to a simple grid. The model of WTDFIG has been implemented in the simulation tool MATLAB/SIMULINK. The simulation includes the induction generator, the shaft system, the aerodynamic model of the wind turbine rotor, the model of convertor system and the pitch control system.

MATERIALS AND METHODS

The study was conducted from March, 2009 to November, 2009.

Wind Turbine Model

The WTDFIG model is base on the following:

The induction generator is represented by the following Eq. 1 (Kundur, 1994):

$$\begin{aligned}
d\lambda_{ds}/dt &= V_{ds} - R_s i_{ds} + \omega\lambda_{qs} \\
d\lambda_{qs}/dt &= V_{qs} - R_s i_{qs} - \omega\lambda_{ds} \\
d\lambda_{dr}/dt &= V_{dr} - R_r i_{dr} + s\omega\lambda_{qr} \\
d\lambda_{qr}/dt &= V_{qr} - R_r i_{qr} - s\omega\lambda_{dr}
\end{aligned} \tag{1}$$

The stator electric values are indicated by the subscript s and the rotor electric values are indicated by the subscript r. v is a voltage, R is a resistance, I is a current, λ is a flux linkage. ω is the stator electrical frequency and s is the rotor slip. The flux linkages are given by Eq. 2 (Kundur, 1994):

$$\begin{aligned}
\lambda_{ds} &= L_s i_{ds} + M i_{dr} \\
\lambda_{qs} &= L_s i_{qs} + M i_{qr} \\
\lambda_{dr} &= L_r i_{dr} + M i_{ds} \\
\lambda_{qr} &= L_r i_{qr} + M i_{qs}
\end{aligned} \tag{2}$$

L_s, L_r and M are, respectively the stator and the rotor leakage inductance and the mutual inductance between the stator and rotor. The mutual inductance is shown by L_m in the rest of the study. The stator and rotor active power (Kundur, 1994; Melício and Mendes, 2004) are given by Eq. 3:

$$\begin{aligned}
P_s &= \frac{3}{2}\left(V_{ds} i_{ds} + V_{qs} i_{qs}\right) \\
P_r &= \frac{3}{2}\left(V_{dr} i_{dr} + V_{qr} i_{qr}\right)
\end{aligned} \tag{3}$$

The mechanical torque and the electrical torque are computed as follows Eq. 4 (Kundur, 1994; Melício and Mendes, 2004):

$$\begin{aligned} P_m &= T_m \omega_r \\ P_s &= T_{em} \omega_s \end{aligned} \tag{4}$$

The shaft system can be represented with lumped-mass system or the two-mass shaft model, in order to show the electromechanical interactions in the voltage stability (Akhmatov, 2003a). The electromechanical interactions are expressed by oscillations of the voltage, the generator current, the generator rotor speed and electromechanical parameters of the WTDFIG. The model equation of lumped-mass system in p.u. system is Eq. 5 (Dusonchet *et al*., 2008):

$$J\frac{d\omega_r}{dt} = T_m - T_{em} \tag{5}$$

The mechanical power of the turbine can be defined as Eq. 6 (Akhmatov, 2003b; Slootweg *et al*., 2002):

$$P_m = \frac{1}{8}\rho\pi D^2 v^3 c_p(\beta, \lambda_i) \tag{6}$$

where, ρ is the air density, D is the diameter of the area covered by the movement of the blades, v is the wind speed, c_p is the power coefficient (Akhmatov, 2003b; Slootweg *et al*., 2002) $c_p(\beta,\lambda_i)$ is given by Eq. 7:

$$c_p(\beta, \lambda_i) = 0.73\left(\frac{151}{\lambda_i} - 0.002\beta - 13.2\right)e^{\frac{-18.4}{\lambda_i}} \tag{7}$$

Where:

$$\lambda_i = \frac{1}{\dfrac{1}{(\lambda + 0.08\beta)} - \dfrac{0.035}{(\beta^3 + 1)}} \tag{8}$$

And:

$$\lambda = \frac{1}{2}\frac{D\omega_r}{v} \tag{9}$$

λ is the tip speed ratio, β is the pitch angle of rotor blades in degrees.

The wind turbine and the doubly fed induction generator are shown briefly in Fig. 1.

The relation between c_p and λ is normally established by the c_p/λ curve. The c_p/λ characteristics, for different values of the pitch angle, are shown in Fig. 2.

To connect a variable speed wind turbine to the grid, always a power electronic converter is necessary. This causes extra investment and additional losses (Mutschler and Hoffmann, 2002). On the other hand, with converter-fed variable speed wind turbine, adaption of the rotor speed to the actual wind speed in order to maximize energy production would be possible (Mutschler and Hoffmann, 2002).

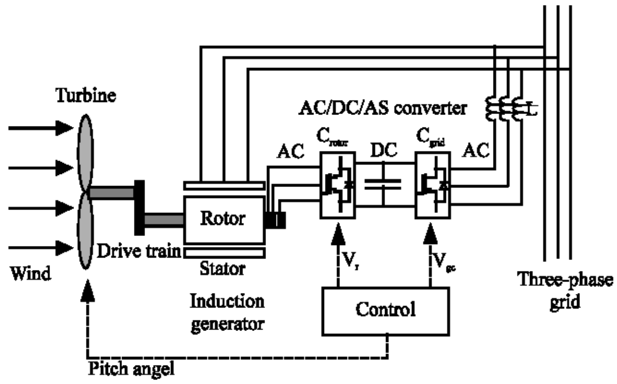

Fig. 1: Schematic of doubly fed induction generator wind turbine

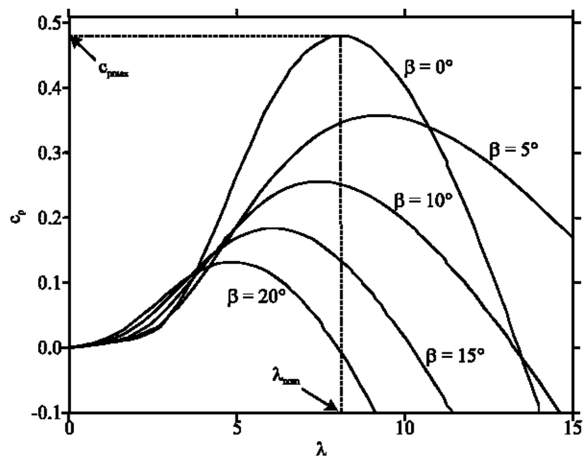

Fig. 2: Performance coefficient versus tip speed ratio characteristics, for different values of the pitch angle

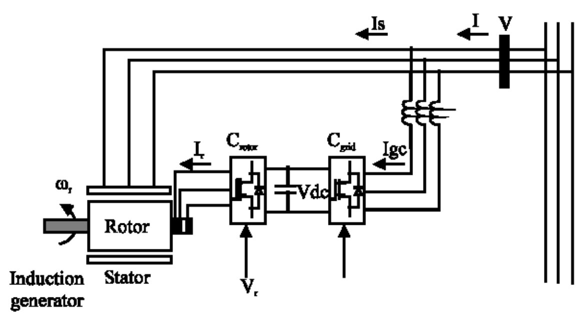

Fig. 3: Schematic of generic control loop

The voltage or the reactive power at grid terminals is controlled by the reactive current flowing in the converter of the generator side as shown in Fig. 3.

The converter of the grid side is used to regulate the voltage of the DC bus capacitor as shown in Fig. 3. In addition, this model allows using the grid side converter to generate or absorb reactive power.

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Point D shows the maximum speed that the wind turbine could work in. WTDFIG could work form 0.7 p.u. till 1.2 p.u. of the nominal speed of the induction generator. Point D is equal to 1.2 p.u. of the nominal speed of the generator. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. For those speeds which are above point D the pitch angle would be set at the maximum degree and for those beyond point D, it would be set at 0 degree as shown in Fig. 4.

The blade-angle is between the minimal value, β_{min} = 0 degree and the maximal pitch value, β_{max} = 24 degree.

The induction generator is connected to a low voltage stiff grid through a transformer and line impedance, Z.

Using the described model above, a three-phase fault is applied close to the wind turbine and would be cleared automatically by fixing the transition times in the related block. The effect different electrical parameters of the induction generator on the voltage stability of this simple case is evaluated and discussed. The considered parameters are the stator and rotor resistance, the leakage stator and rotor inductance and the mutual inductance. For each parameter, the terminal voltage and the generator rotor speed are drawn.

Case Study

The parameters of the WTDFIG, the transformer and the electric line are listed in Table 1-3.

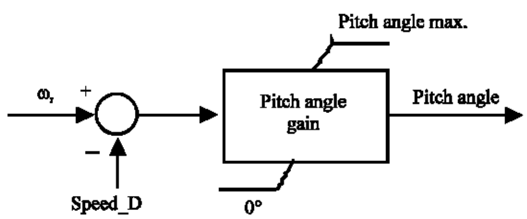

Fig. 4: The pitch angle controller block

Table 1: Generator specifications

Generator specifications	Values
Rated power (MW)	9
Rated voltage (KV)	575
Resistance of the rotor = R_r (p.u.)	0.18
Inductance of the rotor = L_r (p.u.)	0.12
Resistance of the stator = R_s (p.u.)	0.048
Inductance of the stator = L_s (p.u.)	0.076
Mutual inductance = L_m (p.u.)	3.8
No. of pairs of poles	3

Table 2: Grid specifications

Grid specifications	Values
Resistance of the winding 1 of the transformer = Rt_1 (p.u.)	0.025/30
Inductance of the transformer = Lt_1 (p.u.)	0.025
Resistance of the winding 2 of the transformer =Rt_2 (p.u.)	0.025/30
Inductance of the winding 2 of the transformer = Lt_2,(p.u.)	0.025
Magnetization resistance = R_m (p.u.)	500
Magnetization reactance = L_m (p.u.)	inf
Rated power of the transformer, (MVA)	2
Resistance of the line 1 = R_{L1}(ohm km^{-1})	0.1153
Inductance of the line 1 = L_{L1}(H km^{-1})	1.05e-3
Capacitance of the line 1 = C_{L1}(F km^{-1})	11.33e-9

Table 3: Wind turbine specifications

Wind turbine specifications	Values
Rated wind speed = v (m sec^{-1})	12
Blade angle range (degree)	0-45
Maximum rate of change of pitch angle (deg sec^{-1})	2
Nominal mechanical output power (MW)	1.5

RESULTS AND DISCUSSION

Stator Resistance

The effect of different values of stator resistance is shown in Fig. 5a-c. The model is tested for different values of resistance (Rs_1, Rs_2, Rs_3) and the following results are obtained for a fault clearing time 0.2 sec. The considered stator resistance values are:

- $Rs_1 = R_s/2 = 0.024$ p.u.
- $Rs_2 = R_s = 0.048$ p.u.
- $Rs_3 = 2R_s = 0.096$ p.u.

where, R_s is the rated stator resistance of the modeled generator. The goal is to test the transient behavior of the model in the values above and beyond this nominal resistance.

As is shown in the Fig. 5. The system is more unstable when stator resistance increases. The lumped-mass shaft model is used in the simulation; therefore, the rotor speed oscillations are not that much noticeable. The rotor speed oscillations were more obvious if the tow-mass model was taken in to account (Dusonchet *et al*., 2008). A fixed speed wind turbine shows the same reaction to increase of the stator resistance (Dusonchet *et al*., 2008), so the both kind of wind turbine become more unstable when stator resistance increases but the fluctuations of the terminal voltage and rotor speed are more obvious in WTDFIG. Ac voltage schematic in Fig. 5 shows that the system needs much more time to become stable after the fault occurrence when the stator resistance increases.

Leakage Stator Inductance

The effect of different values of stator reactance is shown in Fig. 6a-c. The model is tested for different values of reactance (Ls_1,Ls_2,Ls_3) and the following results are obtained for a fault clearing time 0.2 sec. The considered stator resistance values are:

- $Ls_1 = L_s/2 = 0.038$ p.u.
- $Ls_2 = L_s = 0.076$ p.u.
- $Ls_3 = 2L_s = 0.152$ p.u.

where, L_s is the rated value of the stator inductance assumed in the simulation. The purpose is to test the transient behavior of the model in the values above and beyond this nominal inductance.

As shown in Fig. 6, voltage stability decreases for decreased values of stator inductances. As described earlier that the system is more stable when lumped-mass shaft system is used in the model. Oscillation in the shaft system, excited by the grid disturbance,

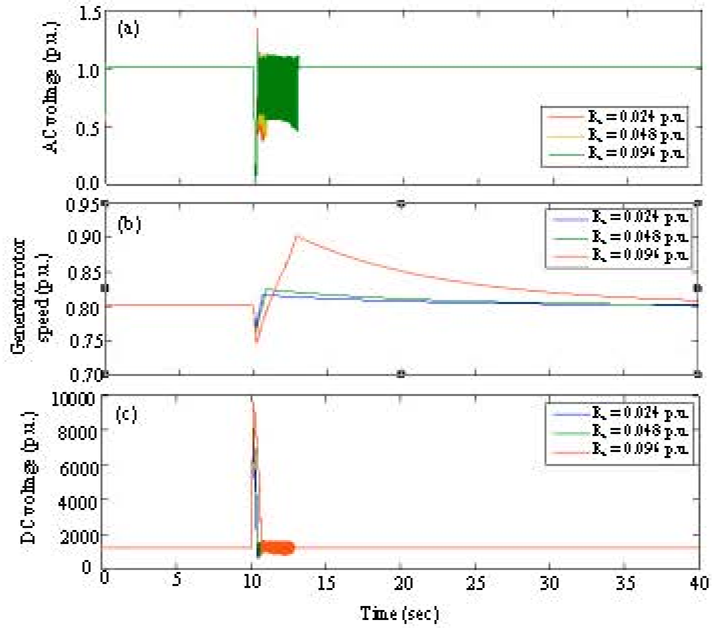

Fig. 5: (a-c) Terminal voltage, generator rotor speed and DC voltage of the convertor, respectively after three-phase short circuit fault for different values of stator resistance

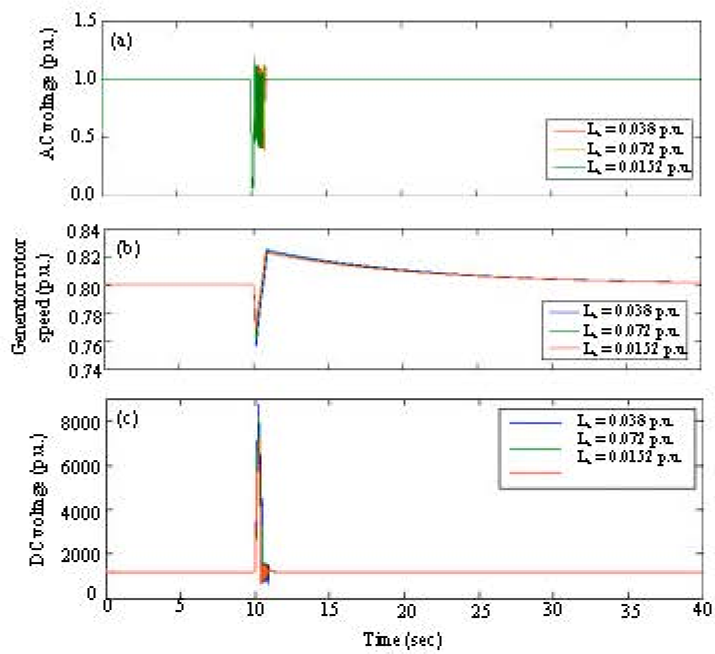

Fig. 6: (a-c) Terminal voltage, generator rotor speed and DC voltage of the convertor, respectively after three-phase short circuit fault for different values of stator inductance

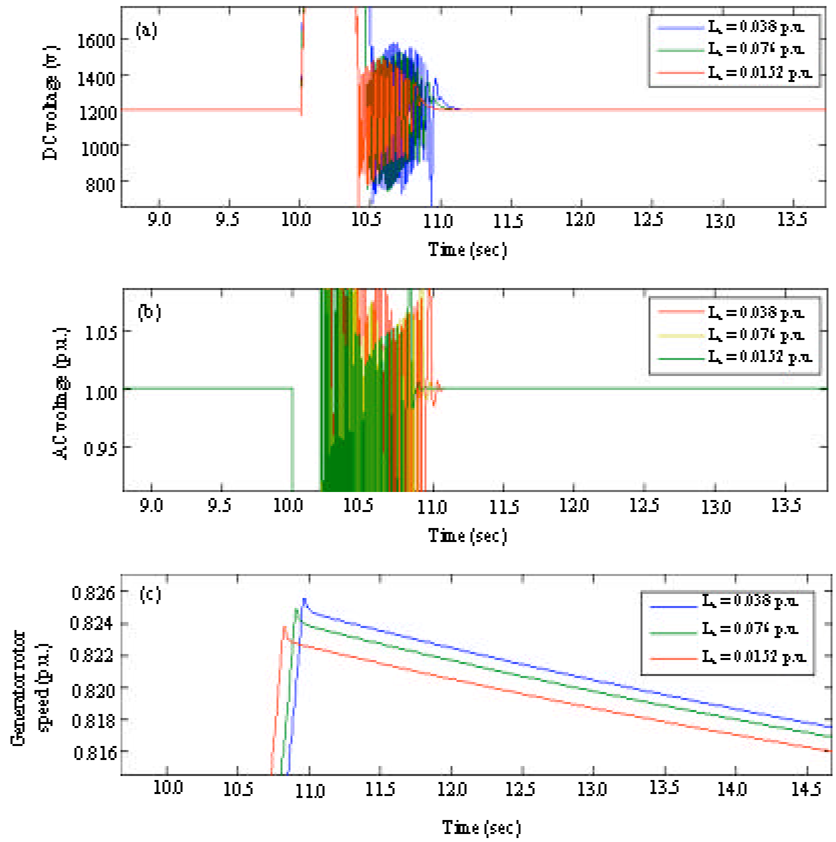

Fig. 7: (a-c) DC voltage of the convertor, terminal voltage and generator rotor speed, respectively with better visualization for different values of stator inductance

can lead to fluctuation of the generator rotor speed and also to fluctuations of the electric parameters of the induction generator in two-mass model (Dusonchet *et al*., 2008). In comparison with fixed speed wind turbine which become more stable when the stator reactance decreases (Dusonchet *et al*., 2008), the WTDFIG become more unstable in the same situation. Figure 7a-c show the DC voltage of the convertor, terminal voltage and rotor speed with better visualization.

Mutual Inductance

The effect of different values of stator resistance shown in Fig. 8. The model is tested for different values of resistance (Lm_1, Lm_2, Lm_3) and the following results are obtained for a fault clearing time 0.2 sec. The considered stator resistance values are:

- $Lm_1 = L_m/2 = 1.9$ p.u.
- $Lm_2 = L_m = 3.8$ p.u.
- $Lm_3 = 2L_m = 7.6$ p.u.

where, L_m is the rated value of the mutual inductance, assumed in the simulations.

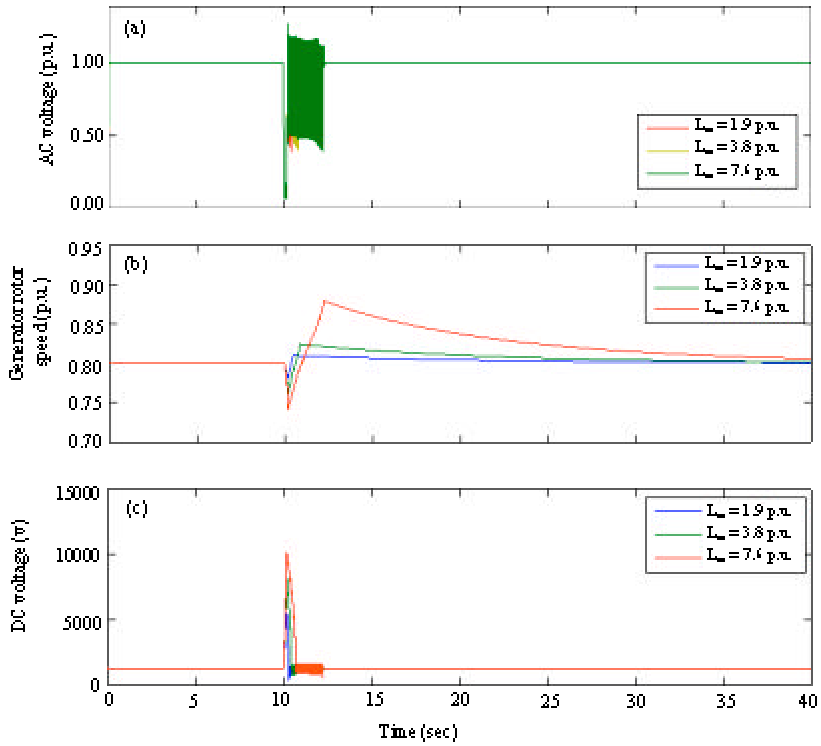

Fig. 8: (a-c) Terminal voltage, generator rotor speed and DC voltage of the convertor, respectively after three-phase short circuit fault for different values of mutual inductance

As shown in (Fig. 8 a-c), the system is more unstable when mutual inductance increases. A fixed speed wind turbine becomes more stable in the same situation (Dusonchet *et al*., 2008).

Rotor Inductance

Figure 9a-c show the voltage fluctuation and generator rotor speed for different values of the rotor inductance (Lr_1, Lr_2, Lr_3). The three-phase short circuit fault occurs at t = 10 sec close to the wind turbine and would be cleared 0.2 sec later.

The considered rotor inductance values are:

- $Lr_1 = L_r/2 = 0.06$ p.u.
- $Lr_2 = L_r = 0.12$ p.u.
- $Lr_3 = 2L_r = 0.24$ p.u.

where, Lr is the rated value of the rotor inductance, assumed in the simulation.

Figure 10a-c shows the DC voltage of the convertor, terminal AC voltage and rotor speed with better visualization. In this case the system is more unstable when rotor inductance decreases. A fixed speed wind turbine shows the different behavior in the same case. It becomes more unstable when the rotor inductance increases and the fluctuations of the terminal voltage and generator rotor speed are more obvious in a fixed speed wind turbine (Dusonchet *et al*., 2008).

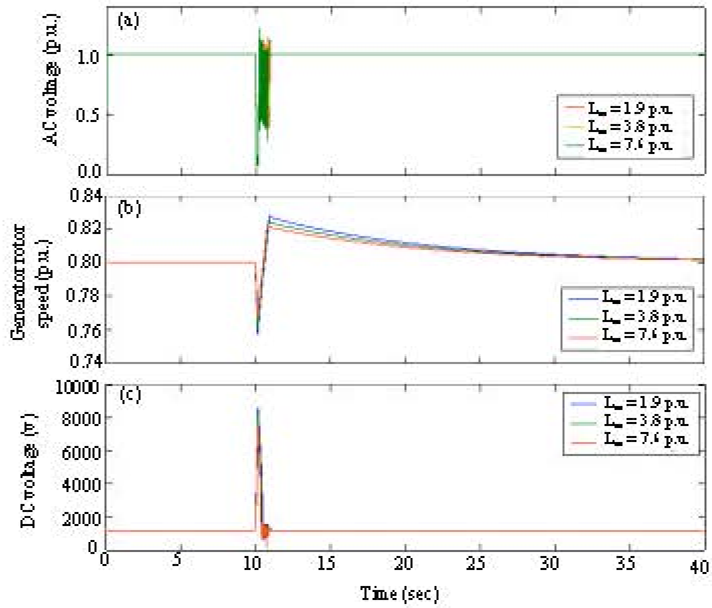

Fig. 9: (a-c) DC voltage of the convertor, generator rotor speed and terminal voltage, respectively after three-phase short circuit fault for different values of rotor inductance

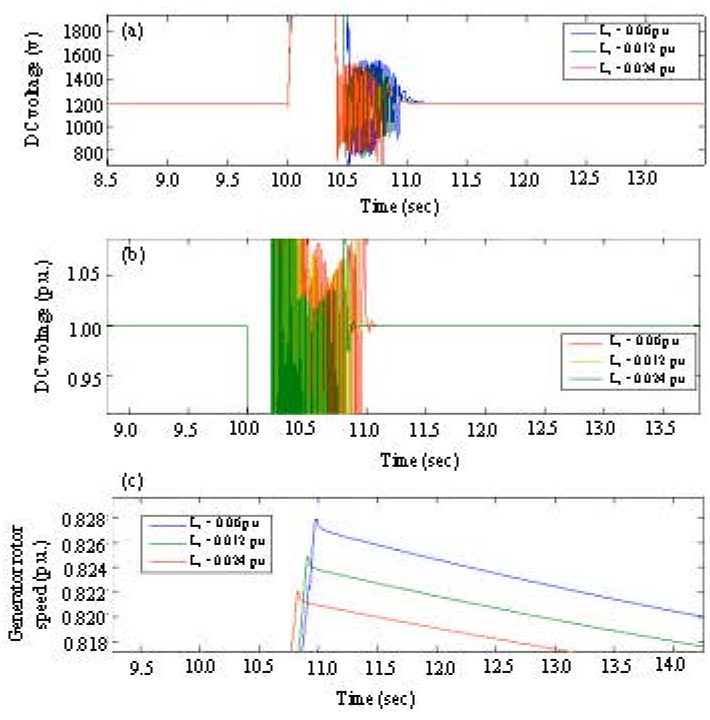

Fig. 10: (a-c) DC voltage of the convertor after three-phase short circuit fault for different values of rotor inductance

Rotor Resistance

At last, the same test is done for different value of rotor resistance (Rr_1, Rr_2, Rr_3) and the following results are obtained.

- $Rr_1 = R_r/2 = 0.09$ p.u.
- $Rr_2 = R_r = 0.12$ p.u.
- $Rr_3 = 2R_r = 0.24$ p.u.

where, R_r is the rated value of the rotor resistance, assumed in the simulation.

In comparison with a fixed speed wind turbine which becomes more stable when rotor resistance increases (Dusonchet *et al*., 2008) a variable speed wind turbine with doubly fed induction generator becomes more unstable (Fig. 11 a-c).

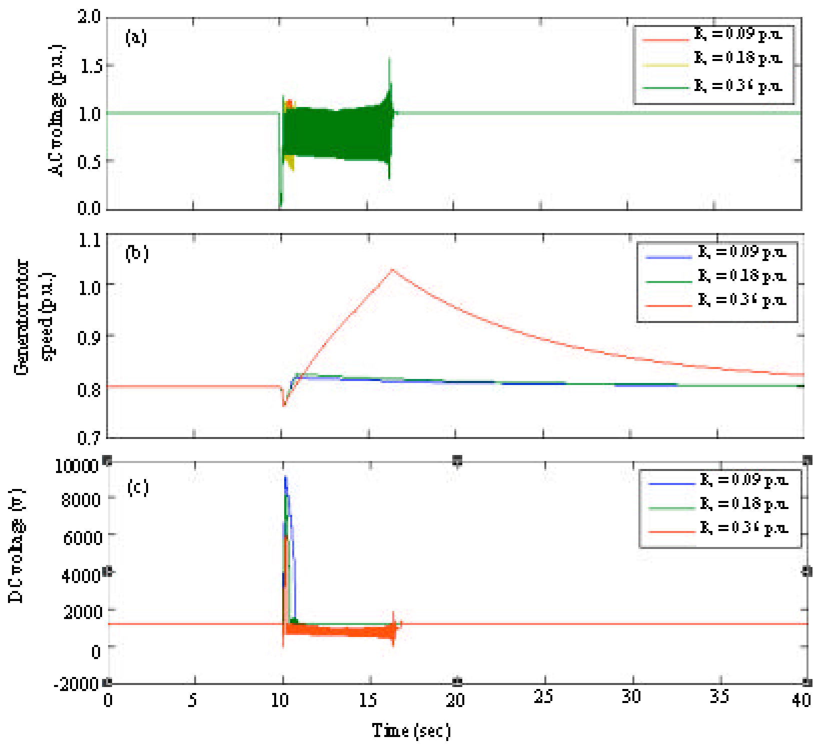

Fig. 11: (a-c) Generator rotor speed, DC voltage of the convertor and terminal voltage, respectively after three-phase short circuit fault for different values of rotor resistance

CONCLUSIONS

The effect of different electrical parameters of the induction generator on the voltage stability of this simple case after applying a short-circuit fault close to the wind turbine, has been evaluated and discussed in this study. Voltage stability depends on the induction generator parameters, such as the stator resistance, the stator reactance, the mutual reactance, the rotor resistance and the rotor reactance. In comparison of a fixed speed wind turbine which needs reduced stator resistance, stator reactance and rotor reactance and increased mutual reactance and rotor resistance (Dusonchet *et al.*, 2008) for an increase of voltage stability, a decrease of voltage stability in a doubly fed induction generator wind turbine is occurred when there is increased stator resistance, decreased stator inductance, increased mutual inductance, decreased rotor inductance and increased rotor resistance. So these two kinds of wind turbines show opposite reactions to the same variances in all of the electrical parameters of an induction generator except stator resistance. The voltage oscillations were completely clear in AC and DC voltage diagrams after a three phase fault is applied. Because of using lumped-mass shaft system the fluctuations in rotor speed weren't noticeable. According to similar studies (Dusonchet *et al.*, 2008) using two-mass shaft system makes the model more unstable, but for further comparisons the model needs to be developed for two-mass shaft system.

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REFERENCES

Akhmatov, V., 2003a. Analysis of dynamic behavior of electric power systems with large amount of wind power. Ph.D. Thesis, Technical University of Denmark, pp: 385.

Akhmatov, V., 2003b. Modeling and transient stability of large wind farms. Int. J. Electrical Power Energy Syst., 25: 123-144.

Dusonchet, L., F. Massaro and E. Telaretti, 2008. Effects of electrical parameters of induction generator on the transient voltage stability of a fixed speed wind turbine. Proceedings of the 43rd International Universities Power Engineering Conference, Sept. 1-4, Padova, pp: 1-5.

Heier, S., 1998. Grid Integration of Wind Energy Conversion Systems. John Wiley and Sons Ltd., New York, ISBN: 978-0-470-86899-7, pp: 385.

Kundur, P., 1994. Power System Stability and Control. EPRI, McGraw-Hill, New Jork, ISBN: 0-07-035958, pp: 1176.

Mutschler, P. and R. Hoffmann, 2002. , Comparison of wind turbines regarding their energy generation. Proc. IEEE 33rd Annu. Power Electr. Specialists Conf., 1: 6-11.

Melício, R. and V.M.F. Mendes, 2004. Doubly fed induction generator systems for variable speed wind turbine. IEEE Trans. Power Syst., 25: 1-4.

Petru, T. and T. Thiringer, 2002. Modeling of wind turbines for power system studies. IEEE Trans. Power Syst., 17: 1132-1139.

Sandra, E., H. Bernhoff and M. Leijon, 2008. Evaluation of different turbine concepts for wind power. Renewable Sustainable Energy Rev., 12: 1419-1434.

Slootweg, J.G., S.W.H. Haan, H. Polinder and W.L. Kling, 2001. Modeling wind turbines in power system dynamics simulations. Power Eng. Soc., Summer Meeting, 1: 22-26.

Slootweg, J.G., D. Haan, H. Polinder and W.L. Kling, 2002. General model for representing variable speed wind turbines in power system dynamics simulations. IEEE Power Eng. Rev., 22: 55-56.

Yi, Z. and S. Ula, 2008. Comparison and evaluation of three main types of wind turbines. Proceedings of the Transmission and Distribution Conference and Exposition, April. 21-24, T and D. IEEE/PES, Chicago, pp: 1-6.