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Analysis of Transient State Response on Doubly-Fed Induction Generator during Asymmetrical Short-circuit

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ABSTRACT

Inductive machines are highly sensitive to asymmetrical performance due to local heating which may happen in stator and really affects on machine life time. In other hand, negative sequential current in machine creates some vibrations in electrical toque which raises phonic noise and also decreases gear box and other parts life time. Thus, in this paper, we study behavior of doubly-fed induction generator (DFIG) during asymmetrical short circuit in grid and simulate performance of protective systems for decreasing destructive effects of current overloading to protect rotor-side converter using MATLAB software

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INTRODUCTION

Today, most of applied turbines in wind farms are based on doubly-fed induction generators, because of superior features of this kind of generators. Some of these features include: capability of production in different speed (infra-synchronous and ultra- synchronous), ability of active and reactive power control, power quality improvement and capability of performing in fault mode (FRT). However, wind turbines which use doubly-fed induction generators are highly sensitive to grid disturbances (Han, A., *et al.*, 2008). Thus, evaluating behavior of these types of generators in facing grid disturbances has significant importance. In this course, during last decade, many paper survived transient-state response of induction generators during grid disturbances. For example, transient state behaviour of doubly-fed induction generator in lack of voltage has been simulated (Han, A., *et al.*, 2008; El-Sattar, A.A., *et al.*, 2008) and it's behaviour in balanced short circuit state simulated (Anca D. Hansen, Gabriele Michalke, 2007; Charles A. Gross, 2007). Although transient state behaviour of doubly-fed induction generator during asymmetrical short circuit has not considered seriously. In this, transient state response of DFIG during three types of unbalanced shunt, i.e. single line to ground (SLG), line to line (L-L) and double line to ground (DLG) are evaluated. Finally, in last section, Crowbar protective system for protecting rotor-side converters is introduced and simulated.

II. Modeling Doubly-Fed Induction Generator:

Generally, equations of ordinary squirrel cage induction generators could be written as 5th order model using park conversion in d-q biaxial system, in which there are two state variables related to stator junction flux and there is one state variable for rotor speed for which we describe following equations. Per unit equation governed on stator and rotor winding are as equations (1) to (4), (Lopez, J., *et al.*, 2007).

$$V_{ds} = -R_s i_{ds} + \psi_{qs} - \frac{1}{\omega_b} \frac{d\psi_{ds}}{dt} \quad (1)$$

$$V_{qs} = -R_s i_{qs} - \psi_{ds} - \frac{1}{\omega_b} \frac{d\psi_{qs}}{dt} \quad (2)$$

$$V_{dr} = -R_r i_{dr} + (1 - \omega_r) \psi_{qr} - \frac{1}{\omega_b} \frac{d\psi_{dr}}{dt} \quad (3)$$

$$V_{qr} = -R_r i_{qr} - (1 - \omega_r) \psi_{dr} - \frac{1}{\omega_b} \frac{d\psi_{qr}}{dt} \quad (4)$$

Also, electromagnetic torque is obtained as following equation:

$$T_e = \omega_{dx} i_{qx} - \omega_{qx} i_{dx} \quad (5)$$

If we assume that angular speeds of rotor and generator are equal, then relation between speed and torque is as follows:

Equations (1) to (6) are true for both squirrel cage induction generators and doubly-fed induction generator. The only difference is that in squirrel cage type, V_{qr} and V_{dr} are equal zero, but in doubly-fed induction generator, rotor windings are feeded by electronic power converter. Thus, V_{qr} and V_{dr} could be non-zero (Ekanayake, J.B., *et al.*, 2003).

III. Modeling Doubly-Fed Induction Generator In Unbalanced State:

By considering zero-sequential component equal zero, unbalanced voltage in a weak grid could be described using positive and negative sequential equations. In positive sequential state, d-axis and q-axis are rotated with two speeds. In this mode, equations are just similar to normal state of generator which presented in section 2. Also, in this mode, slip is defined similar to normal state (Javad Haddadnia, Omid Rahmani Seryasat, 2014).

$$S_t = S = \frac{\omega_e - \omega_r}{\omega_e} \quad (7)$$

Generator negative sequential mode is similar to positive mode, but with an important improvement. Rotor and stator circular field in this mode are rotating in opposite direction. This required us to redefine slip. Thus, slip for negative sequential mode is defined as follows (Javad Haddadnia, Omid Rahmani Seryasat, 2014).

$$S = \frac{-\omega_e - \omega_r}{-\omega_e} = \frac{\omega_e + \omega_r}{\omega_e} = 2 - S \quad (8)$$

IV. Analysis of Different Short Circuit:

In this section, three modes of short circuit have been presented. Single line to ground fault, line to line fault and double line to ground fault. In all above mentions mode, fault occurs in $t=3s$ and repulses in $t=4s$. Simulations for a 690 volts induction generator with 2 MW power and its pacifications has been presented in table 1.

Table 1: Specifications of applied induction generator in simulation

12 p.u.		0.5 p.u.	j
3.8 p.u.		0.048 p.u.	
50 Hz	F	0.018 p.u.	
1 p.u.		0.075 p.u.	

V. Single Line To Ground Fault:

In this mode, grounded phase (example phase **a**) loses its voltage, but two other phases maintain their last fault values. This situation leads to over currents in each three phases. Induction generator accelerates during single line to ground fault and reaches to new permanent value. Mentioned cases in this section are observable in figure (1).

A. Line to line fault:

In this mode we assume that phases **a** and **b** involved in fault. Induction generator phase voltages are obtained from following equation (Johan Morren, Sjoerd W.H. de haan, 2007).

$$V_a(t) = V_b(t) = \frac{1}{2} V_c(t) \quad (9)$$

Figure (2) shows values of short circuit current phase voltages and generator during line to line fault mode and reaches to new permanent value.

B. Double line to ground fault:

In this mode, **a** and **b** phases loss their voltage entirely as shown in figure (3), loosing voltage in phases **a** and **b** creates large current in phase **c** which is larger than instant currents in **a** and **b** phases. Generator speed increases during fault mode until fault be repulsed. In this mode, upon to how long is generator crucial time, either speed may changes to initial permanent value or generator goes to transient state.

VI. Controlling Generator Over Current During Short Circuit:

Main problems for doubly-fed induction generator performance in fault mode are controlling generator and its power converter and also generator self-protection without interrupting grid during fault mode.

Controlling performance of doubly-fed inductive power in range of few milli-seconds is controlled in presence of electronic power components.

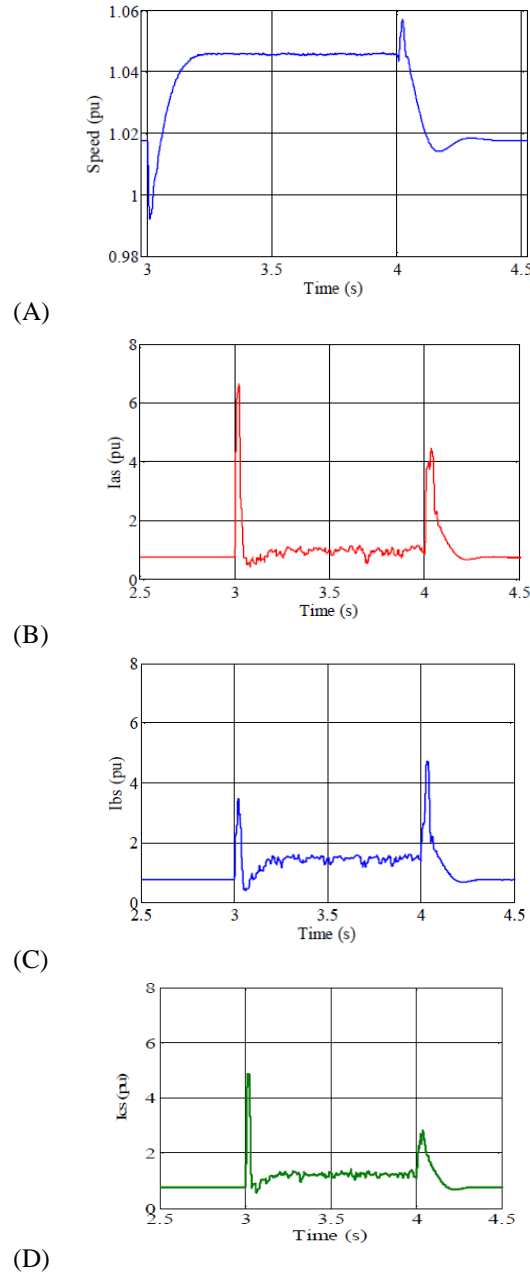
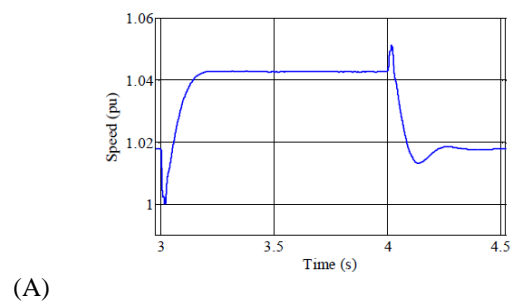


Fig. 1: Transient response of DFIG under single line to ground fault A- Generator speed; B- Current phase a; C- Current phase b; D- Current phase c.



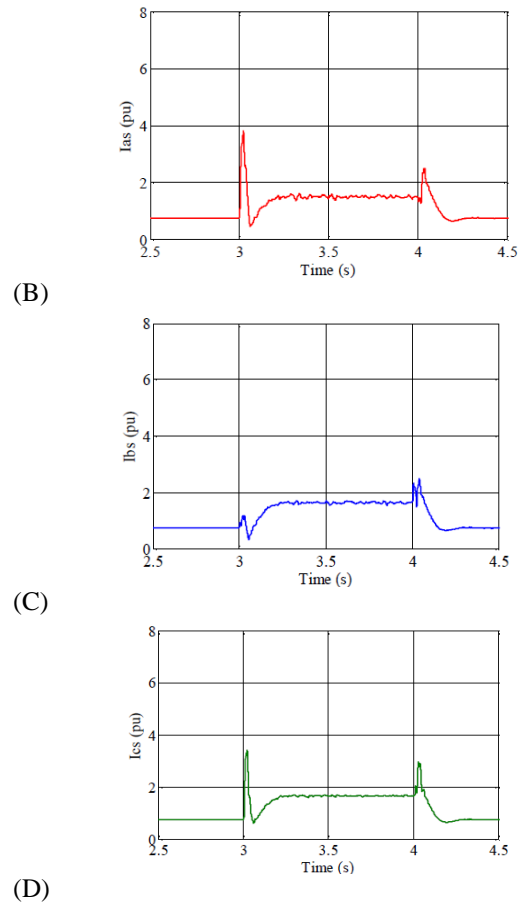
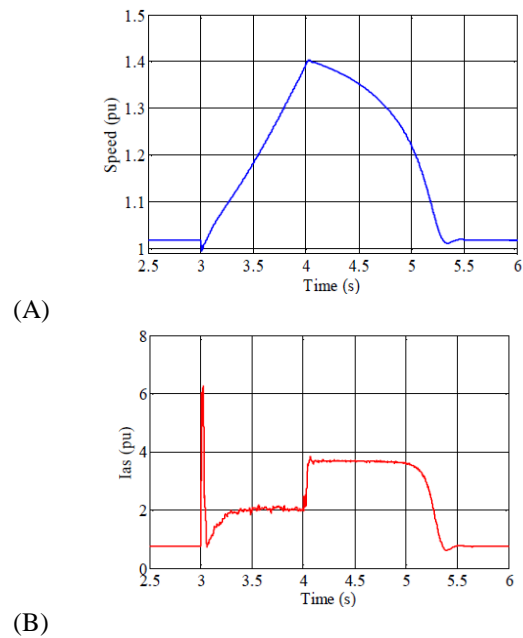


Fig. 2: Transient response of DFIG under line to fault ground fault A- Generator speed; B- Current phase a; C- Current phase b; D- Current phase c.



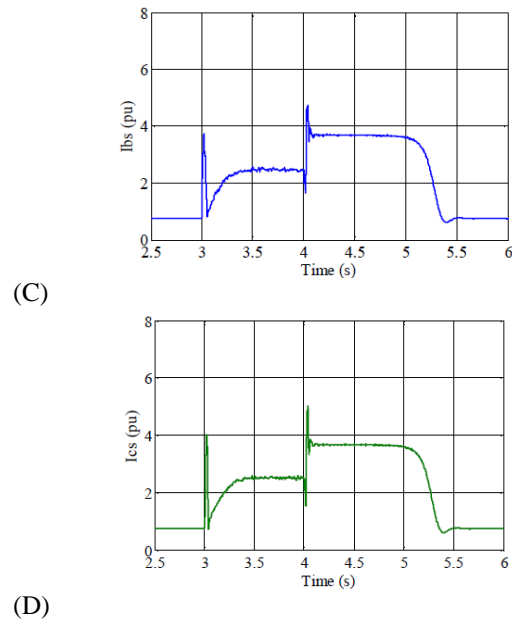


Fig. 3: Transient response of DFIG under double line to ground fault A- Generator speed; B- Current phase a; C- Current phase b; D- Current phase c.

One of applied method for controlling active and reactive power using PI controller is presented figure (4) (Garcia, M., *et al.*, 2008; Mohand Ouhrouche, 2009).

As it was mentioned earlier, one of advantages of doubly-fed induction generators is connecting electronic power converter in rotor side with less power than stator, which this way of connection provides performance ability even in low voltages within grid. However, one of disadvantages of direct connection of doubly-fed induction generator stators to power grid is sensitivity of these machines to grid disturbances, such as voltages drops, frequency changes and unbalancing. The appearance of short circuit causes stator currents raises, which due to magnetic coupling between rotor and stator; this leads to increasing in rotor current becomes higher than nominal converter current, it damages converter. Therefore, generator should be protected against these currents. Usually, we use a circuit called Crowbar to protect generator. When current amplitude becomes larger than protection level, Crowbar by short circuit generator rotor creates a safe path for transient rotor over current.

VII. Protection System:

Using a converter with percentage of perfect power which connects to rotor, makes wind turbine with doubly-fed induction generators attractive to grid turbulences,

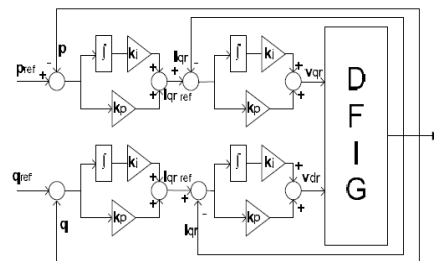


Fig. 4: Controlling active and reactive power using four PI controllers.

For which using reasonable protective system seems necessary (Rahmani, O. and A. Taherkhani, 2014). Without any protective systems, there are concerns about doubly-fed induction generators due to large disturbances which lead to huge fault current in stator in result of direct connection of stator into grid which leads to over voltage and over current within converter fault. Moreover, the wave comes after fault accompanies power rush from rotor terminals towards converter. In this situation, converter rapidly reaches to its current limits and as a result, losses generator control while grid fault when grid voltage drops while fault moment, grid side converter (GSC) couldn't transfer power form rotor side converter towards grid and thus excess energy is spent for charging dc-bus voltage increased quickly. According to above-mentioned matters, it is necessary that

we protect converter against over current and protect rotor and dc-link against over voltage. A simple technique for protecting doubly-fed induction generators while grid fault is short circuit rotor through resistances called Crowbar resistance. Crowbar protection is in fact additional impedance which is connected to rotor through a slipper loop instead converter. Value of Crowbar resistant depends on generator values, applied controlling system, intensity and type of voltage drop. Therefore, for a new generator, a new value for Crowbar resistance should be chosen. Crowbar role is in fact limiting rotor current. When Crowbar is activated, rotor side converter becomes inactive and losses ability of controlling active and reactive power. Grid side converter could stay connected within grid and even injects reactive power voltage into the grids while changing control system in order to over haul voltage.

Crowbar protection could be removing from system after fault repulse, after predetermined time or according to predefined criterion such as grid voltage amplitude. When Crowbar is removed, rotor side converter again is capable to control active and reactive power, independently.

Table 2: Rotor voltage values, during different intervals.

Before occurrence of fault	During fault	After fault repulse	
RSC is determined		RSC is determined	$V_{qr,pos}$
Zero		Zero	
RSC is determined		RSC is determined	
Zero		Zero	

Table 2 shows rotor voltage values within different time interval. Subscript pos. shows positive sequential and subscript neg. shows negative sequential. As it is shown, value of rotor positive sequential voltage before and after fault is determined by control system which depended on reference value of active and reactive powers and also figures (5) shows rotor current while fault mode, in which single line to ground has occurred in stator terminal.

In figure 5, it has assumed that $Q_{ref}=0$ and $P_{ref}=0.8$ p.u. in this figure, single line to ground in stator terminal is occurred at $t=3s$ and rotor current begins to increase, this increase is limited with those Crowbar resistances which are placed in rotor side at fault moment. At $t=3.5s$, short circuit is repulsed, but Crowbar resistances are stayed in circuit in order to avoid high over current. At $t=3.7s$ Crowbar resistances exit from circuit. In this moment, rotor side converter again acquires active and reactive power control and based on reference voltage values, applies reasonable voltage on rotor.

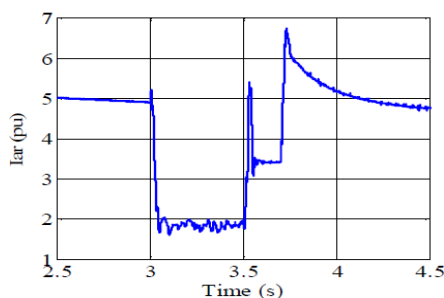


Fig. 5: Rotor current changes while fault occurrence after repulsing it.

Conclusion:

Existence of negative sequential while unbalanced short circuit in induction generators creates some vibrations in stator and rotor electrical torque and current, induction generator accelerates during single line to ground fault and line to line fault and reaches to new permanent value. But in double line to ground fault like three phase short circuit mode, machine speed is increased and if fault repulse time is more than generator critical time, then generator becomes transitory. During unbalanced short circuit it is withdrawn converter protection which is an expensive facility and using a protective system called Crowbar it is preventer of destructive rotor over current effects on converter.

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