Dynamic Behavior of Constant Speed WT based on Induction Generator Directly connect to Grid

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Abstract. The objective of this paper is determinate dynamic behavior of constant step wind turbine with squirrel cage as generator directly connected to a grid. Initially, all models and parameter used for simulation are shown; then a test system is simulated on dynamic state for evaluate the implications of wind speed fluctuations over wind turbine performance. Short circuits on terminals of wind turbines were simulated to evaluate the impact of these technologies on fault conditions. Several implications over clearing time was found on and related in this paper.

Key Words: Squirrel Cage Induction Generator, dynamic behavior, simulation.

1. Introduction

Wind energy is fastest growing energy technology in 1990s, in terms of percents – age of yearly growth of installed capacity per technology source [1]. In the future, many countries around the world are likely to experiment high penetration levels of wind power. The integration of high penetration levels of wind power into power systems that are originally designed around large-scale synchronous generators may require new approaches and solutions [2].

In early 1990s the standard installed wind turbines operated at fixed speed; regardless of wind speed, the turbine's rotor speed is fixed and determinate by the frequency of supply grid, the gear ratio and the generator design. This wind turbines are equipped with an induction generator (squirrel cage typically) that is connected directly to the grid. They are designed to achieve maximum efficiency at one particular wind speed. This scheme has the advantage of being simple, robust and reliable, and well proven. The uncontrollable reactive consumption is one important disadvantage of these wind turbines [1].

The main objective of this paper is determinate dynamic behavior of fixed step wind turbine with squirrel cage as generator directly connected to a grid.

Initially, all models and parameter used for simulation are shown; then a test system is simulated on dynamic state for evaluate the implications of wind speed fluctuations over wind turbine performance. Fault by short circuits on terminals of wind turbines were simulated to evaluate the impact of these technologies on fault conditions. Several implications over clearing time was found on and related in this paper.

2. Modeling

This section presents a number of basic considerations regarding simulations for fixed speed wind turbines with squirrel cage induction generator directly connected to grid (Fig. 1). We focus on modeling of wind turbine and the main objective is also look at the wind turbine as one electromechanical component among many others in the entire power system.

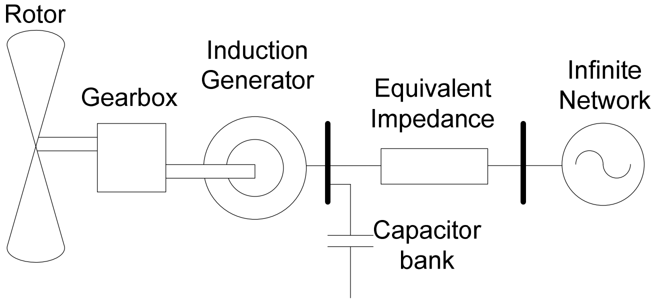

Fig. 1. Fixed speed wind turbine with induction generator

In order to put a reasonable limit on data requirement and computation time, quasistatic approach is used in this paper to describe the rotor of wind turbine. Dynamic behavior is the main interest in this paper, and low frequencies phenomenon with long time constants, due only fundamental frequency component of voltage and current is taking into account. Network representation is by constant admittance matrix, neglecting differential equation associated with network.

Fig. 2 depicts general structure of a model of a constant speed wins turbine. Main model of the most important subsystem, namely the rotor, the drive train, and the generator, combined with a wind speed model.

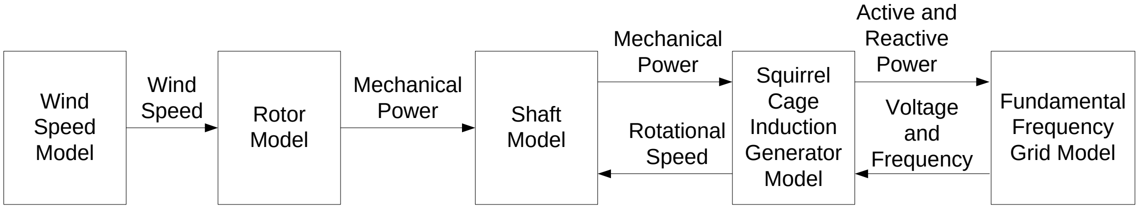

Fig. 2. General Structure of constant-speed wind turbine

2.1. Wind Speed Model

This model generates a wind speed sequence with characteristic controllable. Making possible simulate a wind speed sequence with desired characteristic, by setting the value of the corresponding parameters to an appropriate value. In this paper the well-kwon model of four components is assumed. Wind speed (v_w) is the sum of following component [1]-[4]: the average value (v_{wa}), ramp component (v_{wr}), gust component (v_{wg}) and turbulence (v_{wt}).

$$v_w(t) = v_{wa} + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \tag{1}$$

The wind speed ramp is characterized by three parameters –amplitude of wind ramp A_r (in m/s), the starting time of the wind speed ramp T_{sr} (in s) and the end time of the wind ramp (in s) T_{er}; and following equation describe the ramp component [2]:

$$\begin{aligned} v_{wr} &= 0 && \text{for} \quad t < T_{sr} \\ v_{wr} &= A_r \frac{(t - T_{sr})}{(T_{er} - T_{sr})} && \text{for} \quad T_{sr} \le t \le T_{er} \\ v_{wr} &= A_r && \text{for} \quad T_{er} < t \end{aligned} \tag{2}$$

The wind speed gust is characterized by: amplitude of gust A_g (in m/s), the starting time of the wind speed gust T_{sg} (in s) and the end time of the wind speed gust (in s) T_{eg}; and following equation describe the ramp component [1]-[2].

$$\begin{aligned} v_{wg} &= 0 \quad \text{for} \quad t < T_{sg} \\ v_{wg} &= \hat{A}_g \left\{ 1 - \cos\left[2\pi \left(\frac{t - T_{sg}}{T_{eg} - T_{sg}} \right) \right] \right\}, \text{ for } T_{sg} \le t \le T_{eg} \\ v_{wg} &= 0 \quad \text{for} \quad T_{eg} < t \end{aligned} \tag{3}$$

Turbulence component is complex, but use a model based on power spectral density $S_{wt}(f_i)$:

$$S_{wt}(f_i) = \frac{\dfrac{1}{(\ln(h/z_o))^2} l v_{wa}}{\left(1 + 1.5 \dfrac{f_i l}{v_{wa}}\right)^{\frac{5}{3}}} \tag{4}$$

And the turbulence component is given by [4]:

$$v_{wt}(t) = \sum_{i=1}^{n} \sqrt{S_{wt}(f_i)\Delta f} \cos(2\pi f_i t + \phi_i + \Delta\phi) \tag{5}$$

For detailed discussion of turbulence component see [5].

2.2. Rotor Model

A quasistatic approach is used to describe the rotor of the wind speed. In this case a well-known algebraic equation give the relation between wind speed and mechanical power extracted from the wind [1]-[2],[6]-[7]:

$$P_w = \frac{1}{2}\rho_{AIR} A_{wt} C_p(\lambda) v_w^3 \tag{6}$$

where ρ_{AIR} is the air density (typically 1.225Kg/m^3), A_{wt} is the area covered by the wind turbine rotor, C_p is the power coefficient, λ is the tip speed ratio, and v_w is the wind speed at hub height. In this paper the power coefficient of fixed speed wind turbine is represented by function approximation:

$$C_p(\lambda) = 0.44\left(\frac{125}{\lambda_i} - 6.94\right)e^{-\frac{16.5}{\lambda_i}} \tag{7}$$

Where:

$$\lambda_i = \left[\frac{1}{\lambda} + 0.003\right]^{-1} \tag{8}$$

To approximate the effect of high frequency wind speed variations are very local and therefore even out over the rotor surface, particularly when wind turbine become larger, a low pass filter, with time constant (τ) was set to 4.0 s. We include the tower shadow in the rotor model, to make more realistic modeling. The tower shadow was simulated by periodic pulsation to the mechanical output of the rotor model. In this paper, we include the tower shadow as sequence of pulse of 0.1 p.u on mechanical power, and frequency dependent of the rotor speed.

2.3. Shaft Model

Repeatedly argued in the literature that the incorporation of a shaft representation model of constant speed is very important for correct representation of their behavior during and after voltage drops, and short circuits. In this paper we do not include the shaft model.

2.4. Generator Model

In this paper we use the voltage equations of a squirrel cage induction generator in *dq* reference frame to model the generator. The complete set of equations can be found in the literature, and as follows [1], [8], [9]:

$$\begin{aligned} v_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega\psi_{ds} & \qquad v'_{qr} &= 0 = R'_r\, i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega - \omega_r)\psi'_{ds} \\ v_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} + \omega\psi_{qs} & \qquad v'_{dr} &= 0 = R'_r\, i'_{dr} + \frac{d\psi'_{dr}}{dt} + (\omega - \omega_r)\psi'_{qs} \end{aligned} \tag{9}$$

where v is voltage, i is the current, R is the resistance and ψ is the flux. All quantities are in per unit. Subscripts d and q stand for direct and quadrature component, respectively, and the subscript r and s for rotor and stator, respectively [1].

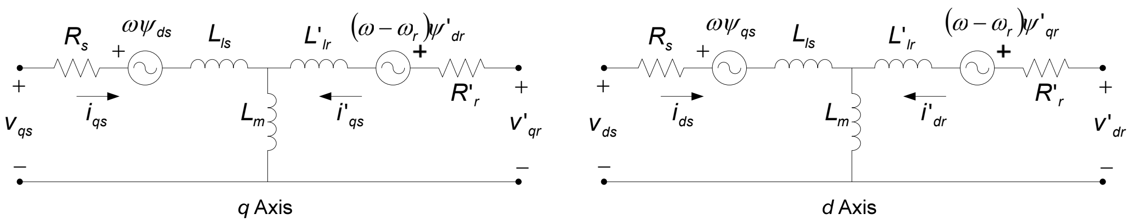

Fig. 3. *dq* frame induction generator model

The electrical torque (T_e) is given by:

$$T_e = \frac{3}{2} p\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{10}$$

And the equation of motion of the generator is:

$$\begin{aligned} \frac{d\omega_m}{dt} &= \frac{1}{2H}\left(T_e - F\omega_m - T_m\right) \\ \frac{d\theta_m}{dt} &= \omega_m \end{aligned} \tag{11}$$

3. Simulations and Results

In this section, models were implemented on Matlab® Simulink™. Fig. 4 show test system implemented.

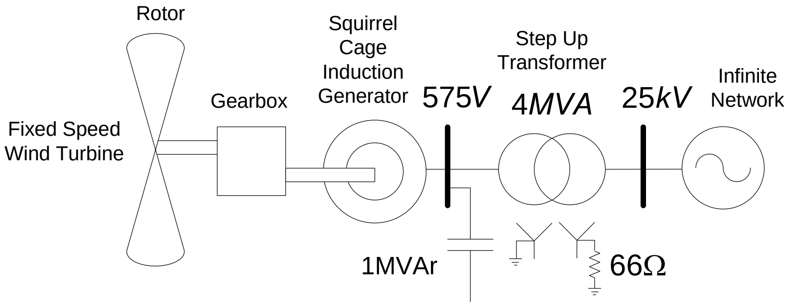

Fig. 4. Test system

All values except wind speed are in per unit and their values are not given. A typical fixed speed wind turbine with characteristic shown on Table 1, was simulated, and Fig 5 represent mechanical power (in per unit) for several wind speed and rotational speed.

On Table 2, we show the parameter of a typical 2MVA, 575 V, single squirrel cage used on fixed speed wint turbine application, and used in this paper.

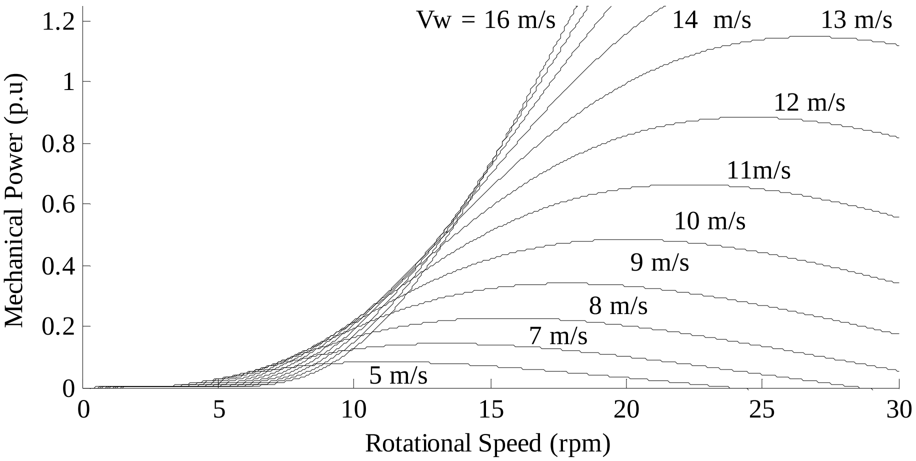

Fig. 5. Mechanical Power of Fixed Speed Wind Turbine Simulated by eq (6)-(8)

Table 1. Characteristic of Simulated Wind Turbine [1], [2]

Wind turbine characteristic	*Value*
Rotor speed	15 RPM
Rotor diameter	75 m
Rotor swept area A_r	4418 m
Nominal power	2 MW
Nominal wind speed	15 m/s
Gear box ratio	1:89

Capacitor for local power factor correction was included with 1MVAr, 575V. An step up transformer, 575V/25kV, X=0.25 p.u, X/R=30 was included to connect the wind turbine to a 25 kV infinite bus.

Table 2. Induction Generator Parameters

Generator characteristic	*Value*
Number pairs of poles	2
Generator speed	1517 RPM
Nominal Power	2 MVA
Nominal Voltage	575 V
Mutual inductance	3.0 p.u.
Stator leakage inductance	0.010 p.u.
Rotor leakage inductance	0.080 p.u.
Stator resistance	0.010 p.u.
Rotor resistance	0.010 p.u.
Compensating capacitor	0.5 p.u.
Inertia constant	5.0 s

We use Matlab® Simulink™ to obtain the simulation results. We use time variable step solver, based on implicit Runge-Kutta formula.

3.1. Short Term Wind Speed Variation

Initially we are interested on investigate the impact of wind speed changes over main wind turbine system variables. Fig. 6 shows a measured wind speed sequence obtained from literature [Ackermann]. Wind speed sequence was applied to the wind turbine delivering nominal power at rated voltage to infinite bus: subsequently the simulated rotor speed and the output power are depicted on Fig 7 and 8.

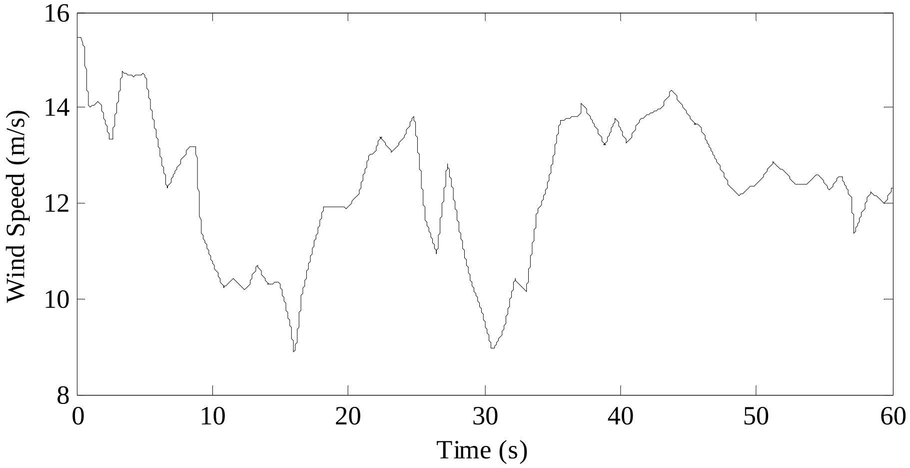

Fig. 6. Wind Speed Sequence

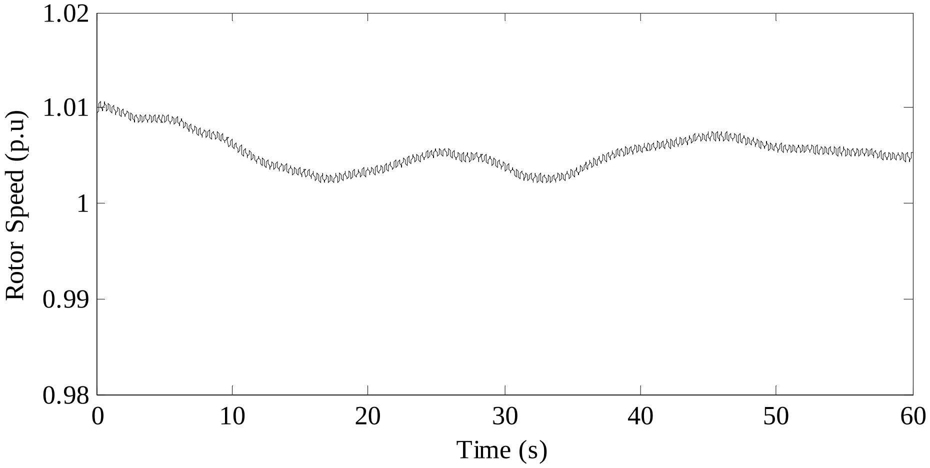

Fig. 7. Simulated Rotor Speed

Short term (second) rotor speed fluctuations look soft and highly damped; inertia of rotor turbine and high inertia constant of induction generator produce a slow and close rotor speed variations; below 0.01 p.u. This result is consequent with fixed speed wind turbine.

Output power fluctuations are severe due the rotor acts as an energy buffer. High exclusion on power output was developed due high wind speed variations. The wind speed sequence simulated has average value below nominal speed wind turbine; and nominal power is not reached.

The periodic torque pulsation of tower shadow; was included on simulations and his impact on mechanical torque is evident on rotor speed (frequency oscillation mode) which results in output power fluctuations with an amplitude of about 0.025 p.u.

The rapid wind speed changes and the tower shadow are not reflected in the rotor speed with notorious impact on the power supplied to the grid.

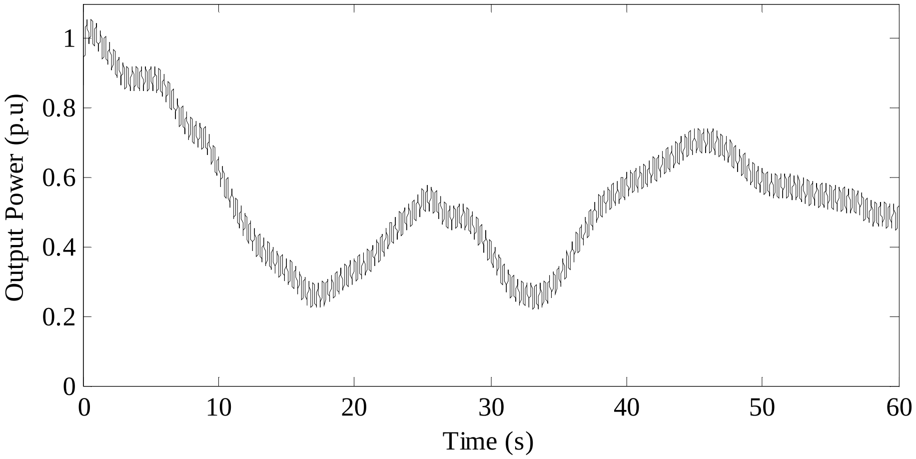

Fig 8. Simulated Output Power

3.2. Short Circuit

Considering a short term constant wind speed as nominal power is delivered to infinite bus on rated voltage. Short circuit on terminals of wind turbine (575V bus) was simulated for several clearing time and results are shown on Fig. 9-11.

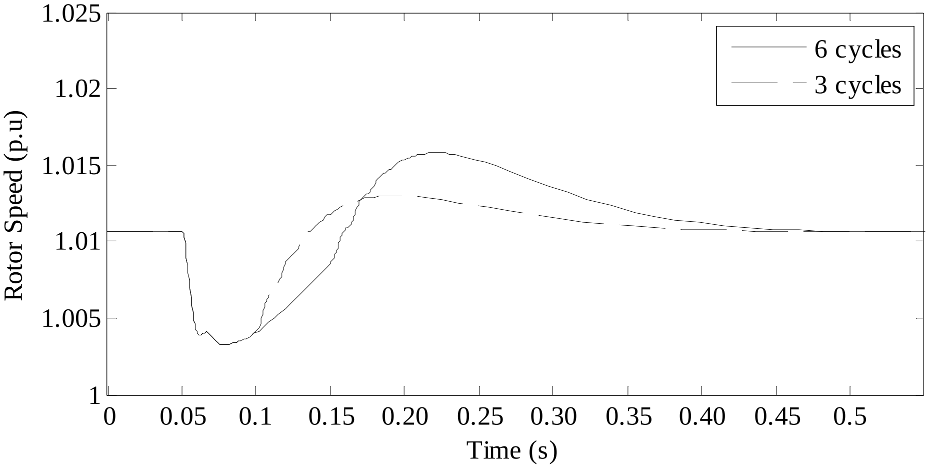

Fig. 9. Rotor speed for 3 and 6 cycles fault

Clearing time has great impact over short circuit behaviour of fixed speed wind turbines based on induction generator. During short circuit, under-damping behaviour with an overshoot dependent of the clearing time results evident on rotor speed. Longer clearing time produce higher overshoot on rotor speed and similar effect is over peak time.

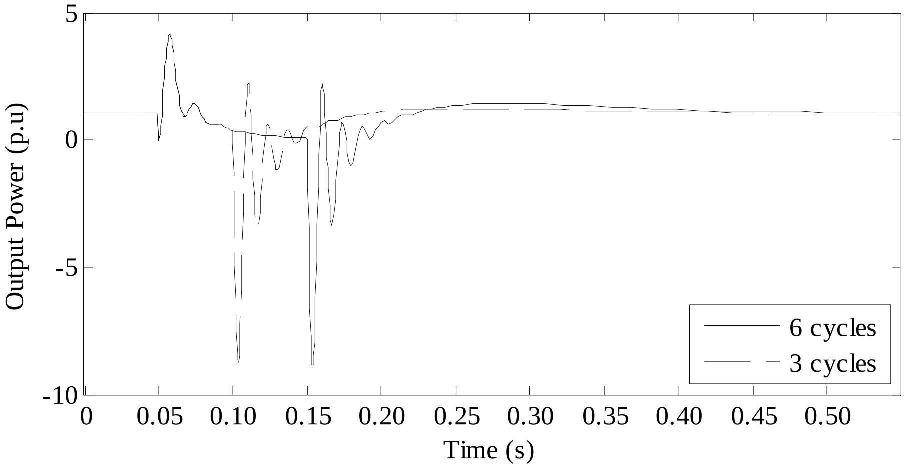

Fig. 10. Output power for 3 and 6 cycles fault

Output current exhibits a particular behavior. Two peaks on current are evident, one on initial time of short circuit and the values of this peak is independent of short circuit duration; and secondary peak is dependent on clearing time. For larger clearing time, secondary peak could be greater than short circuit value. This secondary peak on short circuit current, is origin by demagnetizing action of short circuit current, for long clearing times, recluse over induction generator is seem as very low impedance from infinite bus and high current than short circuit may occur.

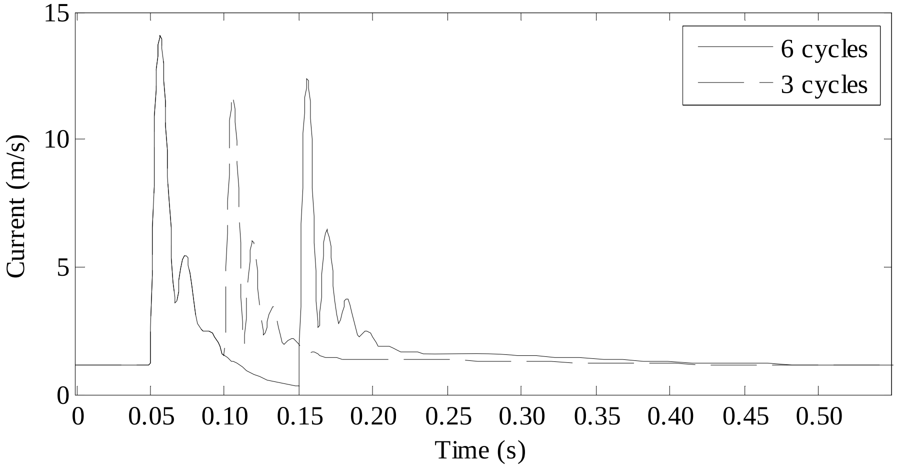

Fig 11. Output Current for 3 and 6 cycles fault

4. Conclusions

In this paper dynamic behaviour of constant step wind turbine with squirrel cage was explored. Models and parameter for simulations of this technology was shown. Short term (second) response of this wind turbine exhibit a good performance, including when tower shadow effect is considered; but all fluctuations in wind speed are further transmitted as fluctuations on mechanical power and then as fluctuations in electrical power on the grid; in this case, infinite bus do not derive in voltage fluctuations, but significant interest would be found in weak transmission system. Consideration of reactive power support would be exanimate in weak networks.

Wind Turbines with single squirrel cage induction generator directly connected to grid in fault condition exhibits an interesting behavior; due induction generator under fault conditions is rather different to that of a synchronous generator. Under short circuit conditions on terminals, interrupt supply of reactive power needed to maintain excitation of the induction generator, and so there is no sustained contribution to symmetrical fault. The fault current has two peaks, one dependent of impedance equivalent and another dependent of clearing time. The time of reclose would make the secondary peak bigger than primary, for this reason induction generator would be keep connected during faults.

5. References

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