MITIGATION OF THE EFFECTS OF GRID FAULTS ON THE WIND-DRIVEN DOUBLE OUTPUT INDUCTION GENERATOR

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Abstract— *In this paper the dynamic behavior of a double-output induction generator (DOIG) driven by wind turbine under wind speed variation and during and after grid faults, is investigated. Two damping methods are tested to reduce the high transient values of currents and voltages at different parts of the wind energy conversion system. First, connecting 3-phase capacitors in the rotor circuit did not reduce the high transients due to wind speed variations, but only improved the system power factor. In the second method, 3-phase inductance is connected in series with the stator terminals. This method reduced these transients by 50% and improved the system power factor. The inductance value has to be limited to avoid deteriorating the generation system performance. Fault ride through is investigated after symmetrical and unsymmetrical faults by insertion of inductance at the stator terminals. This method led to suppress the induced over-voltages and, hence, over-currents in the rotor windings and converters.*
Keyword:

I. Introduction

In order to maximize energy extraction from the wind, wind energy conversion systems (WECS) should be able to operate at variable rotational speed. Although variable speed operation demands higher complexity and initial investment, these drawbacks are offset by the increase of energy capture and the improvement of control flexibility [1]. An interesting configuration among them is the one that uses grid-connected double-output induction generator (DOIG) with slip energy recovery in rotor, shown in Fig. 1. At the cost of a wound rotor, DOIG provides several attractive features [2]. For instance: constant voltage and constant frequency generation (even operating at variable speed), generation above the machine rated power, and smaller converter, and consequently cheaper compared to those required for squirrel cage or synchronous generators (only slip power is processed) [3,4].

Many researchers dealt with grid faults ride through in generation systems involving doubly fed induction generators using different techniques [5-10]. In [5] an analytical study of the dynamic behavior of the DFIG was given, providing a comprehensive description of sag effects on the stator currents and rotor voltages. subject to symmetrical voltage sags. However no practical solution for sags' mitigation was given.

In [6] a low-voltage ride-through technique of a doubly fed induction generator wind turbine system using a dynamic voltage restorer (DVR) was proposed. This technique, in addition to adding complexity to the generation system control, is suitable for low voltage side.

In [7], it was demonstrated that using the rotor crowbar and dc-link chopper can prevent back-to-back converters and dc-link of the DFIG wind turbine from the damages of over-current and over-voltage, but these were not efficacious to mitigate the mechanical system stress, even to transfer the electric system stress to mechanical system stress.

In [8], proposes a new converter protection method, primarily based on a series dynamic resistor (SDR), where simulation results show that the proposed method is advantageous for fault overcurrent protection, especially for asymmetrical faults, while stator side protection was not considered.

In [9] a comprehensive analytical analysis of DFIG grid-fault response was presented, starting with the natural flux-driven short circuit response of the machine, while no solution for fault mitigation was given.

In [10] the authors described the study undertaken to assess the steady state and dynamic behavior of a double-output induction generator (DOIG) driven by wind turbine after its disconnection from the grid, without proposing solutions to associated problems

In this paper a simple technique for mitigating the effect of grid faults on wind-driven DOIG is proposed. This technique consists of connecting a 3-phase inductance through an electronic switch in series with the stator terminals during abrupt wind speed. The electronic switch is operated by sensors that close the switch at abrupt changes in wind speed and / or grid voltage dips. The value of the external inductance L_{ext}, is tested through simulation. Results showed that its optimum value equals the stator self inductance. Results showed also that external inductances have to be connected for short time, which can be accomplished via the electronic switch. This method reduced current and voltage transients in stator, dc link, and rotor by 50% and improved the system power factor. Fault ride through is investigated after symmetrical and unsymmetrical faults using this proposed technique. Another method is tested, by adding parallel 3-phase capacitors at stator terminals. Results showed that although the generation system power factor was improved, however the over-current was not solved.

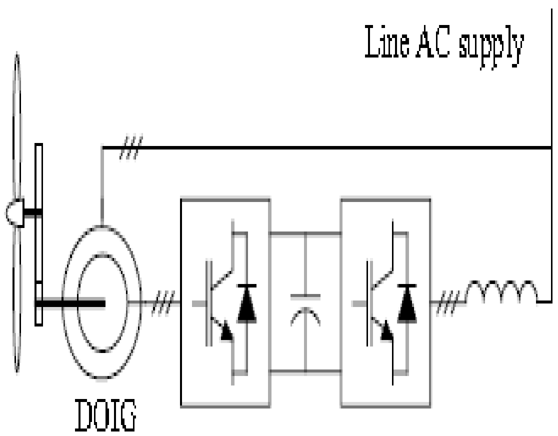


Fig. 1 Basic configuration of DOIG wind turbine

II. System Description

In the basic configuration shown in Fig. 1, the rotor side converter is replaced by a three-phase full-wave diode bridge rectifier. This rectifier connected to the rotor windings via slip rings, converts a portion of slip power into DC which in turn is converted into line frequency AC by a three-phase PWM voltage source inverter and fed back to the AC mains via a transformer. An inductor between rectifier and inverter is placed to reduce the DC current ripple.

The three phase voltage equations of the DFIG are transformed into d,q axes reference frame rotating at synchronous frequency ω, and neglecting saturation, the terminal voltage equations are given by:

$$V_{ds} = R_s I_{ds} + p\Psi_{ds} - \omega\, \Psi_{qs} \quad (1)$$

$$V_{qs} = R_s I_{qs} + p\Psi_{qs} + \omega\Psi_{ds} \quad (2)$$

$$V_{dr} = R_r\, I_{dr} + p\Psi_{dr} - \omega_r \Psi_{qr} \quad (3)$$

$$V_{qr} = R_r I_{qr} + p\Psi_{qr} - \omega_r \Psi_{dr} \quad (4)$$

$$\Psi_{ds} = L_s I_{ds} + M I_{dr} \quad (5)$$

$$\Psi_{qs} = L_s\, I_{qs} + M\, I_{qr} \quad (6)$$

$$\Psi_{dr} = L_r\, I_{dr} + M\, I_{ds} \quad (7)$$

$$\Psi_{qr} = L_r\, I_{qr} + M\, I_{qs} \quad (8)$$

Torque equation:

$$Te = 1.5\, P\, M\, (\Psi_{qs}\, I_{dr} - \Psi_{ds}\, I_{qr}) / L_s \quad (9)$$

Where, sufixes s and r stand for stator and rotor parameters respectively,

V is the voltage, I is the current, M is the magnetizing inductance, L is the self inductance, R is the resistance per phase, ω is the synchronous speed, P number of pairs of pole, and "p" is the d/dt operator.

Figure 2 shows the model of the grid-connected DOIG in Matlab/Simulink. A 3-phase diode rectifier, dc link, a 3-phase IGBT inverter, and step-up transformer are interfacing the rotor circuit to the electrical grid. The transmission line connecting the two ports of the DOIG, and the transformer interfacing the rotor circuit to the grid are represented. A PID controller is applied to adjust the inverter output as the wind turbine speed varies. The system currents, voltages, active and reactive power, and power factor are monitored at different system points (stator, rotor, inverter, and dc link). The system performance is tested at different rotor super-synchronous speeds.

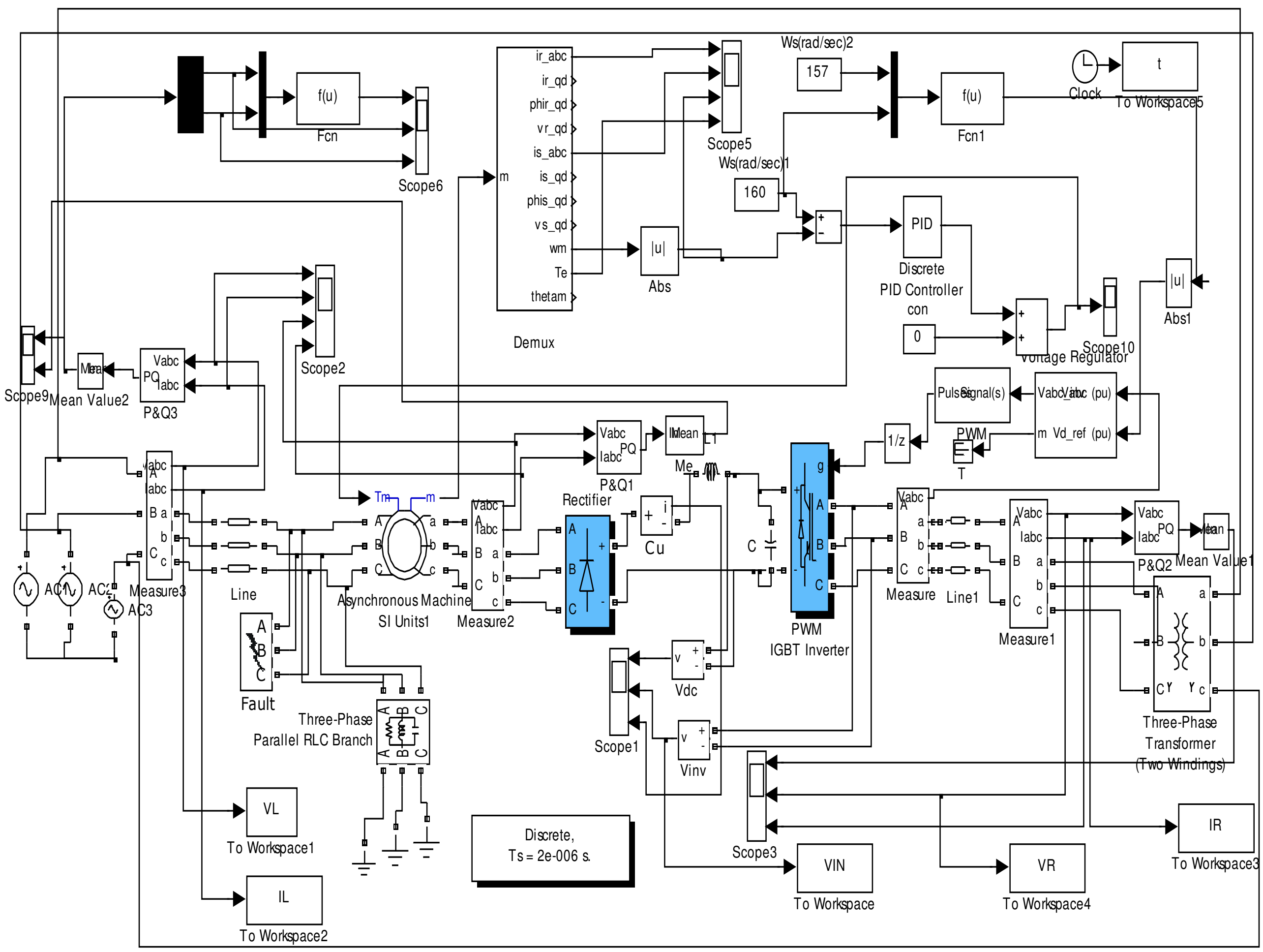


Fig. 2. DOIG modeling

III. System Transients due to Wind Speed Variation

The effect of inserting inductances, with value equal to stator self inductance, at stator terminals is investigated at sharp wind speed variation. Connecting inductances to stator terminals modify equations (1) –(9) where Ls is replaced by Ls + Lext. Figures 3-6 show the stator and rotor current the dc link current and the system power factor respectively. In these figures the time at which speed changes abruptly is considered as =zero. In all these figures it is clear that the transients' magnitude is approximately 10 times the steady state value. These high transients may lead to insulation failure. Also the poor value of the system power factor is obvious.

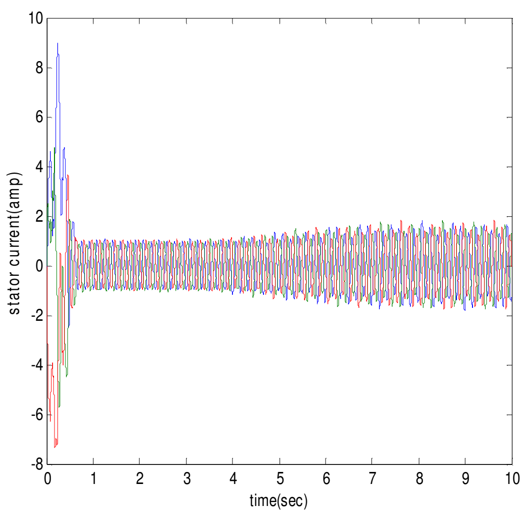


Fig. 3, Stator current at abrupt wind speed variation.

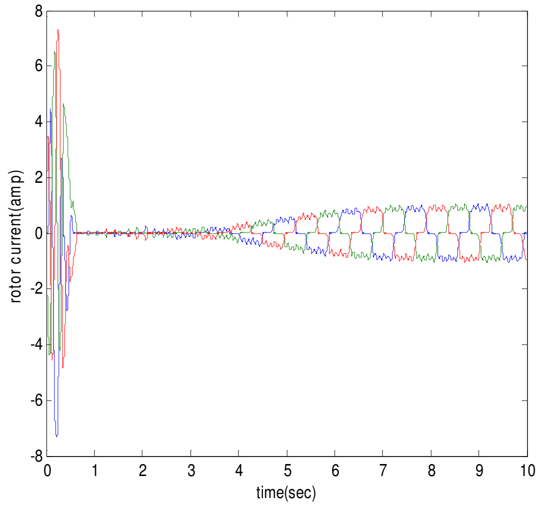


Fig. 4 Rotor current at abrupt wind speed variation.

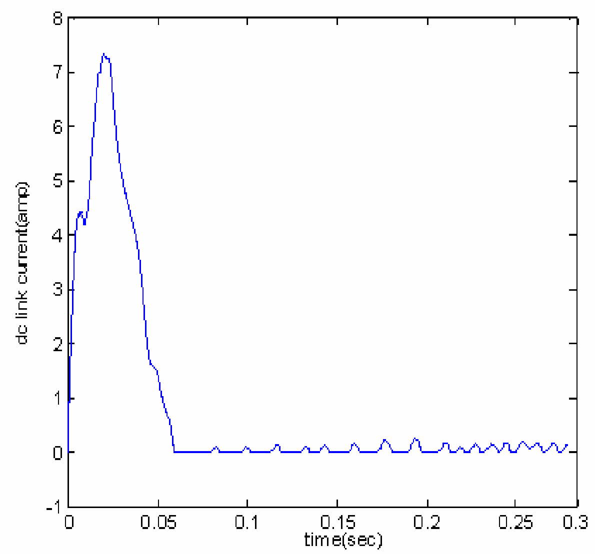


Fig. 5 Dc link current

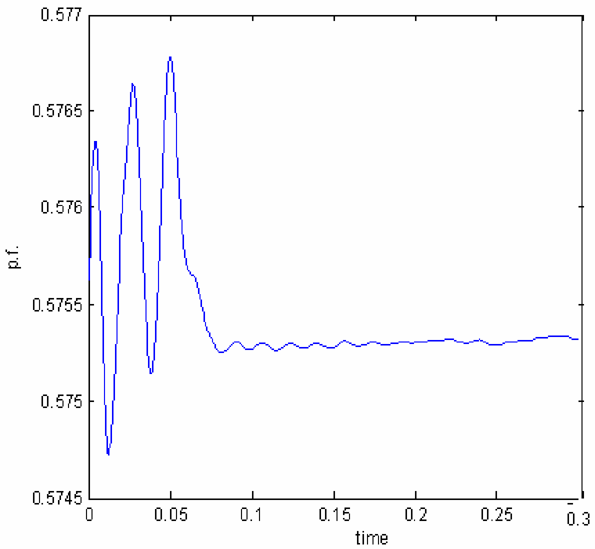


Fig. 6 System power factor.

III. Capacitor Banks for Reducing Transients

Parallel three-phase capacitor bank is added at stator terminals and current transients monitored. Figure 7 shows the stator current, revealing the higher transient value than its value without capacitors when comparing with figure (3). It is shown that the peak value of the transient stator current is 35 A., while without capacitor bank it was 9 A. only. The same argument applies to the rotor current transients shown in Fig. 8, where the peak value of the transient rotor current is 30 A., while without the capacitor bank it was 7 A. only when compared to figure (4). However, the only benefit is the improvement of the system power factor as shown in Fig. 9 when compared with figure (6).

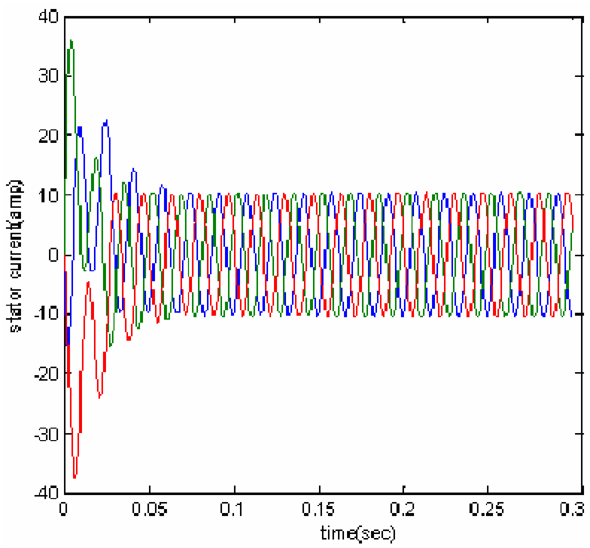


Fig. 7 Stator current with C bank.

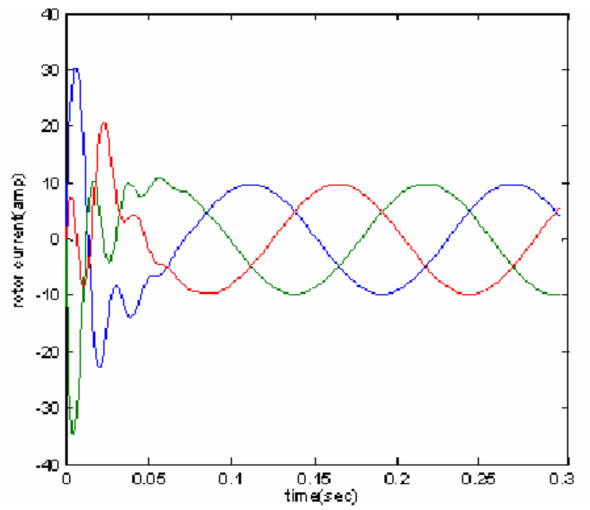


Fig. 8 Rotor current with C bank.

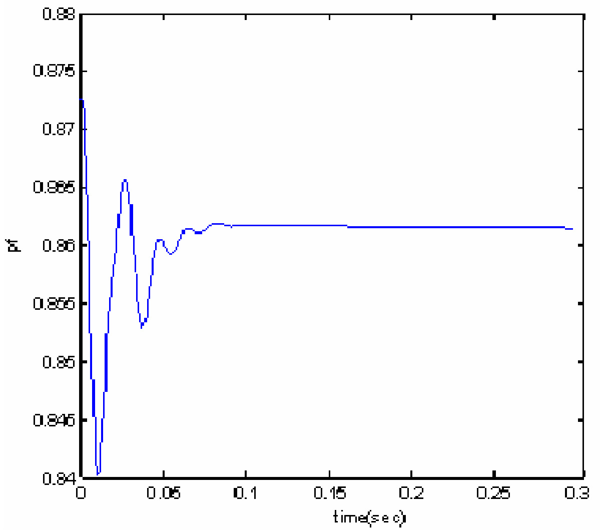


Fig. 9. System power factor with C bank.

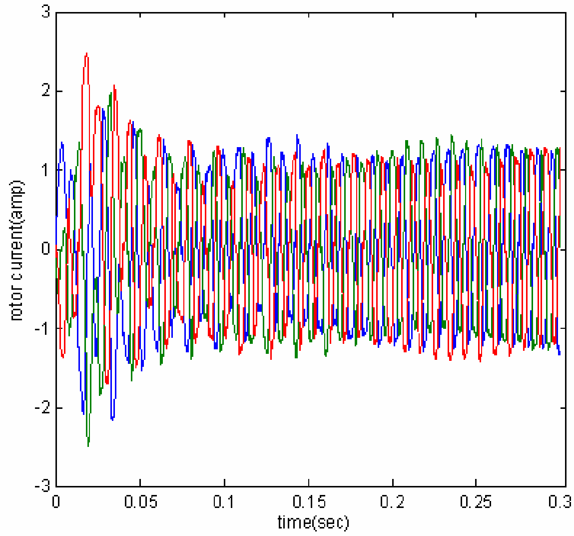


Fig. 10 Stator current at abrupt wind speed variation with inductances.

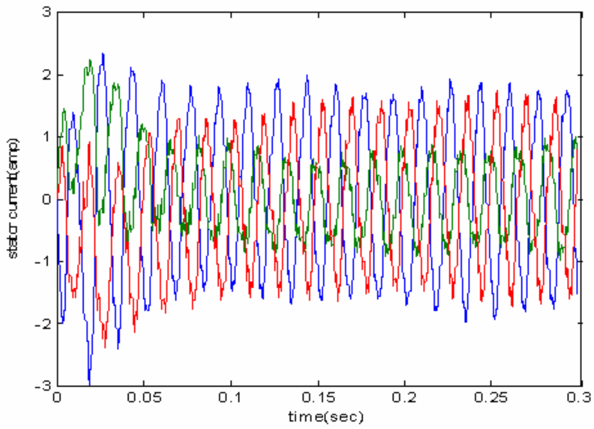


Fig. (11) Rotor current at abrupt wind speed variation with inductances

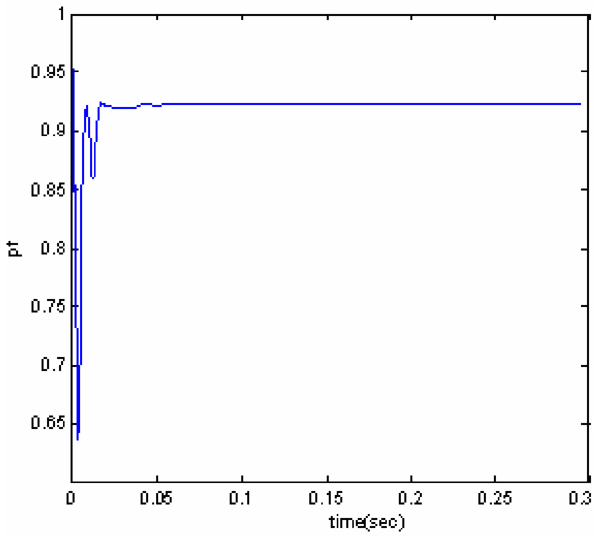


Fig. 12 System p.f. with Inductances.

IV. Inductances for Reducing Transients

A 3-phase inductance, equal to magnitude of DOIG self inductance, is inserted at stator terminals for a time equivalent to time taken to reach steady state. It is then disconnected using a timer switch, since its pertinent existence affects the generator performance. The effect of inserting these inductances is investigated at sharp wind speed variation. Connecting inductances to stator terminals modify equations (1) –(9) where the stator self inductance Ls is replaced by Ls + L_{ext}., where L_{ext} is the proposed added external inductance.

The applied external inductances, reduced the stator and rotor currents and voltage to nearly steady state value, as shown in Figs. 10 and 11. Also the system power factor is improved as shown in Fig. 12 (steady state p.f. value = 0.92), when compared to Fig.6, which demonstrates the system power factor without inductances(steady state p.f. value = 0.575).

IV. Reducing the Effects of 3-Phase Short-Circuit Grid Fault

A three phase ground fault is assumed at t=4sec. for one second duration at DOIG speed equals 1.05 of synchronous speed. Figure 13 shows the effect of the 3-phase fault on stator current without added inductances.

Figure 14 shows the effect of 3 phase fault on stator current after adding the inductances at stator input. As shown, the current transients are mitigated. Fig. 15 reveals the effect of inductances on the system power factor. In Fig. 15-(a), where the external inductance is not yet added, it is clear that the p.f. is reduced by 30% during fault and is restored to its previous value after fault removal with high spikes. When adding the inductances, as shown in Figure 15-(b), these spikes are removed and the value of p.f. has improved.

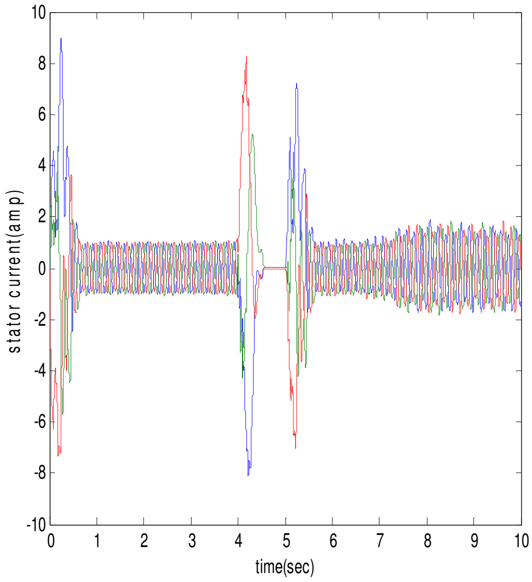


Fig. 13, Stator current at 3 phase ground fault.

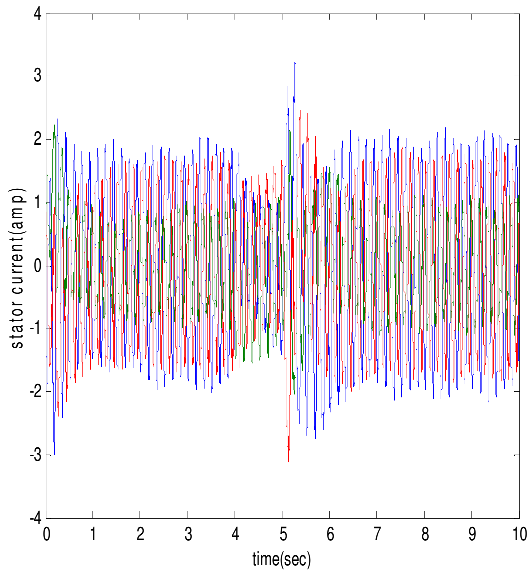
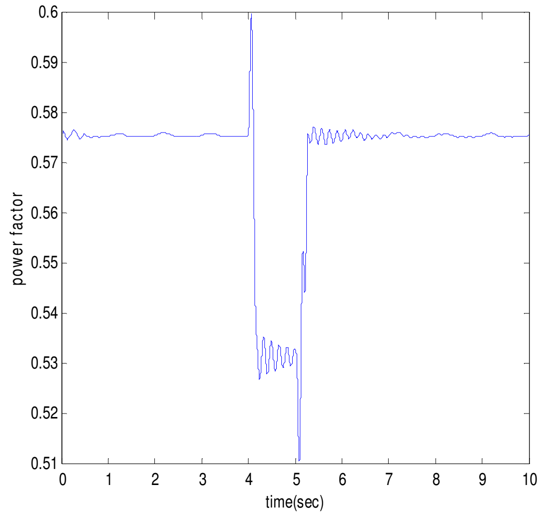
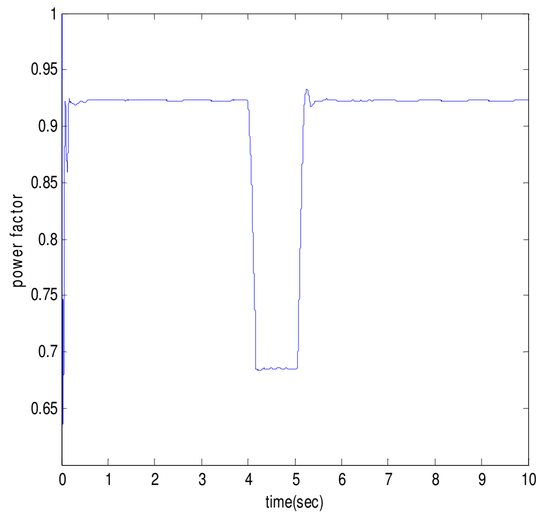


Fig. 14, Stator current at 3 phase ground fault with inductances



(a) without inductance



(b) with inductance

Figs 15 p.f. without and with inductances respectively

The simulation is repeated for another value of DOIG speed, namely 1.1 of synchronous speed. Figure 16 shows the oscilloscope of stator currents I_{abcs}, rotor currents I_{abcr}, rotor speed W_r, and electrical torque Te with external inductance. The smooth variations in speed and torque during the 3-phase fault is obvious.

V. Conclusion

In this paper, solutions for two problems encountered with wind energy conversion systems employing double output induction generators are investigated. The first problem is the transients occurring in generator currents and voltages due to

abrupt changes in wind speed. The second problem is the sharp transients taking place after grid faults to ground.
Two solutions are proposed, the first is by adding 3-phase capacitor banks at the stator input. Adding capacitor bank improved system power factor but is not effective in mitigating current transients due to wind speed variations.
The second proposed solution is adding 3-phase inductances whose value equal to stator self inductance. Results proved that adding 3 phase inductances at stator input terminals for few seconds damped the transient stator and rotor currents and voltages for the case of wind speed variations and 3-phase grid to ground faults. Also these external inductances improved the system power factor.
Simulation results showed an approximate 50% reduction in stator and rotor current transients and an approximate 30% increase in system power factor due to the external inductances.

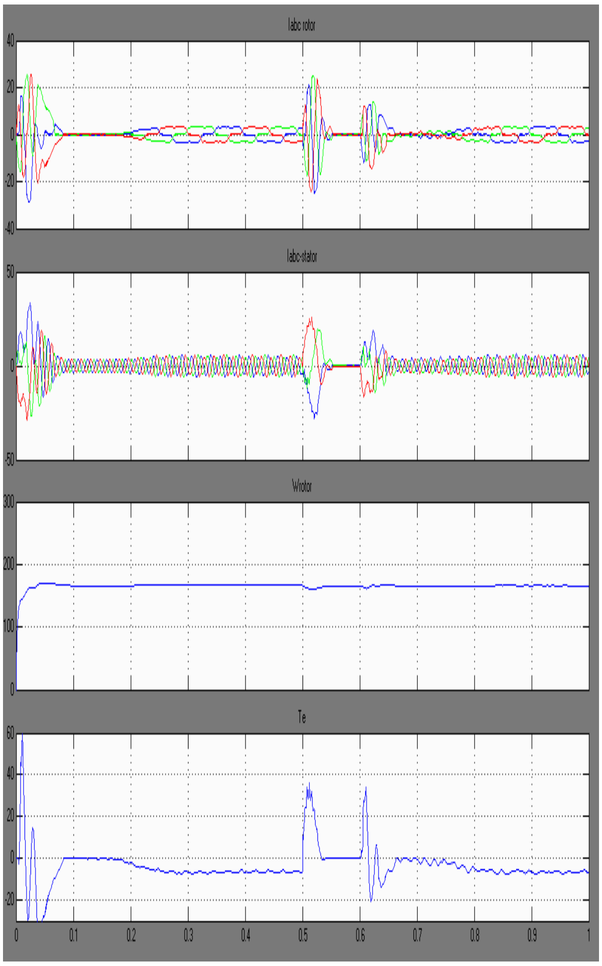


Fig. 16 Effect of Inductance on DOIG performance during 3-phase fault.

Appendix

Machine parameters:
P=3.7Kw, V_s =460 V,
R_s=1.115ohm, L_s=0.006H,
R_r=1.083Ohm, L_r=0.006H,
L_m= 0.2037H, p=4,
J=0.00575kg m2, K=0.02
PID controller parameters at super synchronous speed equivalent to s=-0.05:
K_p = 5, K_i = 1,
K_d = 0.02

List of Symbols:

P :active power
V_s :stator voltage
p: number of poles
R_s :stator resistance
R_r :rotor resistance
L_s: stator self inductance
L_r: rotor self inductance
L_m: mutual inductance
J: moment of inertia
K: friction constant
ω_r : rotor speed (rpm)
s= slip
L_{ext}: external inductance
K_p: proportional gain
K_i: integral gain
K_d: derivative gain

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