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Dynamic Behaviour of a Doubly Fed Induction Machine with Generator-side Converter under Abnormal Condition

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Abstract: This paper describes the dynamic behaviour of a doubly-fed induction machine, operating with wind turbine. The rotor circuit of the machine consists only of a generator-side converter working under abnormal condition at stator side (fault condition and voltage drop take place in transmission lines of the grid system). The induction machine model is based on the stationary reference frame and the control-unit model is based on the line-voltage oriented reference frame. The generator-side controller provides good decoupling between active and reactive power. A powerful MATLAB/SIMULINK was used for the simulation of the wind energy conversion system of a 4 kW wind generator. The simulation results of the generator side converter show that the speed, torque and the sinφ (power factor) can be regulated independently to match the reference signals. The effects of assumed abnormal condition in the grid system are discussed with regard to stator current and rotor current of the induction machine. The results indicate that during a fault condition the inverter should be disconnected in order to reduce the high oscillation in stator currents and rotor currents. In the case of a voltage drop, it indicates that the inverter should be automatically disconnected with a protective relay.

Keywords:Doubly Fed Induction Generator, Decoupled Control, Power Factor, Line Voltage Oriented.

Introduction

Wind energy conversion system with a squirrel-cage induction generator, there are three methods that the stator can be connected to the grid, namely

- direct grid connection method
- grid connection via direct-current intermediate circuit method
    - o with thyristor conveter
    - o with pulse inverter
- grid connection via direct a.c. converter method If the generator is a wound rotor induction machine, the control schemes include
- dynamic slip control method
- oversynchronous static Kraemer system method
- doubly fed induction machine (DFIM) method

Various control algorithms have been recommended to implement on the operation of a doubly fed induction machine. The rating of the power converter in the rotor circui needs only to be about 30 % of the power rating of the generator. Quang, Dittrich and Thieme [1] showed a control algorithm with decoupling of torque, power factor and electrical equation systems of the DFIM using line voltage oriented reference frame. The important concept of the line voltage orientation is that, it requires the accurate and robust acquisition of the phase angle of the line voltage fundamental wave. Usually, this is fulfilled by means of a phase locked loop (PLL). The control design concept is implemented via the continuous and time discrete state space models. Dittrich, Hofmann, Stoev and Thieme [2] presented comparisons between the modeling of the field orientation controlled induction machine and line voltage orientation methods. However, the final design of the control unit was based on the line voltage orientation and the controllers are designed to regulate with torque and $\sin\varphi$ as reference values. Pena, Clare and Asher [3] showed control strategies focused on using back-to-back PWM voltage source converter (Scherbius scheme) in the rotor circuit which can overcome the disadvantage of the naturally commutated DC-link and cycloconverter schemes. The line orientation method is used for the supply-side converter (connected to grid) and the stator flux orientation method for the generator side converter (connected to rotor of the machine). Yifan Tang and Longya Xu [4] studied optimal operation by the variable speed constant frequency mode (VSCF) using stator flux oriented control with digital simulation. They suggested that expansion of the speed range and reduction of the slip power losses could be done simultaneously by means of doubly fed rotor windings. Mitsutoshi Yamamoto and Osamu Motoyoshi[5] described a control method using a rotating reference frame fixed on the air-gap flux of the generator and cycloconvertor which can control the active and reactive power with good stability and independently. The steady state analysis of an induction machine operated at varying shaft speeds in the subsynchronous and super-synchronous region was derived byI.Cadirci and M.Ermis [6]. The main concept is to control both the magnitude and direction of the slip power. Leonhard [7] studied the field oriented control Scherbius scheme of doubly fed induction machine with cycloconverter via current control. The mathematical model of the symmetrical induction machine and the control part are transformed to field coordinate.

In this paper a control strategy is presented for a wound rotor induction generator. The induction machine model is based on the stationary reference frame and the control-unit model is based on the line-voltage oriented reference frame.The generator-side controller provides good decoupling between active and reactive power. The powerful MATLAB/SIMULINK has been used for the simulation of the wind energy conversion system with 4 kW generator. The effects of assumed abnormal conditions in the grid system are discussed with regard to stator current, rotor current and torque in the drive train of the induction machine.

System Study

This study is made with simulation on the Matlab/Simulink and Power System Block Set modules. The induction machine is modeled on the stationary reference frame [8]. Because of the transient studies of adjustable-speed drives, stationary reference frame is usually more convenient than synchronously rotating reference frame, which is appropriate for power system studies. With stationary reference frame, the speed of the reference frame is equal to zero. Stator and rotor voltage equation, flux linkage equation and torque equation are utilized for modeling in term of q component, d component and zero component. Stator and rotor circuits are assumed to be star connected. In addition, all rotor parameters are transformed to stator side via stator-rotor turns ratio (in this study a turn ratio of 1 is assumed). In addition, the model of grid system corresponds to the typical transmission system which consists of electrical source 110 kVL-L, step down transformer 110kVL-L/30kVL-L and 2 sections of transmission lines. The transmission lines are modeled with distributed parameters for medium voltage level of 30kVL-L. A step down 30kVL-L/1.195kVL-L transformer connects the transmission lines to the wind generator.The simulation the abnormal conditions, for example, fault condition and voltage drop occur at the grid system.

Concerning the control part, this study concentrates only on the generator-side converter structure as shown in Fig. 1 (solid line). For modeling, the mathematical model of generator-side converter is transformed to line voltage oriented reference frame. Line voltage oriented reference frame is one of the reference frame of vector control schemes which include stator flux orientation and rotor flux orientation. Stator current and rotor current are transformed to the D and Q axis of this reference frame. This is because setting up controller in D,Q axis is easier than three phase ABC. The PI controller is implemented to regulate the speed, torque, sinφ and current reference values.

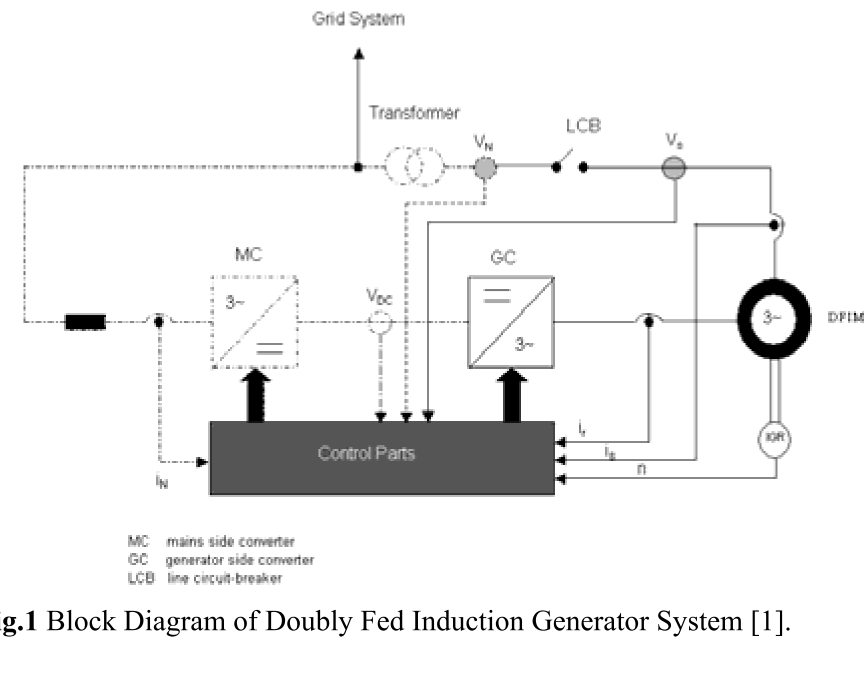

Fig.1 Block Diagram of Doubly Fed Induction Generator System [1].

Generator-Side Control

The concept of generator-side control was implemented by [1]. The wound rotor induction machine is controlled in a line-voltage orientation dq axis reference frame, with the daxis oriented along the line voltage vector position. In this way, a decoupled control between the electrical active power and the reactive power is obtained. The definition of line voltage orientation is shown by the following formula:

$$u_{qs} = 0, \Psi_{ds} = 0 \tag{1}$$

Since the stator is connected to the grid, the influence of the stator resistance is small, the stator magnetizing current *ms i* can be considered as constant. With line voltage orientation, the relationship between the torque and the voltages, the currents and the fluxes (all quantities are normalized by their AC per phase quantities) can be written as:

$$\begin{aligned}
\Psi_s &= \Psi_{qs} = L_s i_{qs} + L_m i_{qr} = L_m i_{ms} \\
\Psi_{dr} &= i_{dr} L_r \sigma \\
\Psi_{qr} &= \frac{L_m^2 i_{ms}}{L_s} + L_r i_{qr} \sigma \\
i_{ds} &= -\frac{L_m i_{dr}}{L_s}
\end{aligned} \tag{2}$$

As shown in Fig. 2, there are three control loops with PI controllers, the so-called rotor speed loop or torque loop (selectable) and sinφ control loop. The rotor speed and sinφ error are manipulated by PI controller to give * *dr i* and * *qr i* . In case of torque error, the current component * *dr i* is calculated according to Eq. (3).

$$T_{em} = -\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}\Psi_{qs} i_{dr} = -\frac{3}{2}\frac{P}{2}\frac{L_m^2 i_{ms} i_{dr}}{L_s} \tag{3}$$

The *dr i* and *qr i* error are processed by the inner loop PI controller to give ' *dr v* and ' *qr v* respectively. Eq. (4) and (5) can be written as follow:

$$v'_{dr} = R_r i_{dr} + L_r \sigma \frac{di_{dr}}{dt} \tag{4}$$

$$v'_{qr} = R_r i_{qr} + L_r \sigma \frac{di_{qr}}{dt} \tag{5}$$

To ensure good tracking of these currents, compensation terms are added to ' *dr v* and ' *qr v* to obtain the reference voltage* *dr v* and * *qr v* according to the following equations.

$$\begin{aligned}
v^*_{dr} &= v'_{dr} - \omega_{slip}(\Psi_{qs}\frac{L_m}{L_s} + L_r i_{qr}\sigma) \\
v^*_{qr} &= v'_{qr} + \omega_{slip} L_r i_{dr}\sigma \\
\omega_{slip} &= \omega_s - \omega_r \\
\sigma &= 1 - \frac{L_m^2}{L_s L_r} \\
\theta_s &= \int \omega_s dt
\end{aligned} \tag{6}$$

Fig. 2 shows a schematic block diagram for the generatorside control which is designed to control either with

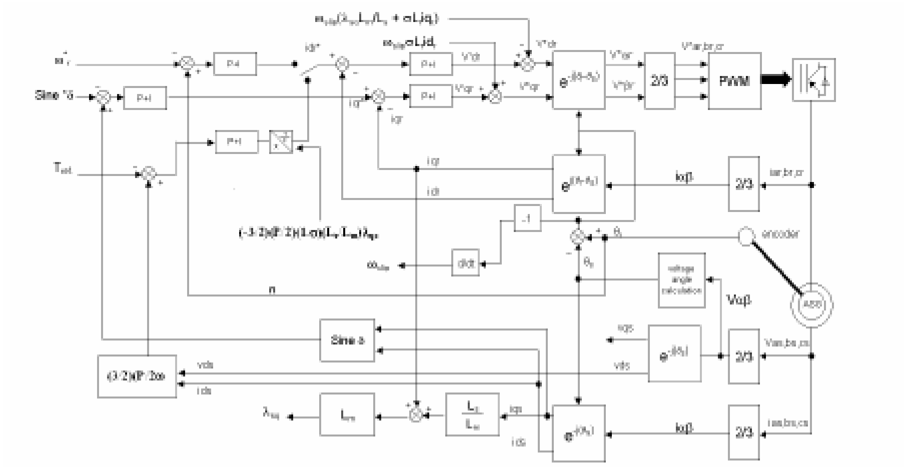

Fig. 2 Schematic of Generator-side control structure * adapted from [1].

Simulation Results

The generator-side control strategies have been validated using the simulation program set up in Fig.2. A 4 kW DFIG wind generator was simulated.

Simulation Results of Decoupled Control of Speed and Sinφ (power factor)

The reference speed was initially set to 400 rad/sec and sinφ reference was set to zero. After approximately 4 seconds, reference speed was reduced to 300 rad/second. Finally, after about 7 seconds, sinφ reference was changed from 0 to -0.6. Fig. 3 shows that the change in speed (at 4 sec)

does not affect on Sinφ (power factor) in the lower curve, decoupling of generator speed and sinφ (power factor) or with decoupling of torque and sinφ (power factor). and the change in Sinφ (at 7 sec) does not have any effect on the speed in upper curve.

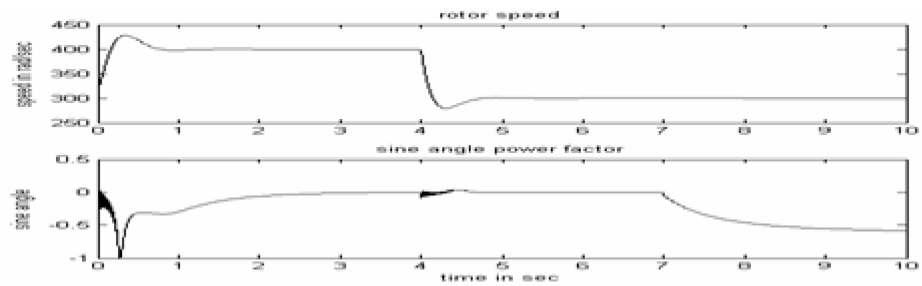

Fig. 3 Simulation result of decoupled control of speed and Sinφ (power factor).

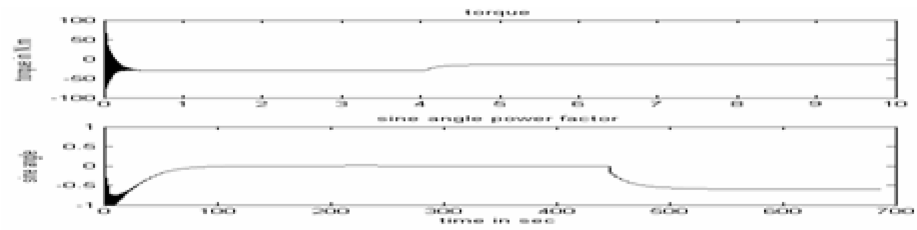

Fig. 4 Simulation result of decoupled control of torque and Sinφ (power factor).

Simulation Results of Decoupled of Torque and Sin φ (power factor) Control

The torque reference was initially set to -30 N.m and sinφ of 0.0. After approximately 4 second, the torque reference is reduced -15 N.m. Finally, after about 7 sec, sinφ reference was changed from 0.0 to-0.6.Fig.4 shows that the change in torque (at 4 sec) does not affect on Sinφ (power factor) as shown in upper curve and the change in Sinφ (at 7 sec) does not have any effect on the torque in the lower curve.

Simulation Result for Abnormal Conditions

This simulation was implemented to study the dynamic behavior of induction machine under abnormal conditions on grid system. The generator speed and sinφ controller were used for this simulation. The sinφ reference was set to zero. The generator speed reference (ω_{ge}) was set to 300 rad/sec and the external torque was set to 25 N.m.

a. Short Circuit Fault on Transmission Lines

Short circuit fault was applied on transmission lines by using 3 phase fault model. The 3 phase fault was applied after 5 seconds. The simulation result is shown in Fig. 5 for keeping the inverter connected all time and shown in Fig. 6 for disconnecting inverter after 5 second. The results obtained indicate that during a fault condition the oscillation amplitude of the rotor and the stator current was reduced if the inverter was disconnected.

b. Volt age drop on transmission

The voltage source was modified with the voltage gain block of the SIMULINK in order to adjust the desired voltage to 50 % of nominal voltage. The voltage drop was applied after 5 seconds. The simulation result was shown in Fig. 7 for keeping the inverter connected all time and shown in Fig. 8 for disconnecting inverter after 5 seconds. The results show that the oscillation amplitude of the rotor and the stator currents are similar in both cases.

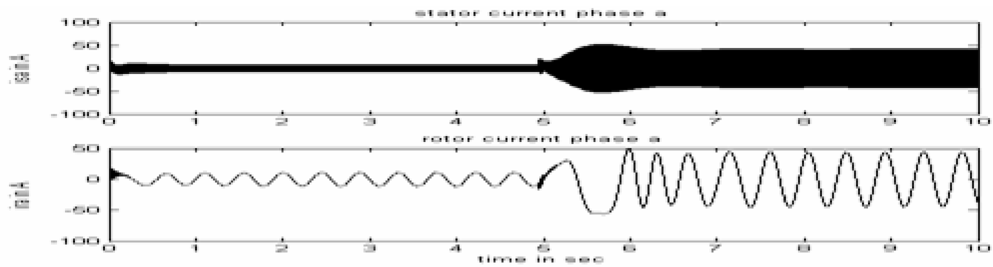

Fig.5 Simulation Result of 3 phase fault with connecting inverter all time.

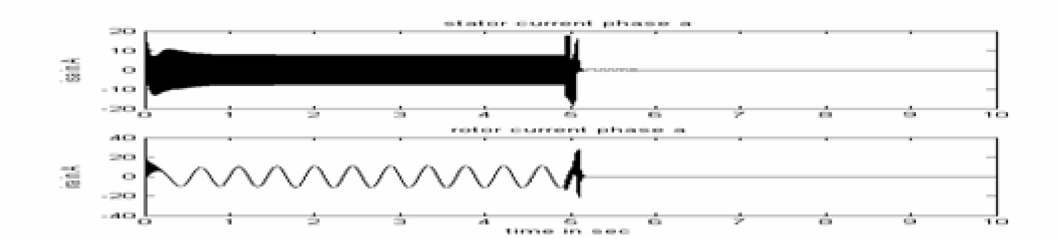

Fig. 6 Simulation Result of 3 phase fault with disconnecting inverter after 5 seconds

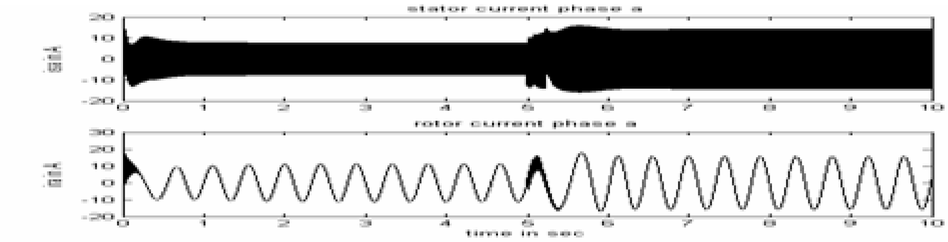

Fig.7 Simulation Result of voltage drop with connecting inverter all time

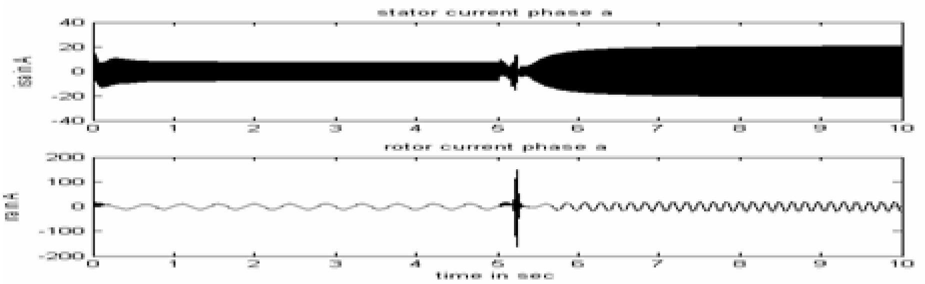

Fig. 8 Simulation Result of voltage drop with disconnecting after 5 seconds.

Conclusion

The dynamic behavior of a DFIG with generator- side converter was investigated. The decoupled controls of speed and sinφ , torque and sinφ of the DFIG were achieved by adjusting P+I controller and line-voltage oriented reference frame technique. Under abnormal condition in the grid system, the results indicate that during a fault condition the inverter should be disconnected in order to reduce the high oscillation in stator currents and rotor currents. In the case of a voltage drop, it can also be concluded that the inverter should be automatically disconnected with a protective relay.

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References

[1] Quang, N.P., Dittrich, A and Thieme, A. (1997). *Doublyfed induction machine as generator :control algorithms with decoupling of torque and power factor*, Electrical Engineering, **80**, pp. 325-335.

[2] Dittrich, A., Hoffmann, W.,Stoev, A. and Thieme, A. *Design and control of a wind power station with double fed induction generator*, EPE'97, pp. 2.723-2.728.

[3] Pena, R., Clare, J.C. and Asher, G.M.. (1996). *Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation*, IEE Proc.-Electr. Power Appl. **Vol.143**, No.3 pp. 231-241.

[4] Yifan, T., Longya, X. (1992). *Stator field oriented control of doubly excited induction machine in wind power generating system*, IEEE Transactions on Power Electronics, pp. 1446-1449.

[5] Yamamoto, M., Motoyoshi, O. (1991). *Active and reactive power control for doubly-fed wound rotor induction generator*, IEEE Transactions on Power Electronics **Vol. 6**. No. 4 pp. 624-629.

[6] Cadirci, I.., Ermis, M. (1992). *Double- output induction generator operating at subsynchronous and supersynchronous speeds: steady-state performance optimisation and wind-energy recovery*, IEE Proceedings-b, **Vol.139**, No. 5.pp. 429-442.

[7] Leonhard, W. *Control of Electrical Drives*, Springer- Verlag.

[8] Chee, M. O. *Dynamic Simulation of Electric Machinery,* Prentice Hall PTR.

LIST OF SYMBOLS

$v_{ds}, v_{qs}, v_{dr}, v_{qr}$	= 2-axis machine voltages
$i_{ds}, i_{qs}, i_{dr}, i_{qr}$	= 2-axis machine currents
Ψ	= flux linkage
L_s, L_r, L_m	= machine inductance per phase
R_r, R_s	= machine resistance per phase
σ	= leakage factor
i_{ms}	= magnetizing current referred to stator
ω_s, ω_r	= stator, rotor angular frequency
ω_{slip}	= slip angular frequency
θ_s, θ_r	= stator voltage, rotor angle
T_{em}	= electromagnetic torque

Suffices

d,q	= d-q (line voltage orientation) axes
α, β	= α, β (stationary) axes
s,r	= stator, rotor

Superscripts

'	= referred to stator side
*	= demanded (reference value)