Stator Field Oriented Control of Doubly-Excited Induction Machine in Wind Power Generating System

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Abstract- Optimal operation of a wind power generating system is featured by the variable-speed constant-frequency mode in which maximum-power-capturing from the wind turbine and constant-frequency-interfacing with the power system are the primary concerns. A slip power recovery system with a doubly excited wound rotor induction machine is attractive in this situation. In this paper, field orientation control for doubly-excited induction machines is studied. Since the operational condition and control objectives of the variable-speed constant-frequency generating system are significantly different from those of a variable speed drive system, implementation strategy of field orientation control of induction machines must be re-examined. A stator field orientation control method suitable for the doubly excited induction machine in a wind power generating system is developed. Digital simulation is carried out showing that the doubly excited induction generator with the proposed control strategy can track the optimal torque-speed profile of a wind turbine very well. In addition, flexible reactive power control is also accomplished.

INTRODUCTION

Variable-speed operation is critical to gain high efficiency for certain generating systems. For example, in a wind power generating system, it is required that the generator track a prescribed torque-speed profile, usually a square function [1], or otherwise not only the generating system can not capture the largest possible energy available from wind but the blades of the wind mill will subject to torsional stress and windage friction. On the other hand, to interface the generating system with the power system, the frequency of the output voltage from the generator must be constant.

To configure a variable speed constant frequency (VSCF) system, induction generator is considered very attractive for its flexible rotor speed with respect to the constant stator frequency. While the rotor speed of an induction machine is allowed to vary, the slip power losses set the limit for the rotor speed range. Whenever the rotor speed is beyond the limit, slip power losses become unacceptable and the efficiency of the machine becomes very low. The solution to expand the speed range and reduce the slip power losses simultaneously is to doubly excite the stator and rotor windings. In the doubly excited scheme, a solid-state power converter regenerates the majority of the slip power back to the power grid, thus improving system efficiency significantly.

Various control algorithms have been suggested to implement operation of a doubly excited induction machine. For a doubly-excited induction motor, Ioannidou and Tegopoulos [2] studied the relations of rotor current, torque, slip power, power factor and efficiency with speed, rotor voltage magnitude and phase angle. It was suggested that by controlling the latter three quantities, it is possible to meet any torque-speed requirement, and optimize some of the performance indexes such as efficiency and power factor. For a doubly-excited induction generator, Holmes and Elsonbaty [1] and Vicatos and Tegopoulos [3] expressed the complicated torque-speed relation in stator and rotor voltages along with machine parameters. It was derived that there are three torque components, namely, two asynchronous torque produced by the stator source and the rotor source respectively and a synchronous torque produced by the interaction of the two sources. A constant stator frequency can be maintained over a wide speed range by supplying the rotor circuit with slip-frequency voltage, and the speed may be sub-synchronous, when slip-power is subtracted from the rotor circuit, or super-synchronous, when slip-power is supplied to the rotor circuit [1,3].

Therefore, we can conclude that it is possible for a wound rotor induction machine to achieve VSCF operation and to recover slip power, by implementing control in the rotor circuit. However, using the existing models and methods [1,2,3], both performance analysis and control of torque, speed, power, etc., seems a formidable task.

In this paper, a field orientation control method for doubly-excited induction machines is developed, based on the stator flux d-q model. Field orientation control for well-known variable speed induction motors is reviewed and the fundamental differences of an induction machine in variable speed drives and VSCF generating systems are discussed, then a field orientation control method suitable for a doubly-excited induction machine in a wind power generating system is developed, with digital simulations.

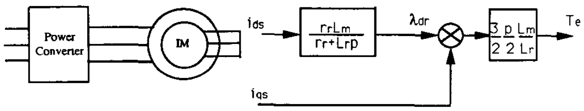
FIELD ORIENTATION CONTROL FOR DOUBLY-EXCITED INDUCTION MACHINES

A. Operational principle and modeling of doubly-excited induction machines

Field orientation or vector control of an induction motor drive systems has been actively researched for the last decade. The decoupled torque and flux control in AC motors based on the concept of field orientation has become a standard of comparison for high performance AC drives. Although the subject of field orientation control (FOC) is not a closed chapter in the story of AC drives, it is at a relatively mature stage [4].

However, theory and implication of applying field orientation control technique to the variable speed constant frequency generating system remained a nearly unexplored territory. The operational condition and control objectives of drive systems and generating systems are vastly different. It is, therefore, instructive to examine the fundamental differences of the two systems.

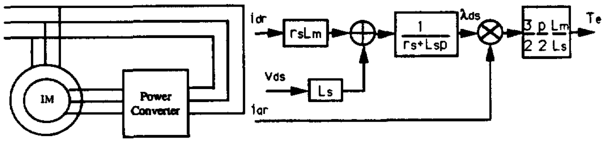
Figure 1(a) shows the structure of a cage induction motor in a variable speed drive system. At the rotor side, the input voltage is identically zero because of the short-circuit cage while at the stator side, the input voltage is completely conditioned to a proper magnitude, frequency and phase angle according to the FOC algorithm so as to achieve desirable performance. Torque production diagram for FOC is described in Figure 1(b).



(a) Structure (b) Torque Production

Fig. 1. Singly-excited Induction Machine

Compared with a cage induction motor with FOC, the terminal constraints of a doubly-excited induction machine are somewhat interchanged in a VSCF generating system. As shown in Figure 2(a), the magnitude and frequency of the stator voltage are constants defined by the utility power supply while the rotor terminal receives fully controlled voltage from a power converter. In addition, in the doubly excitation scheme, the power converter processes only part of the total power converted by the induction machine, corresponding to the slip power of the machine.



(a) Structure (b) Torque Production

Fig. 2. Doubly-excited Wound-rotor Induction Machine

Under the new terminal constraints, which is substantially different from that of a singly-excited induction machine, operation of a doubly excited induction machine has the following features :

1) The levels of the stator flux, airgap flux and rotor flux are approximately unchanged over a wide speed range, since the frequency and magnitude of the stator voltage are fixed.

2) The speed of its rotating field is constant, whereas for a singly-excited induction motor, the speed of the rotating flux is controllable and so is the slip of the rotor. For a doubly-excited induction machine to achieve variable speed operation, the only possibility is to change the slip frequency, instead of changing both the stator frequency and the slip frequency as in the case of singly-excited induction motor.

3) Speed and torque are controllable through the power converter linked to the rotor circuit. For the system to achieve a higher efficiency, the energy circulation via the slip power recovery process is inevitable. The slip power may be substracted from or supplied to the rotor circuit, when the system is operating in sub-synchronous speed or super-synchronous speed, respectively.

The stator voltage equations of the induction machine in the arbitrary rotating *d-q-n* reference frame can be written as [5]

$$\underline{v}_{dqs} = r_s \, i_{dqs} + \frac{d\underline{\lambda}_{dqs}}{dt} + \underline{\omega} \times \underline{\lambda}_{dqs} \tag{1}$$

where $\underline{\lambda}_{dqs} = \begin{pmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{ns} \end{pmatrix}$, $\underline{\omega} = \begin{pmatrix} 0 & -\omega & 0 \\ \omega & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$,

$\underline{v}_{dqs} = \begin{pmatrix} v_{ds} \\ v_{qs} \\ v_{ns} \end{pmatrix}$, $i_{dqs} = \begin{pmatrix} i_{ds} \\ i_{qs} \\ i_{ns} \end{pmatrix}$,

$i_{dqr} = \begin{pmatrix} i_{dr} \\ i_{qr} \\ i_{nr} \end{pmatrix}$,

and "x" represents vector cross product. ω is the rotating speed of the reference frame. The stator flux linkages are related to the currents, also in matrix form,

$$\underline{\lambda}_{dqs} = \underline{L}_s \, \underline{i}_{dqs} + \underline{L}_m \, \underline{i}_{dqr} \tag{2}$$

where $\underline{L}_s = \begin{pmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{pmatrix}$ $\underline{L}_m = \begin{pmatrix} L_m & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & 0 \end{pmatrix}$

The torque equation can be written as

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_{ds} \, i_{qr} - \lambda_{qs} \, i_{dr}) \tag{3}$$

Note that the voltage equations of the rotor circuit are not included assuming that the current i_{qr} and i_{dr} are known quantities produced by a current regulated PWM converter.

B. Stator field orientation control

In a wind power generating system, control schemes for the doubly-excited induction machine are expected to achieve the following objectives: 1) The induction generator is required to track a prescribed torque-speed curve, for maximum wind power capturing; 2) The stator output voltage frequency must be constant; 3) Flexible reactive power control is achievable. Other issues such as stability and parameter sensitivity are also important.

The stator field orientation control is based on the stator flux d-q model, where the reference frame rotates synchronously with respect to the stator flux, with its d-axis overlaps the instantaneous axis of the stator flux. Therefore, $\omega = \omega_e$, where ω_e is the angular frequency of the stator voltage, and $\lambda_{qs} = 0$. For such a reference frame selection, the system equations, in scalar form, are reduced to

$$v_{ds} = r_s \, i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{4}$$

$$v_{qs} = r_s \, i_{qs} + \omega_e \lambda_{ds} \tag{5}$$

$$\lambda_{ds} = L_s \, i_{ds} + L_m \, i_{dr} \tag{6}$$

$$\lambda_{qs} = 0 = L_s \, i_{qs} + L_m \, i_{qr} \tag{7}$$

$$v_{qs}^2 + v_{ds}^2 = v_m^2 \tag{8}$$

where v_m is the constant stator voltage magnitude.

Since the d-axis of the reference frame is chosen to be the instantaneous axis of the stator field, the phase angle of the stator voltage is generally not a constant, although its frequency and magnitude are constants constrained by the power system.

The electromagnetic torque is now

$$T_e = \frac{3}{2}\frac{p}{2} \lambda_{ds} \, i_{qr} \tag{9}$$

A torque production diagram derived from (4) through (9) is shown in Fig. 2(b), which is analogous to Figure 1(b), with the role of the stator circuit and the rotor circuit somewhat interchanged.

As discussed previously, the level of the stator flux remains approximately unchanged, constrained by the constant magnitude and frequency of the stator voltage. Therefore, torque control can be most conveniently achieved by controlling the rotor current component orthogonal to the stator flux.

The reactive power at the terminal of the stator winding, in motor convention, can be expressed as

$$Q_s = \frac{3}{2}(v_{qs} \, i_{ds} - v_{ds} \, i_{qs}) \tag{10}$$

From (4) and (5), with the stator flux remaining unchanged, the reactive power can also be expressed as

$$Q_s = \frac{3}{2} \omega_e \lambda_{ds} \, i_{ds} \tag{11}$$

As indicated by (6), i_{ds} is controllable by i_{dr}. Therefore, from (11), the d-axis component of the rotor current, i_{dr}, can be controlled to regulate the reactive power.

As can be seen from (9) and (11), control of torque via i_{qr} and control of reactive power via i_{dr} are essentially decoupled; thus a decoupler is not needed to implement field orientation control. In addition, flux control is unnecessary since it maintains a constant level, while control of the reactive power becomes possible.

STATOR FOC IMPLEMENTATION IN VSCF WIND-POWER GENERATING SYSTEM

Fig. 3 shows an implementation of the stator field oriented control of a doubly-excited induction machine. A current-regulated PWM voltage-source inverter (CRPWM-VSI) is used on the machine side; on the power network side, another PWM-VSI is used. This PWM-VSI can maintain a constant voltage at the DC side; therefore the size of the DC link filter can be reduced; it can also improve interface performance (power factor and harmonic distortion factor) at the AC side. The ability of bi-directional power flow is necessary for the generating system to achieve both sub-synchronous and super-synchronous speed operation. The kVA rating of the power converters is only a portion of the full rating of the machine, depending on the speed range and normal power factor requirement.

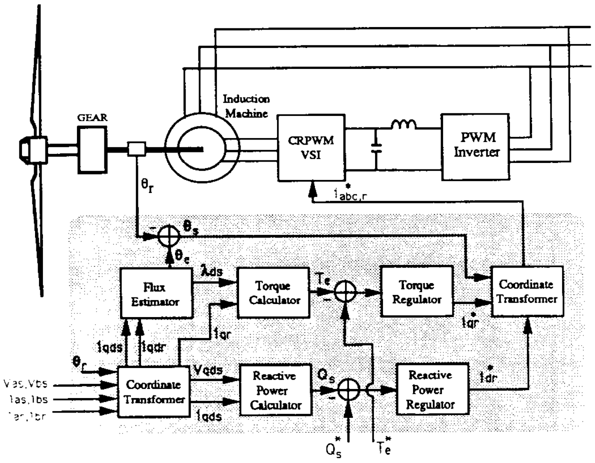


Fig. 3. Field Orientation Control Implementation

In order to control the dynamic torque, the instantaneous position and magnitude of the stator flux is made available through a flux estimator. A rotor current vector is injected orthogonally to the stator field, proportional to the command of the torque. Flexible reactive power control is achieved by controlling the stator current component in the d-axis of the stator field. In addition, the second PWM converter can provide reactive power to the rotor circuit.

A. Steady-state Performance

Using the stator flux model, electromagnectic torque control is decoupled from reactive power control. This and other steady-state characteristics of the doubly-excited induction machines are shown in Fig. 4, over a speed range covering both sub-synchronous and super-synchronous speeds. A typical wind-turbine characteristic is assumed [1], from which optimal power extraction and corresponding wind-turbine torque over a wide speed range can be determined, as shown in Fig. 4(a). The electromagnetic torque T_e is directly controlled by i_{qr} to track the optimal torque-speed profile of the wind-turbine. The reactive power Q_s is directly controlled by i_{dr}, as indicated in Fig. 4(b). In addition, Fig. 4(c) shows that λ_{ds} is nearly unaffected by i_{qr} or i_{dr}, and Fig. 4(d) shows that v_{ds} is negligibly small.

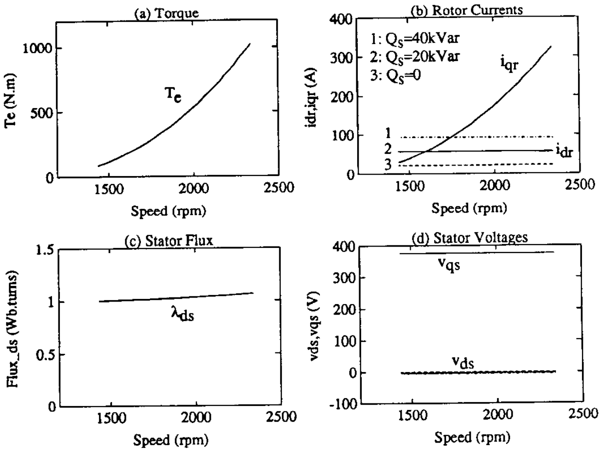
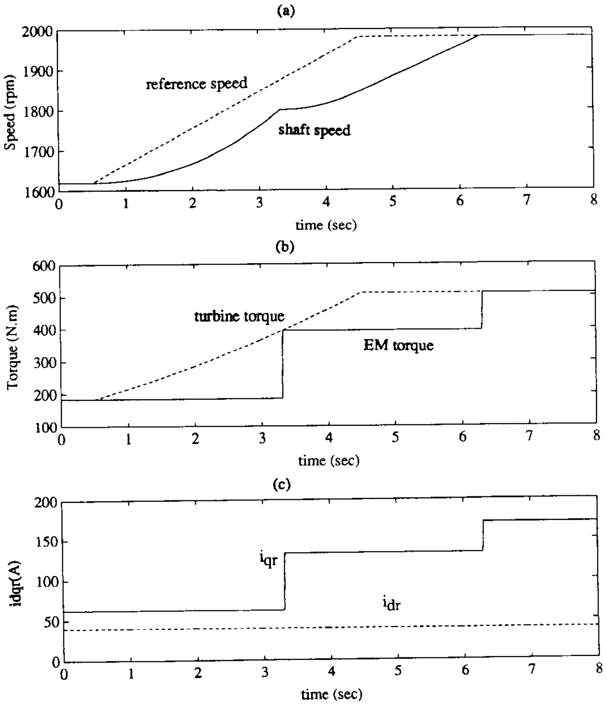


Fig. 4. Steady-state Performance

B. Dynamic Performance

Fig. 5 shows speed-tracking capability of the field orientation controlled doubly-excited induction machine. When wind speed increases linearly in 4 seconds, through appropriate gearing between the wind-turbine and the generator shaft, the corresponding speed reference covers both sub-synchronous and super-synchronous speeds, as shown in Fig. 5(a). Assume an optimal torque-speed reference of Fig. 4(a). In this particular simulation, electromagetic torque is controlled to have two step changes, one at the instant speed reaches synchronous speed and the other at the instant speed reaches steady-state. As can be seen from Fig. 5(d), the rotor currents are controlled by the power converter to have correct slip frequencies.

Fig. 6 shows the control of T_e, with the reactive power command unchanged. Fig. 7 shows the control of Q_s, with the torque command unchanged. Corresponding i_{qr}, i_{dr} and stator winding phase current and voltage i_{as} and v_{as} are also shown.



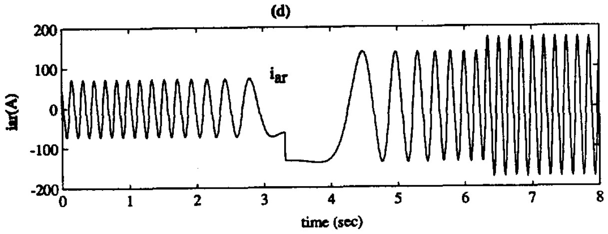


Fig. 5. Speed-tracking by Field Orientation Control

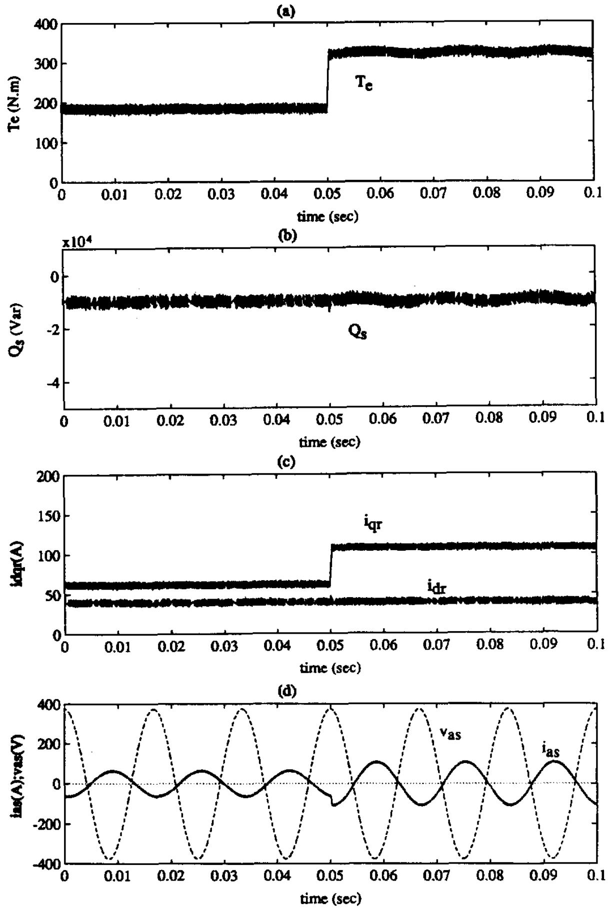


Fig. 6. Control of Electromagnetic Torque

CONCLUSIONS

A stator field oriented control method for doubly-excited wound-rotor induction machines is developed, using a stator flux d-q model. Variable-speed constant-frequency operation of a wind power generating system is studied as an application. High-performance and optimal operation can be achieved, while parameter sensitivity problem associated with field oriented control of induction motor drives is not encountered.

REFERENCES

1) P.G.Holmes, N.A.Elsonbaty, "Cycloconverter-excited Divided-winding Doubly-fed Machine as a Wind-power Converter", IEE Proceedings, Vol. 131, Pt. B, No. 2, March 1984, pp. 61-69

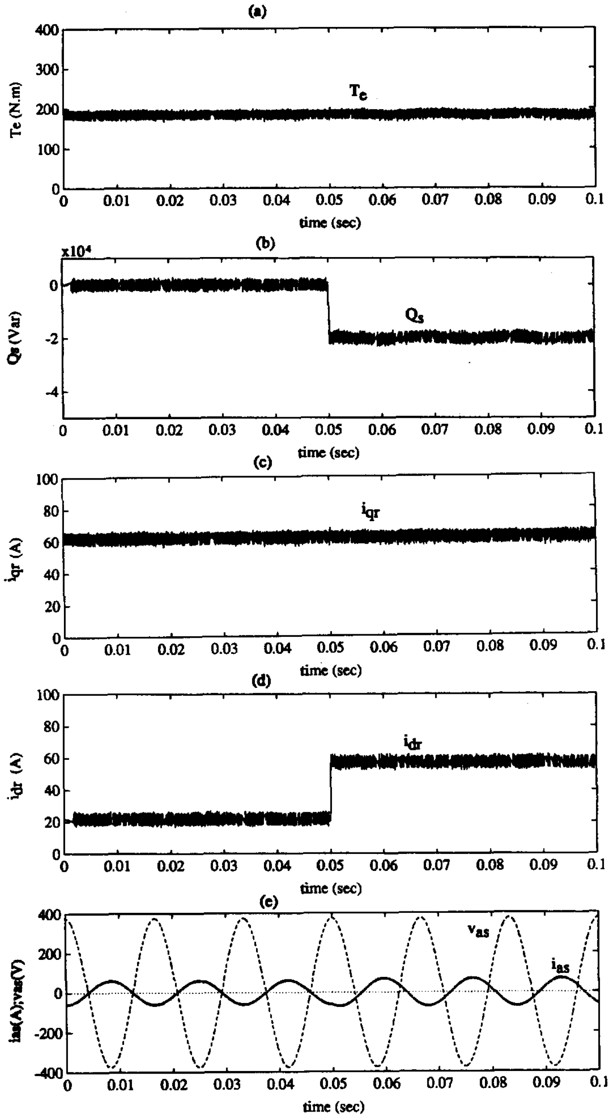


Fig. 7. Control of Reactive Power

2) M.G.Ioannidou, J.A.Tegopoulos, "Generalized Optimization Slip Power Recovery Drives", IEEE Trans. Energy Conversion, Vol. 5, No. 1, March 1990, pp. 91-97

3) M.S.Vicatos, J.A.Tegopoulos, "Steady State Analysis of a Doubly-fed Induction Generator under Synchronous Operation", IEEE Trans. Energy Conversion, Vol. 4, No. 3, September 1989, pp. 495-501

4) D.W.Novotny, R.D.Lorenz, (edited) "Introduction to Field Orientation and High Performance AC Drives", Second Edition, IEEE Industry Application Society Tutorial Course, 1986

5) P.C.Krause, "Analysis of Electric Machinery", McGraw Hill, 1986