Loss Minimization of DFIG for Wind Power Generation

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ABSTRACT

This paper proposes a loss minimization algorithm for doubly-fed induction generator (DFIG) by controlling the stator reactive power. The proposed strategy directly controls the rotor current to achieve the operating point of minimum generator loss and maximum power point tracking. The maximum power is obtained by tracking the q-axis rotor current with generator speed variation and the minimum generator loss is achieved by controlling the d-axis rotor current. Experimental results are shown to verify the validity of the proposed scheme.

1. Introduction

Since the wind energy generation systems (WEGS) consists of different mechanical components like drive train gearbox, generator, etc., numerous losses can be found in the system. The total WEGS losses are divided into two main categories, that is, mechanical and electrical losses. A general power flow diagram for a WEGS is shown in Fig. 1. Minimizing the total generator losses becomes important issue specially as increasing WEGS ratings to MW range. In DFIGs, at a certain generator speed, reactive power flow can be regulated between the stator and rotor windings. This feature can be utilized to minimize the generator losses associated with the given operating point [2].

In this paper, the proposed strategy controls the rotor current to achieve the DFIG minimum loss. The minimum total generator losses are achieved by controlling the stator reactive power level by controlling the rotor d-axis current. The proposed controller does not require the wind speed information. The optimum efficiency of DFIG wind generation system has been implemented experimentally.

2. Control strategy of DFIG

Configuration of the overall wind generation system is shown in Fig. 2. The stator of DFIG is directly connected to the grid and the rotor is connected through back-to-back PWM converters. The DFIG is controlled in a rotating d-q reference frame with the d-axis aligned with the stator flux vector. The stator active and reactive power is controlled by regulating the rotor current and voltage. Therefore the rotor current and voltage needs to be decomposed into the component related to the stator active and reactive power.

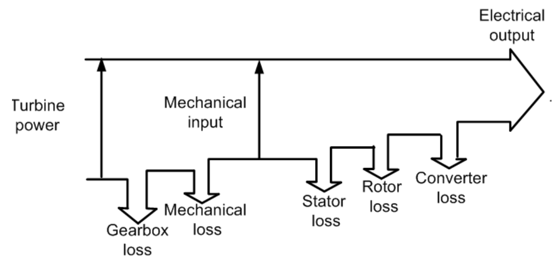

Fig. 1 Power flow in the wind power generation system.

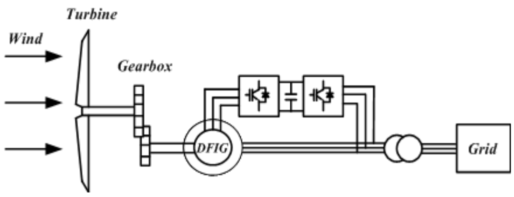

Fig. 2. Configuration of DFIG wind power systems.

2.1 DFIG model

Fig. 3 shows the d-q equivalent circuits of DFIG. Under stator flux-oriented control, the fluxes, currents and voltages can be expressed as [3]

$$\lambda_s = \lambda_{ds} = L_m i_{ms} = L_s i_{ds} + L_m i_{dr} \tag{1}$$

$$\lambda_{qs} = 0 \tag{2}$$

$$\lambda_{dr} = \frac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{dr} \tag{3}$$

$$\lambda_{qr} = \sigma L_r i_{qr} \tag{4}$$

where $\sigma = 1 - \frac{L_m^2}{L_r L_s}$

L_m : magnetizing inductance;

L_s, L_r : stator and rotor self-inductances;

$\lambda_{ds}, \lambda_{qs}$: stator d-q flux linkage;

$\lambda_{dr}, \lambda_{qr}$: rotor d -q flux linkage;

i_{ms}, i_{ds}, i_{dr} : magnetizing, stator and rotor d-axis currents.

Rotor voltages in d-q reference frame can be expressed as a function of rotor and magnetizing currents,

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_{sl} \sigma L_r i_{qr} \quad (5)$$

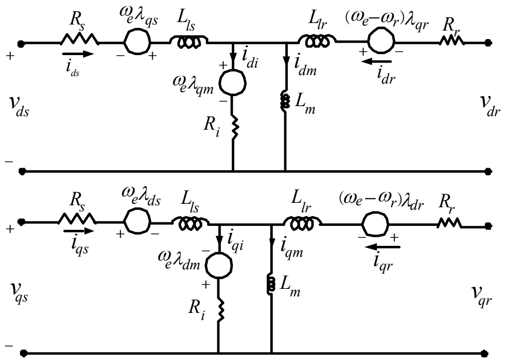

Fig. 3. Equivalent circuits of DFIG.

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_{sl} \left(\frac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{dr} \right) \quad (6)$$

where

v_{dr}, v_{qr}: rotor d-q voltages

R_r: rotor resistance;

ω_{sl}: slip angular frequency.

It is obvious that the cross-coupling effect of the dq-axis components is compensated by adding the decoupling terms in (5) and (6).

The stator flux angle is calculated from

$$\theta_s = \tan^{-1}\left(\frac{\lambda_{qss}}{\lambda_{dss}}\right) \quad (7)$$

where θ_s is the phase angle of the stator-flux vector.

2.2 Power control

Using the flux equations (1)-(4), an interaction between the rotor and stator current components can be obtained

$$i_{qs} = -\frac{L_s}{L_m} i_{qr} \quad (8)$$

$$i_{ds} = \frac{\lambda_{ds}}{L_s} - \frac{L_m}{L_s} i_{dr} \quad (9)$$

Expressing the stator active and reactive power with the stator voltages and currents and using the stator current components in (8) and (9)

$$P_s = \frac{3}{2}(v_{qs} i_{qs} + v_{ds} i_{ds}) = -\frac{3}{2}\frac{L_m}{L_s} v_{qs} i_{qr} \quad (10)$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (11)$$
$$= \frac{3}{2}\frac{L_m}{L_s} v_{qs}(i_{ms} - i_{dr})$$

It is noticeable that the stator active power component is proportional to the i_{qr} and the stator reactive power component is proportional to i_{dr}. Fig. 4 shows schematic

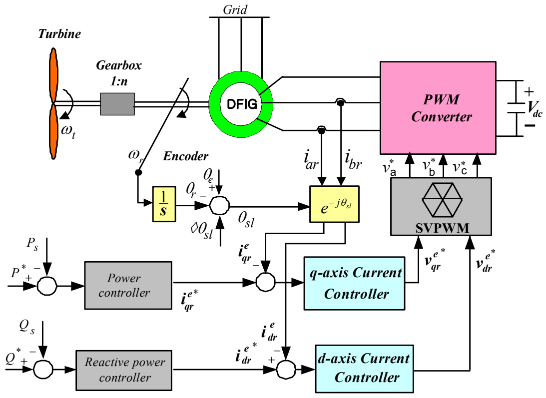

Fig. 4. Rotor-side control of DFIG.

configuration of the DFIG wind turbine system and its simplified control scheme.

2.3 Loss minimization of DFIG

The generator copper loss can be expressed as

$$P_{culoss} = 1.5(i_{ds}^2 + i_{ds}^2)R_s + 1.5(i_{dr}^2 + i_{dr}^2)R_r \quad (12)$$

By substituting (9) and (10) into (12), the copper losses can be derived as a function of stator currents as

$$P_{culoss} = 1.5(i_{ds}^2 + i_{ds}^2)R_s + 1.5((L_s i_{qs}/L_m)^2 \quad (13)$$
$$+ ((\lambda_{ds} - L_s i_{ds})^2/L_m^2))R_r$$

In (13), i_{qs} is used to control the torque or active power, and λ_{ds} remains approximately unchanged due to constant source voltage and frequency, so the amount of machine copper losses is a function of i_{ds}. In steady state, the q-axis current is constant based on the stator active power. The change in the stator d-axis flux in steady state is zero

$$\frac{d\lambda_{ds}}{di_{ds}} = 0 \quad (14)$$

To represent the iron loss, a resistor is connected in parallel with the magnetic branch. The magnetizing flux linkages in the d-q reference frame are as follows

$$\lambda_{dm} = \lambda_{ds} - L_{ls} i_{ds} \quad (15)$$

$$\lambda_{qm} = \lambda_{qs} - L_{ls} i_{qs} \quad (16)$$

Voltage equations in magnetic branch are expressed as

$$R_i i_{di} = \frac{d\lambda_{dm}}{dt} - \omega_e \lambda_{qm} \quad (17)$$

$$R_i i_{qi} = \frac{d\lambda_{qm}}{dt} - \omega_e \lambda_{qm} \quad (18)$$

The flux in d-q synchronous reference frame is almost constant in constant torque region and varies very slowly according to speed variation in the field weakening region. Therefore the flux variation term in synchronously rotating d−q reference frame can be neglected and the current flowing in core loss branch can be expressed as

$$i_{di} = -\omega_e(\lambda_{qs} - L_{ls} i_{qs})/R_i \qquad (19)$$

$$i_{qi} = -\omega_e(\lambda_{ds} - L_{ls} i_{ds})/R_i \qquad (20)$$

The generator iron losses can be expressed as

$$P_{ironloss} = 1.5((-\omega_e(\lambda_{qs} - L_{ls} i_{qs})/R_i)^2 + (\omega_e(\lambda_{ds} - L_{ls} i_{ds})/R_i)^2)R_i \qquad (21)$$

To minimize the total losses, the derivative of these losses with i_{ds} is set to zero,

$$3\frac{\omega_e^2}{R_i}(L_{ls}^2 i_{ds} - L_{ls}\lambda_{ds}) + 3R_s i_{ds} + 3\frac{R_r}{L_m^2}(-L_s\lambda_{ds} + L_s^2 i_{ds}) = 0. \qquad (22)$$

The d−axis current for minimum losses

$$i_{ds} = \frac{(L_s R_r R_i + L_m^2 \omega_e^2 L_{ls})\lambda_{ds}}{L_m^2 R_s R_i + L_s^2 R_r R_i + L_m^2 \omega_e^2 L_{ls}^2} \qquad (23)$$

The reactive power reference can be adjusted based on this value as

$$Q_s^* = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) = \frac{3}{2} v_{qs} i_{ds}$$

(24)

3. Experimental results

To test the proposed control strategy, the experimental verification of DFIG loss minimization are performed. Fig. 5 shows the generator performance at 5[m/s] wind speed. The DFIG starts with the zero reactive power reference, and then the loss minimization algorithm is activated and remains activated as shown in Fig. 5 (c). The total generator loss decreases when the generator reactive power is set to the optimum value. The power loss is decreased from 130[W] to 100[W], it means about 26% saving of power loss is obtained. Fig. 6 shows the power loss for the given condition versus the wind speed. It can be seen that the loss minimization control by setting the reactive power to a certain value rather than zero is effective.

4. Conclusions

It is well known that wind generation system may operate at a fraction of the rated power most of the time. Reducing the generator losses is critical issue for reducing the cost of energy in such conditions. In this paper, a loss minimization algorithm for wind driven DFIG was proposed. The total generator losses are minimized through controlling the stator reactive power. To verify the effectiveness of the proposed algorithm, the experimental verifications have been performed for a 3[kW] doubly−fed induction generator system. The experimental results have shown that it is possible to reduce the power loss up to 30% at 7[m/s] wind speed.

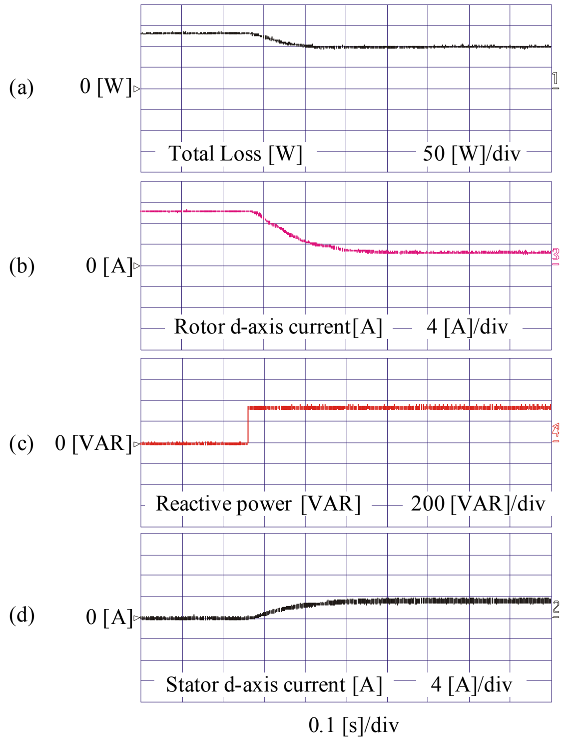

Fig. 5. (a) Rotor d−axis current (b)total loss (c) Stator reactive power (d) stator d−axis current.

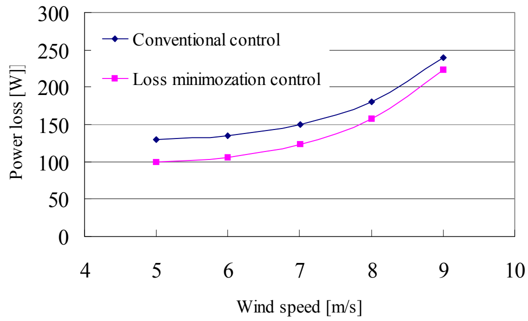

Fig. 6. Generator loss minimization.

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