Output Power Control of Wind Generation System by Machine Loss Minimization

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Key words : wind power, MPPT control, adjustable speed control, induction generator, back-to-back PWM converter, grid connection.

Abstract : Generator efficiency optimization is important for economic saving and environmental pollution reduction. In general, the machine loss can be reduced by the decreasing the flux level, resulting in the significant reduction of the core loss. This paper proposesan model-based controller is used to decrement the excitation current component on the basis of measured stator current and machine parameters and the q-axis current component controls the generator torque, by which the speed of the induction generator iscontrolled according to the variation of the wind speed in order to produce the maximum output power. The generator reference speed is adjusted according to the optimum tip-speed ratio. The generated power flows into the utility grid through the back-to-back PWM converter. The grid-side converter controls the dc link voltage and the line-side power factor by the q-axis and the d-axis current control, respectively. Experimental results are shown to verify the validity of the proposed scheme.

Nomenclature

ρ :Specific density of air [kg/m^3]
υ :Wind speed [m/s]
R :Radius of the turbine blade
λ : Tip-speed ratio
C_p :Power conversion coefficient
R_S :Stator resistance [Ω]
R_r :Rotor resistance [Ω]
R_{fe} :Iron loss resistance [Ω]
L_m :Magnetizing inductance [H]
i_{qs} :Stator q-axis current [A]
i_{ds} :Stator d-axis current [A]
ω_e :Supply angular frequency [rad/s]
ω :d,q-frame angular frequency [rad/s]
ω^*_m : Reference speed
P_{loss} :Total power loss

1. Introduction

In recent years, there has been a growing interest in wind energy as it is a potential source for electricity generation with minimal environmental impact. With the evolution of aerodynamic designs and material, wind turbines which can capture a few M[W] of power are commercially available. When such wind energy conversion systems (WECS) are integrated to the grid, they can supply a substantial amount of power, which can supplement the base power generated by thermal, nuclear, and hydro power plants [1].

The wind turbine blade has its own optimum operating speed at which the maximum power can be captured from wind energy. By controlling the generator speed at this value, it can produce the output power maximally [2]. However, there is still a potentiality to increase the output power by reducing the machine loss itself for the same mechanical input power. It is well known that the operating efficiency of the motor drive system can be improved by reducing the flux level which results in the significant decrease of the core loss [3],[5]. There are two kinds of method to find the flux level giving the maximum output power. One is the model-based method [3], [4] and the other is the search-based method [5]. In the former, the ratio of V/f or the d-axis current level for the maximum output is calculated from the machine model at the given speed and torque. It gives fast transient responses. However, its performance depends on the machine parameter variation. In the latter, the optimal operating point can be reached by perturbing the flux level and measuring the output power. This method gives sluggish transient response.

In this paper, the model-based method is applied to the flux control of the cage-type induction generator for grid-connected wind power systems. The generator is operated in indirect vector control mode, where the d-axis current controls the flux level and the q-axis current controls the machine speed which is determined so as to capture the maximum energy from the wind. For grid connection, a back-to-back PWM converter is used between the machine terminal and the grid. The validity of the proposed control scheme has been verified by the experimental results for the 3[kW] cage-type induction generator which is driven by the dc motor torque control at the laboratory.

2. Maximum Power Point Tracking

According to the aerodynamic characteristics of wind turbine blade, there is an optimum rotating speed to give the maximum wind energy capture as shown in Fig. 1. The theoretical power obtainable from the wind passing through a circular area is given by

$$P_{air} = 0.5\rho\pi R^2 v^3 \tag{1}$$

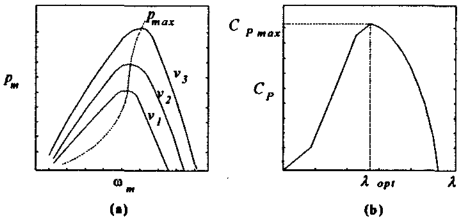

Fig. 1 Characteristic curves of wind blade.

(a) output power versus rotational speed

(b) power conversion coefficient versus tip-speed ratio.

The power conversion coefficient of the rotor (C_p) is defined as the ratio between the mechanical power available at the turbine shaft and the power available in wind. Neglecting the friction losses, the mechanical power available to be converted by the generator is given by

$$P_{air} = 0.5\rho\pi C_p R^2 v^3 \tag{2}$$

The power conversion coefficient is a function of the tip-speed ratio, λ, which is defined as

$$\lambda = \frac{\omega_m v}{R} \tag{3}$$

Fig. 1(a) shows that the power captured in turbine blade is a function of the rotational speed and that it is maximum at the particular rotational speed. Fig. 1(b) shows that the C_p is a function of λ and it is maximum at the particular λ_{opt}. Hence, to fully utilize the wind energy, λ should be maintained at $\lambda_{opt.}$, which is determined from the blade design. Then, from (2),

$$P_{air} = 0.5\rho\pi C_{pmax} R^2 v^3 \tag{4}$$

The reference speed of the generator is determined from (3) as

$$\omega_m^* = \frac{\lambda_{opt}}{R} v \tag{5}$$

Once the wind velocity is measured, the reference speed for extracting the maximum power point is obtained from (5).

3. Loss Minimization

A lot of minimum-loss control schemes for induction motor drives have been reported in the literatures. In this study, a loss minimization technique is applied to determine the optimal excitation level. Neglecting the mechanical loss and stray loss, the loss of induction machines can be classified into the copper loss and the iron loss, the rotor iron loss is often neglected since the slip frequency is so small at normal operating condition.

The d-q equivalent circuits of induction machine considering the stator iron loss are shown in Fig. 2.

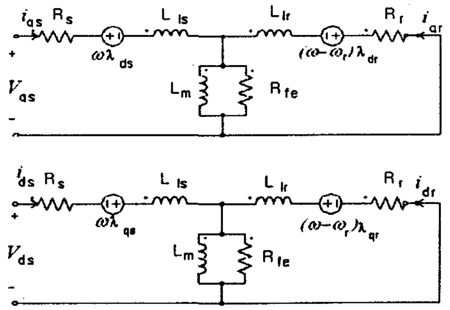

Fig. 2 The d- q equivalent circuits of three-phase induction machine.

The power loss can be expressed as

$$P_{loss} = \frac{L_m^2 \omega_r^2}{R_s + R_{fe}} i_{ds} + R_s (i_{ds}^2 + i_{qs}^2) + \frac{R_r R_{fe}}{R_r + R_{fe}} i_{qs}^2 \tag{6}$$

The total power loss is in a function of the stator d-q currents and the loss curve is illustrated in Fig. 3. The iron loss is decreased by reducing the flux at a given constant machine torque and speed. The machine flux can be reduced by decreasing the d-axis current. Since the electromagnetic torque is proportional to the product of the rotor flux and the q-axis current under vector control condition, the q-axis current should be increased in order to maintain the same torque at the reduced rotor flux. The d-axis current decreases while the q-axis current increases. However, the total stator current is reduced, leading to a decrease in stator copper loss and a slight increase in rotor copper loss.

To obtain the minimum loss point, taking the derivative of (6) with regard to the d-axis current and equating to zero. Then, the optimum excitation current i_{ds_opt} is obtained as

$$i_{ds\_opt} = |i_{qs}| \sqrt{\frac{R_{fe}R_r + R_{fe}R_s + R_sR_r}{R_{fe}R_s + R_sR_r + M^2\omega_r^2}} \qquad (7)$$

4. Control of Grid-Connected System

In order to control the grid-connected induction generator system, the back-to-back PWM converter is used. The generator-side converter works as an inverter which is operating in regenerative mode and the grid-side converter functions as an ac/dc boost converter capable of reversing the power flow.

The generator controller controls the rotational speed so as to produce the maximum output power. The control part consists of a speed controller and the d-q current controllers. The d-axis current component is adjusted according to the minimum power loss condition of (7), while the speed control loop generates is adjusted according to the minimum power loss condition of (7), while the speed control loop generates the q-axis current component to control the generator torque and speed at different wind speed. Fig. 3 shows the control block diagram of the induction generator.

To achieve the full control of the grid-side current, the dc-link voltage is controlled so as to keep the dc-link voltage constant. To maintain the dc-link voltage constant and to ensure the reactive power flowing into the grid at null, the grid-side converter currents are controlled using the d-q vector control approach. The dc-link voltage is controlled to the desired value by using a PI controller and the change in the dc-link voltage represents a change in the q-axis current. For unity power factor, the demand for the d-axis current is zero.

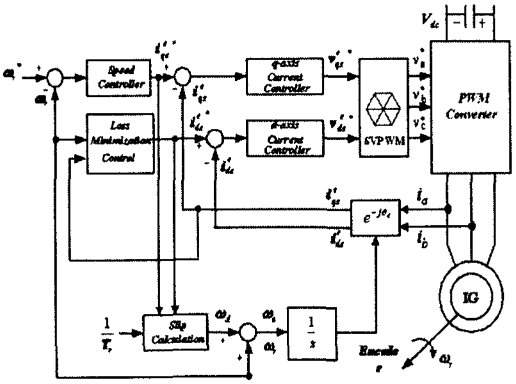

Fig. 3 Control block diagram of induction generator.

5. Experiment and Discussion

The characteristics of the wind turbine are simulated using a torque-controlled dc motor drive. The inverter switching frequency is 5[kHz] and the current and the speed control sampling periods are 100[μs], 1[ms], respectively. The output signal of the function generator is used as a wind speed, which is read into both the DSPs through the D/A converters. This signal is needed for the maximum output power control of the generator as well as for the dc motor torque control as a wind turbine simulator.

Fig. 4 shows the output power corresponding to the maximum at the given wind speed. For each wind speed the rotational reference speed is adjusted to the value which gives the maximum power.

Fig. 5 shows the different variables in case of the wind speed varying in a saw-tooth waveform, even though the wind speed varies continuously, the output power level is maximum. It is seen that according to the wind speed variation the generator speed varies and that its output power is produced corresponding to the wind speed variation. For the vector control of the induction generator, its d-axis current and the q-axis current are varied for the speed control. The dc link voltage is controlled at 340[V]. For the grid-side converter, the d-axis current is controlled to be zero for unity power factor and the q-axis current is controlled so as to deliver the power to the grid-side from the dc link. It is also seen that the speed and the power respond very fast to the wind speed variation. It means that the dynamic performance of the induction generator is improved and so the transient power loss is reduced.

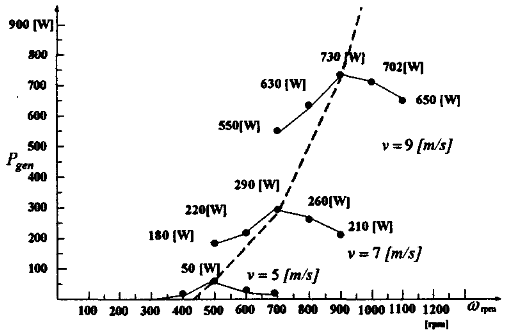

Fig. 4 Measured output power for different wind speeds

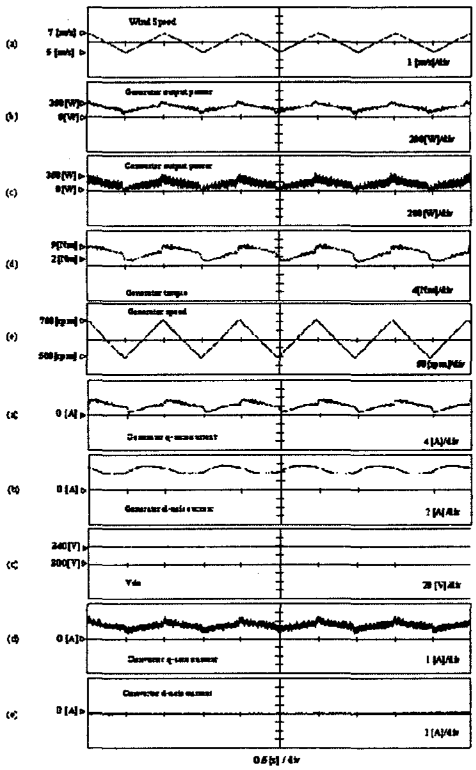

Fig. 5 Different waveforms in case of saw-tooth wind speed variation between 6[m/s] and 8[m/s].

Fig. 6 shows the increase of the generator output power in the low and medium speed range due to the reduction of loss. At high wind speed, the increment of the output power is negligible since the d-axis current increases up to the rated value for high torque so that there is no reduction of the iron loss.

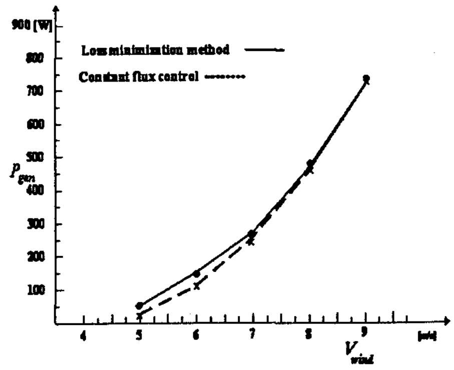

Fig. 6 Output power of induction generator

6. Conclusions

This paper proposed a complete control algorithm to conversion system considering the generator loss. The induction generator was controlled in indirect-vector control method and its speed reference was determined according to the wind speed, based on the tip-speed ratio. The d-axis current of the generator controls the excitation level which minimizes the total loss. The back-to-back PWM converter was used to connect the generator and the grid. The grid-side converter controls the dc-link voltage and the ac current at unity power factor. The validity of the proposed algorithm has been verified by experimental results for a small-scaled system.

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