A Flexible Active and Reactive Power Control Strategy for a Variable Speed Constant Frequency Generating System

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Abstract- Variable speed constant frequency generating systems are used in wind power, hydro power, aerospace and naval power generations to enhance efficiency and reduce friction. In these applications, an attractive candidate is the slip power recovery system comprising of doubly-excited induction machine or doubly-excited brushless reluctance machine and PWM inverters with dc link. In this paper, a flexible active and reactive power control strategy is developed, such that the optimal torque-speed profile of the turbine can be followed and overall reactive power can be controlled, while the machine copper losses has been minimized. At the same time, harmonics injected into the power network has also been minimized. In this manner, the system can function as both a high efficient power generator and a flexible reactive power compensator.

I. Introduction

Variable speed constant frequency (VSCF) power generating is desirable in many situations. A salient example is the wind power generation, where turbine speed should be able to vary according to the wind speed, such that energy efficiency can be achieved with a reduced torsional stress and windage friction on the wind mill blades. While in variable speed, the system output voltage should be maintained at a constant frequency to interface with the power system. Other applications of VSCF include hydro power generation, aerospace and naval power generation.

A promising VSCF generating concept is the slip power recovery system composing of a doubly-excited induction machine and power converters. In recent years, many researchers have made contributions to the progress of this concept. Among them, [1] proposed a decoupled active and reactive power control strategy for doubly-fed induction machines. A cycloconverter was used in the rotor circuit, resulting in control simplicity while restricting control flexibility. The overall system power flow problem was not studied, as only the output power from the stator side is controlled. [2] studied the overall power flow of a self-cascaded induction generator, for which a synchronous condenser is needed to provide the necessary reactive power for field excitation. Since only simple thyristor inverters were employed in the system, the system's ability to handle reactive power is disabled. [3] studied power regeneration of a typical singly-fed adjustable speed drive by simple thyristor rectifier using an innovative dc reactor circuit. It is a good example of cost-reduction for power regeneration of high-power drives. For a generating system, however, this scheme would not be a wise choice if reactive power control is required. In our previous work, we had proposed a stator field oriented control of doubly-fed induction machine, in which both active and reactive power of the stator are controlled by a PWM regulated current in the rotor circuit. We have also shown that the concept in [4] is applicable to the doubly-excited brushless reluctance machine [5].

Nevertheless, many issues in slip power recovery VSCF system have not been fully addressed, such as the flexible control of both active and reactive power of the overall system, stability problem as especially associated with the dc link voltage, control coordination between the two inverters, etc. In this paper, power control of VSCF slip power recovery generating system are discussed. A closed-loop control strategy is developed to coordinate the dual PWM inverters in the rotor circuit. Flexible and stable control of overall active and reactive power is obtained, while the machine coppor losses are minimized. It is shown that with the control strategy proposed, the VSCF system can actually function both as a power generating system and as a reactive power compensator. Application in wind power generation is simulated to verify the proposed control strategy.

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II. Control Strategy Development

A schematic slip power recovery system is shown in Fig. 1, with the reference directions of active and reactive power as indicated. As a generating system, obviously in most situations $P_s < 0$. When the machine in variable speed operates below synchronous speed, slip power $P_r > 0$; when the machine operates above synchronous speed, $P_r < 0$. Note that doubly-excited generators are inherently capable of super-synchronous speed operation. To ensure sub-synchronous and super-synchronous speed range operation, the requirement lies in the configuration of the power converter.

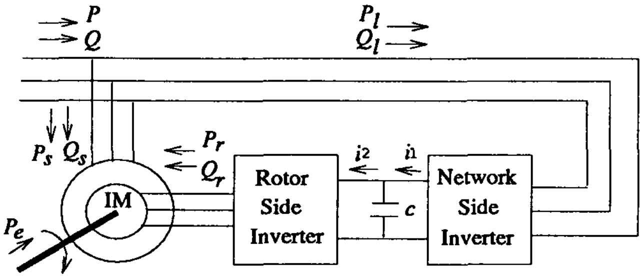

Fig.1 Power Flow of Slip Power Recovery System

Both cycloconverters and thyristor inverters can be used in this situation. Harmonic distortion and poor power factor are the major shortcomings, along with limited control flexibility. To realize field oriented control of the variable speed generator, and to achieve overall active and reactive power control and harmonic reduction, the dual PWM inverter structure with dc link is an attractive candidate. As a result, many new control issues arise and of most importance is the coordination between the two PWM inverters. For convenience, in the following analysis the two inverters are termed rotor side inverter and network side inverter respectively.

A. *Field Oriented Control Through Rotor Side Inverter*

In a VSCF 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 power capturing; 2) The stator output voltage frequency must be constant; 3) Flexible reactive power control is achievable. Of course, these control objectives must be achieved with the system stability.

The stator field orientation control is based on the stator d-q model, where the reference frame rotates synchronously with respect to the stator flux, with the d-axis of the reference frame instantaneously overlaps the axis of the stator winding flux. In short, $\omega = \omega_e$ and $\lambda_{qs} = 0$. For such a reference frame selection, the machine dynamical equations can be written as [4]

$$v_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{1}$$

$$v_{qs} = r_s i_{qs} + \omega_e \lambda_{ds} \tag{2}$$

$$\lambda_{ds} = L_s i_{ds} + L_r i_{dr} \tag{3}$$

$$\lambda_{qs} = 0 = L_s i_{qs} + L_r i_{qr} \tag{4}$$

$$v_{qs}^2 + v_{ds}^2 = v_m^2 \tag{5}$$

Since the d-axis of the reference frame is the instant axis of the stator winding flux, the phase angle of the stator voltage is generally not a constant in the reference frame, although its frequency and magnitude are constants constrained by the power system. The electromagnetic torque and stator active power can be derived as

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{ds} i_{qr} \tag{6}$$

$$P_s = \frac{3}{2}\frac{P}{2}\omega_e \lambda_{ds} i_{qr} \tag{7}$$

In the doubly-excited induction machine, the level of the stator flux remains approximately unchanged, restricted by the constant magnitude and frequency of the stator voltage. Therefore, as can be observed from (6), the torque control can be achieved by controlling the rotor current component orthogonal to the stator winding flux. Then from (7), stator active power is subsequentely controlled.

The reactive power at the terminal of the stator winding can be derived as

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \tag{8}$$

or, from (1) and (2), with the stator flux remains unchanged,

$$Q_s = \frac{3}{2}\frac{P}{2}\omega_e \lambda_{ds} i_{ds} \tag{9}$$

As (3) indicates, i_{ds} is controllable by i_{dr}, with λ_{ds} unchanged. Therefore, the d-axis component of the rotor current, i_{dr} can be controlled to regulate the stator reactive power.

Since the control of stator active power P_s via i_{qr} and the control of stator reactive power Q_s via i_{dr} are essentially decoupled, a decoupler is not necessary to implement field orientation control for the slip power recovery system. The flux control is generally unnecessary since it maintains a constant level, while the control of reactive power becomes possible.

B. *Minimization of Machine Coppor Losses*

It is well known that slip power recovery configuration has improved energy efficiency. Field oriented control described above enhances this improvement by permitting variable speed operation with reactive power control. There is, however, still another improvement possible. By controlling the reactive power circulation of the system, the coppor losses can be minimized. This will be analyzed in this subsection.

The machine overall coppor losses can be written as

$$P_{cu} = \frac{3}{2}(i_{qs}^2 + i_{ds}^2)r_s + \frac{3}{2}(i_{qr}^2 + i_{dr}^2)r_r \tag{10}$$

By using (1) to (4), (10) can be derived as

$$\begin{aligned} P_{cu} = & \frac{3}{2}\left(r_s + \frac{L_s^2}{L_m^2}r_r\right)i_{qs}^2 + \frac{3\lambda_{ds}^2}{2L_m^2}r_r \\ & -\frac{3\lambda_{ds}L_s r_r}{L_m^2}i_{ds} + \frac{3}{2}\left(r_s + \frac{L_s^2}{L_m^2}r_r\right)i_{ds}^2 \end{aligned} \tag{11}$$

In (11), i_{qs} has been used to control torque or active power, and λ_{ds} remains approximately unchanged as described above, then the machine coppor losses is a function of i_{ds}. It can be shown that for P_{cu} to achieve the minimum, it is necessary that

$$i_{ds} = \frac{L_s r_r \lambda_{ds}}{r_s L_m^2 + r_r L_s^2} \tag{12}$$

However, in the field oriented control, as already discussed, i_{ds} controls the stator reactive power. Therefore, it is sufficient to conclude that stator reactive power flow determines the level of coppor losses. From (9) and (12), the optimal stator reactive power flow can be shown as

$$Q_s = \frac{3}{2}\frac{P}{2}\omega_e \frac{L_s r_r \lambda_{ds}^2}{r_s L_m^2 + r_r L_s^2} \tag{13}$$

C. *Control of Network Side Inverter*

Through field oriented control of the rotor side inverter, the optimal torque-speed profile can be tracked and stator output reactive power can be separately controlled. The dc link capacitor provides dc voltage to the rotor side inverter and any attempt to store active power in the capacitor would raise its voltage level. Thus to ensure stability of the system, power flow of the inverter should guarantee the following control objective:

$$P_l = P_r \tag{14}$$

The dc link dynamical equation can be written as

$$C\frac{dV_d}{dt} = i_1 - i_2 \tag{15}$$

in which V_d is the dc bus voltage and C is the capacitance, and assuming no power losses for the inverters, then the dc link currents i_1 and i_2 as indicated in Fig. 1 can be derived as

$$i_1 = \frac{P_l}{V_d} \tag{16}$$

$$i_2 = \frac{P_r}{V_d} \tag{17}$$

Then from (15) through (17), as long as (14) is satisfied, dc link voltage maintains stable, though small ripples might be present due to the instantaneous inequality between P_l and P_r and a small variation may occur during transient as a result of energy tranferring. As can be seen from Fig. 1, another result of (14) is that the overall generated active power equals to the electromagnetic active power, i.e.

$$P = P_e = \frac{3}{2}\frac{P}{2}\omega_r \lambda_{ds} i_{qr} \tag{18}$$

Reactive power flow constitutes another control objective:

$$Q_l = Q^* - Q_s \tag{19}$$

where Q^* is the overall reactive power command required by the power network.

In the stator flux d-q reference frame,

$$P_l = \frac{3}{2}(v_{qs}i_{dl} + v_{ds}i_{dl}) \tag{20}$$

$$Q_l = \frac{3}{2}(v_{qs}i_{dl} - v_{ds}i_{ql}) \tag{21}$$

Since $v_{ds} \approx 0$, $v_{qs} \approx v_m$, P_l and Q_l can be controlled by i_{ql} and i_{dl} respectively. In the same reference frame as determined by the machine stator flux, i_{ql} and i_{dl} are also field oriented currents, produced by the network side current regulated PWM inverter.

III. Implementation and Simulations

A. Implementation Scheme of Closed Loop System

Based on the control strategy discussed above, Fig. 2 shows an implementation of the overall control system, which enables the slip power recovery system to function as both a VSCF generating system and a reactive power compensator. Individual control of the rotor side inverter and of the network side inverter and related feedback between the two inverters are shown.

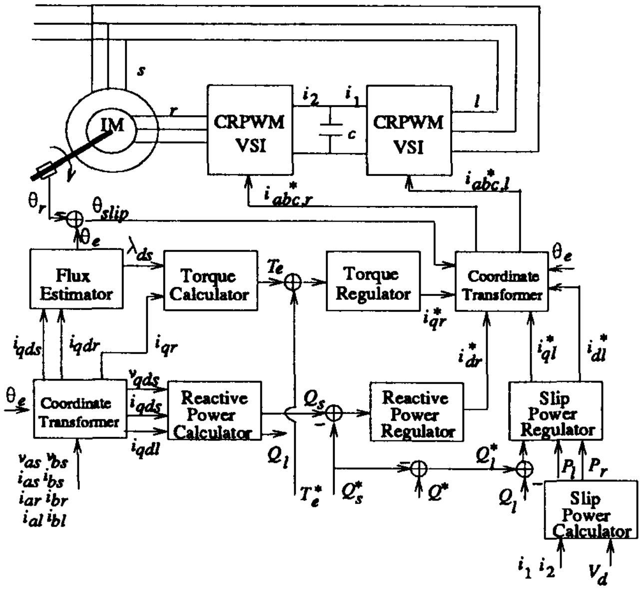

Fig.2 Control Implementation

A current-regulated pulse width modulation (CRPWM) voltage source inverter provides field oriented currents i_{qr} and i_{dr} to the rotor circuit, controlling electromagnetic torque and stator reactive power, respectively. Torque command is given by the turbine optimal torque-speed profile and reactive power command is calculated to minimize the machine copper losses. Overall active power generated is directly related to the torque, as indicated by (6) and (18).

Another CRPWM voltage source inverter is used to interface with the power network. In the same d-q reference frame as determined by the machine stator flux, its currents i_{ql} and i_{dl} are also field oriented, controlling P_l and Q_l respectively. Therefore, as discussed earlier, P_l is controlled through i_{ql} to stablize the dc bus voltage and Q_l is controlled through i_{dl} to meet the overall reactive power command.

B. Dynamic Speed Tracking Response

Wind power generation is a typical application where VSCF generating system is becoming very attractive. For a maximum wind power capturing, the generator turbine is required to track a prescribed torque-speed profile. This can be readily achieved by the proposed control strategy, as simulated in this section. Figs. 3 to 5 show speed-tracking response of the system when the wind speed increases linearly in 4 seconds. Ideal inverter output currents are assumed in the simulation.

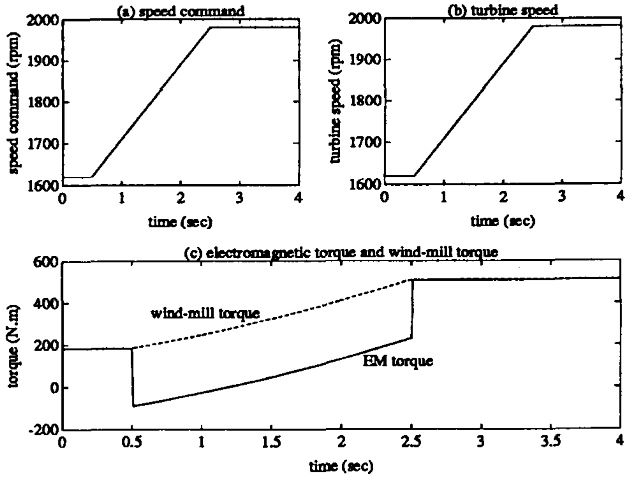

Fig.3 Turbine Speed Tracking

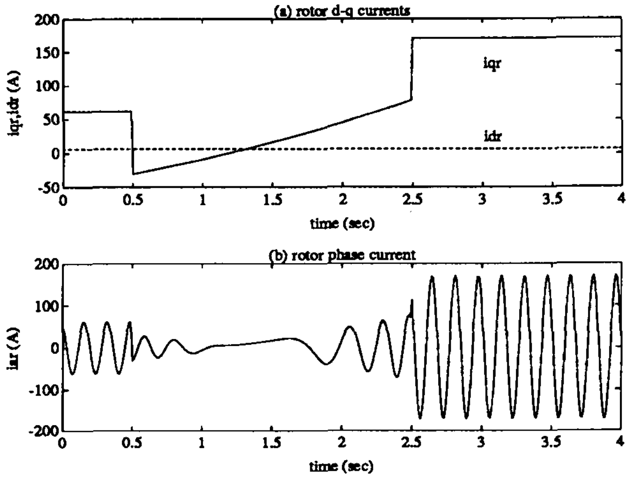

Fig.4 Rotor Current Waveform during Speed Tracking

As shown in Fig. 3(a), through appropriate gearing between the wind-mill and the generator shaft, the corresponding speed reference covers both sub-synchronous and super-synchronous speeds. Optimal wind turbine torque-speed curve has been assumed to be a square profile. As shown in Fig. 3(c), electromagnetic

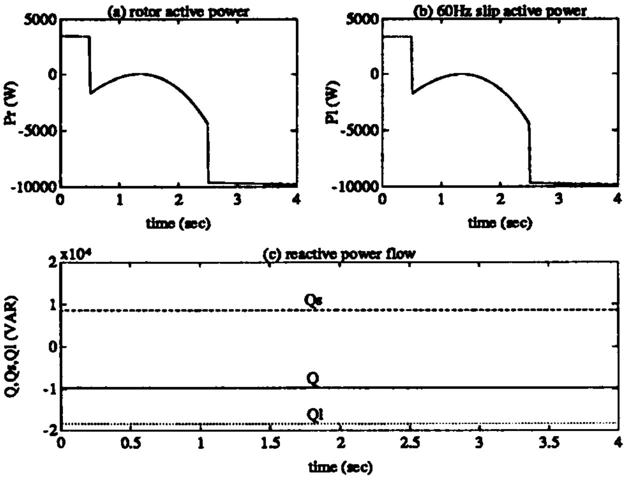

Fig.5 Power Flow of the System during Speed Tracking

torque is controlled in such a way that the net torque accelerates the turbine speed linearly, following speed command instantaneously.

As shown in Fig. 4(a), i_{qr} controls the torque, and i_{dr} remains unchanged since the stator reactive power maintains its optimal value. As can be seen in Fig. 4(b), rotor current is controlled by the rotor side inverter to have correct slip frequencies.

As explained earlier, to maintain dc bus voltage level, active power flow of the two inverters should equal. This is shown in Figs. 5(a,b). Fig. 5(c) shows the reactive power flow of the system. Stator reactive power flow Q_s is controlled to minimize the coppor losses, while the overall reactive power command Q^* is satisfied by controlling the slip reactive power Q_l.

C. *Steady State Operation With PWM Regulated Currents*

With regulated currents produced by the two PWM inverters, Figs. 6 to 8 simulate the operation of the slip power recovery system. Note that the overall reactive power command is zero, proving that the system is capable of operating at unity power factor. Hence with the proposed control strategy, the slip power recovery system is also attractive for adjustable speed drive applications.

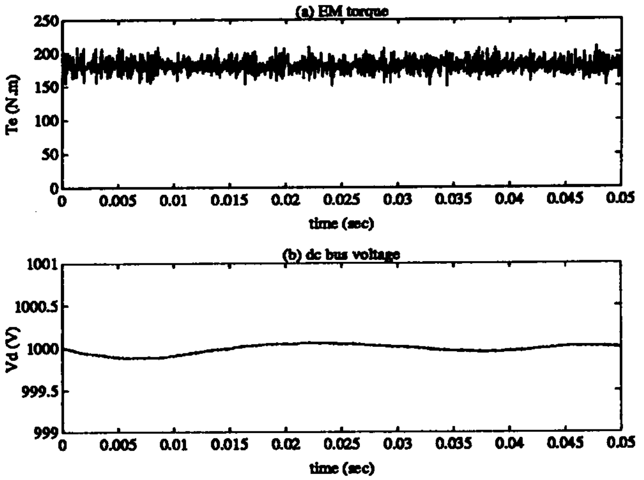

Fig.6 Controlled Torque and DC Bus Voltage

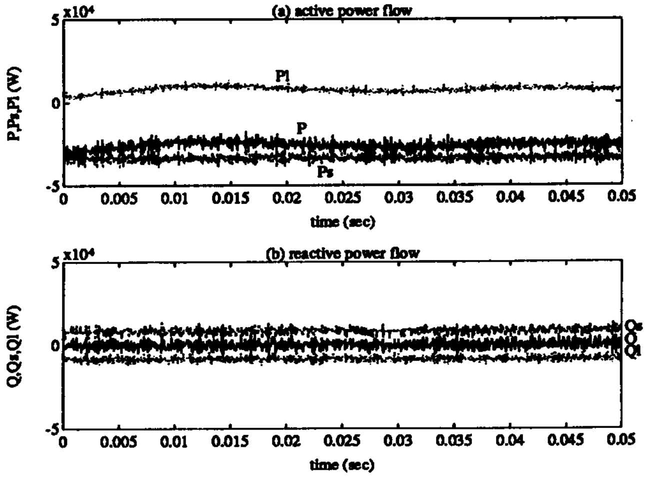

Fig.7 Power Flow with PWM Regulated Currents

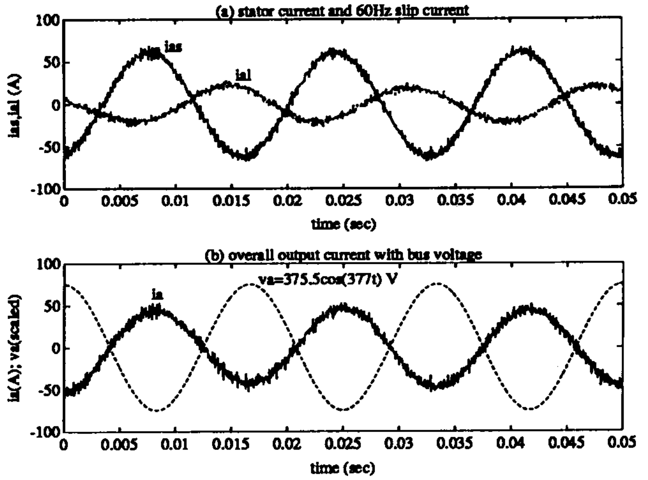

Fig.8 PWM Regulated Currents

D. *Dynamic Active and Reactive Power Step Response*

Dynamic performance of the system for a step change in active power command is simulated in Fig. 9, and dynamic performance for a step change in reactive power command is simulated in Fig. 10. Active power control and reactive power control is essentially decoupled. Note that in wind power generation, it is more desirable to capture maximum wind energy by controlling electromagnetic torque, than meeting active power requirements. The step change in active power in Fig. 9 actually further demonstrates speed tracking capability as simulated in Fig. 3.

It's noticeable in Fig. 9(a) and Fig. 10(a) that dynamic overall active power is decreasing slightly after the simulation start-up and the step transition. This is due to the decrease in slip active power from the network side inverter, P_l, to restore the dc bus voltage to the nominal value. When a steady active power is preferred over a nominal dc bus voltage, slip active power can be maintained while the dc bus voltage is having small variations from its nominal value.

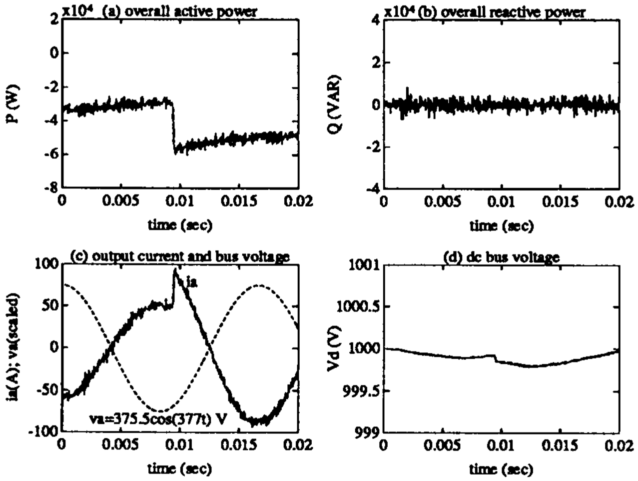

Fig.9 Active Power Control Dynamics

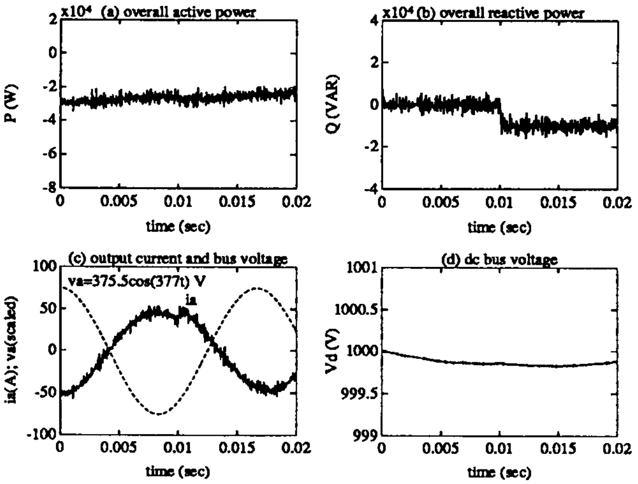

Fig.10 Reactive Power Control Dynamics

IV. Conclusions

In this paper, an overall control strategy has been proposed for a VSCF power generating system, comprising of a doubly-excited induction machine and dual PWM inverters. Stable and decoupled active and reactive power control is achieved through field oriented current regulation. In addition, machine coppor losses are minimized through controlling reactive power circulation in the system. The cost of the dual PWM inverter system is more than justified by the reduction of the rating of the power converter, the flexible controllability of active and reactive power and the satisfactory current harmonic spectrum, in addition to substantial improvement in efficiency.

Acknowledgment

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