Computer Aided Power Control for Wound Rotor Induction Generator

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Abstract: In this study, a new power control system for a wound rotor induction generator has been developed. This study is a new theoretical approach and this power control system has applied a control method using a rotating reference frame fixed on the air-gap flux of the generator. By using this control system, the active and reactive power of generator can be controlled independently and stably. Therefore, to realize this purpose, in this study, firstly the complex power expression (and thus the active and reactive power expressions) for an induction machine in space vector notation and in two-axis system has been gotten. Then, power and current control which are fundamental subjects have been analyzed and as a result a computer aided circuit is given to realize the power and current control.

Key Words: doubly-fed wound rotor induction generator; power control in induction generator; active and reactive power control

INTRODUCTION

In recent years, there has been an increased attention toward wind power generation. Conventionally, grid-connected cage rotor induction machines are used as wind generators at medium power level. When connected to the constant frequency network, the induction generator runs at near-synchronous speed drawing the magnetizing current from the mains, thereby resulting in constant speed constant frequency (CSCF) operation. However, the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed. In such variable speed constant frequency (VSCF) application, rotor side control of grid-connected wound rotor induction machine is an attractive solution (Datta & Ranganathan, 2001). A doubly fed wound rotor induction generator can produce constant stator frequency even though rotor speed varies. This system can be controlled by a small capacity converter compared with the generator capacity, when the control range speed is narrow. Because of these features, this system is currently considered to be adaptable to power systems for hydroelectric and wind-mill type power plants (Nakra & Dube, 1988, Herrera et.al., 1988, Holmes & Elsonbaty, 1984).

When adapted to the power system, it is important to examine the effects of this system on the power system. In the system under consideration, the stator is directly connected to the three phase grid and the rotor of the doubly-fed induction machine is excited by three-phase low frequency ac currents, which are supplied via slip rings by either a cycloconverter or a voltage-fed PWM rectifier-inverter. The ac excitation on the basis of a rotor-position feedback loop makes it possible to achieve stable variable-speed operation. Adjusting the rotor speed makes the induction machine either release the electric power to the utility grid or absorb it from the utility grid (Akagi & Sato, 2002). The concept of power control was applied to reactive power compensator applications some 20 years ago, but the application to electrical machine control is new (Betz & Cook, 2001).

In literature, two kinds of approach are proposed for independent control of active and reactive powers. One of them is stator flux oriented vector control with rotor position sensors. Other one is position sensorless vector control method. The control with rotor position sensors is conventional approach and
the performance of the system depends on the accuracy of computation of the stator flux and the
accuracy of the rotor position information derived from the position encoder. Alignment of the position
sensor is moreover, difficult in a doubly-fed wound rotor machine (Datta& Ranganathan, 2001).

Position sensorless vector control methods have been proposed by several research groups in the recent
torque angle controller is proposed. This method uses integration of the PWM rotor voltage to compute
the rotor flux; hence satisfactory performance can not be achieved at or near synchronous speed
(Xu&Cheng, 1995). Most of the other methods proposed make use of the measured rotor current and
use coordinate transformations for estimating the rotor position (Datta&Ranganathan, 1999, Morel
et.al, 1998, Bogalacka, 1993). Varying degree of dependence on machine parameters is observed in all
these strategies.

Alternative approaches to field oriented control such as direct self control (DSC) and direct torque
control (DTC) have been proposed for cage rotor induction machines. In these strategies, two hysteresis
controllers, namely a torque controller and a flux controller, are used to determine the instantaneous
switching state for the inverter. These methods of control are computationally very simple and do not
require rotor position information. However, the application of such techniques to the control of
wound rotor induction machine has not been considered so far. A recently developed another algorithm
for independent control of active and reactive powers with high dynamic response in case of a wound
rotor induction machine is direct power control. In direct power control, the directly-controlled
quantities are the stator active and reactive powers. The proposed algorithm as direct power control
also differs from DTC in that it does not use integration of PWM voltages. Hence, it can work stably
even at zero rotor frequency. The method is inherently position sensorless and does not depend on
machine parameters like stator/rotor resistance. It can be applied to VSCF applications like wind power
generation as well as high power drives (Datta& Ranganathan, 2001).

Little literature has been published on control strategy and dynamic performance of doubly-fed
1993, Bhownik et.al., 1998). Leonhard, 1985 describes a control strategy for an adjustable-speed
doubly-fed induction machine intended for independent control of active power and reactive power.
The control strategy provides two kinds of current controllers; inner feedback loops of the rotor
currents on the $d$-$q$ coordinates and outer feedback loops of the stator currents on the $K-N$
coordinates. However, it is not clarified theoretically why the control strategy requires the two kinds of current
controllers.

This paper describes the power control characteristics on the rotating reference frame fixed on the air-
gap flux of a doubly fed wound rotor induction generator and proposes a new approach to control with
rotor position sensor. By using this control system, the active and reactive power of generator can be
controlled independently and stably.

Analysis of the control system

For the stable control of the active and reactive power, it is necessary to independently control them.
As known, the active power control is the control of torque produced by the machine and the reactive
power control is the control of flux.

The stator active and reactive power of doubly-fed wound rotor induction generator are controlled by
regulating the current and voltage of the rotor windings. Therefore, to realize independent control, the
current and voltage of the rotor windings must be divided into components related to stator active and
reactive power. It is well known that an induction machine can be modelled as a voltage behind a total
leakage inductance. Therefore, after a three to two phase power variant transformation, the induction
machine model becomes that of Fig. 1 (Betz&Cook, 2001).

Approximate vector diagram of an induction machine is shown in Fig. 2. In this section, the analysis of
the doubly fed wound rotor induction generator on the rotating frame fixed on the air-gap flux (K-N
frame) is carried out.
The K-axis is fixed in the air-gap flux and the N-axis is fixed in the quadrature with the K-axis. The relation of stator $\alpha_1-\beta_1$ axis, rotor $\alpha_2-\beta_2$ axis and K-N axis are shown in Fig. 3.

**Complex power expression**

Assuming that the voltage vector is used as the reference for the determination of lagging and leading, we can write the complex stator power expression for a machine in space vector notation as:
\[ S_i = I_i \cdot U_i^* \]  

(1)

which can be written in two phase stationary frame variables as:

\[ S_i = [I_{K1,N1}] [U_{K1,N1}]^* \]  

(2)

where \([I_{K1,N1}] = I_{K1} + j I_{N1}\) and \([U_{K1,N1}]^* = U_{K1} - j U_{N1}\)

Expanding (2) we get the expressions for the stator active and reactive power as defined in Akagi et al., 1984:

\[ S_i = U_{K1} I_{K1} + U_{N1} I_{N1} + j (U_{K1} I_{N1} - U_{N1} I_{K1}) \]  

(3)

Therefore:

\[ P_i = U_{K1} I_{N1} + U_{N1} I_{K1} \]  

(4)

\[ Q_i = U_{K1} I_{N1} - U_{N1} I_{K1} \]  

(5)

where \(P_i\) is the stator active power, and \(Q_i\) is the stator reactive power, \(I_{K1}\) and \(I_{N1}\) are the K and N axis stator currents, and \(U_{K1}\) and \(U_{N1}\) are the K and N axis stator voltages.

**Power control**

The relationship between stator power and rotor current is analyzed in this section. In (4) and (5), the stator active and reactive power were expressed by the stator current based on the K-N frame. The relationships between the rotor and stator currents are

\[ I_{N1} = I_{q1} \cdot \cos \gamma - I_{d1} \cdot \sin \gamma \]  

(6)

\[ I_{N2} = I_{q2} \cdot \cos \gamma - I_{d2} \cdot \sin \gamma \]  

(7)

\[ I_{N1} + I_{N2} = (I_{q1} + I_{q2}) \cos \gamma - (I_{d1} + I_{d2}) \sin \gamma \]  

(8)

\[ I_{d1} = I_{K1} \cdot \cos \gamma; I_{d2} = I_{K2} \cdot \cos \gamma \]  

(9)

\[ I_{q1} = I_{K1} \cdot \sin \gamma; I_{q2} = I_{K2} \cdot \sin \gamma \]  

(10)

(11)

By using (9) and (10), the term of \((I_{N1} + I_{N2})\) is expressed in terms of \(\psi_6\) and \(M\).

\[ I_{N1} + I_{N2} = (\psi_6 / M) \sin \gamma \cos \gamma \cdot (\psi_6 / M) \cos \gamma \sin \gamma = 0 \]  

(12)

\[ \psi_6 = M (I_{K1} + I_{K2}) \]  

(13)

where \(\psi_6\) is the air-gap flux, \(I_{K2}\) and \(I_{N2}\) are the K and N axis rotor currents and \(M\) is the mutual inductance.

By using (12) and (13), the stator active and reactive power are expressed in terms of \(\psi_6\) and \(M\).

\[ P_i = U_{K1} [(M (I_{K1} + I_{K2}) / M) - I_{K2}] + U_{N1} (-I_{N2}) \]  

(14)

\[ Q_i = U_{K1} (I_{K1}) - U_{N1} [(M (I_{K1} + I_{K2}) / M) - I_{K2}] \]  

(15)

\[ P_i = -U_{N1} I_{N2} \]  

(16)

In this system, the stator winding is directly connected to the power system. The conditions \(U_{K1} = 0, U_{N1} = \text{constant}, \psi_6 = \text{constant}\) are derived from this feature (Yamamoto & Motoyoshi, 1991). By using these relationship and (12), (13), (14) and (15), the stator active and reactive power are expressed in terms of rotor current. Equations (4) and (5) are rewritten as follows.
Equation (16) shows that the stator active power \( P_1 \) is expressed by the terms proportional to the rotor current \( I_{k2} \). Equation (17) shows that the stator reactive power \( Q_1 \) is expressed by the terms proportional to the rotor current \( I_{k2} \) and constant value \( (\psi_2/M)U_{n1} \). From the above relationships, the rotor current is divided into the active power \( P_1 \) and the reactive power \( Q_1 \) components. That is, the independent control of the stator active and reactive power can be actualized by regulating rotor currents \( I_{k2} \) and \( I_{n2} \).

**Current control**

The relationships between the rotor currents and the rotor voltages are analyzed in this section. The equations for wound rotor induction machine based on K-N frame are shown as follows.

\[
\begin{align*}
U_{k1} &= R_{k1}I_{k1} + L_{k1\sigma}dl_{k1}/dt - (\omega_1 + \omega_2)I_{k1\sigma}l_{k1} + d\psi_{k1\delta}/dt - (\omega_1 + \omega_2)\psi_{n1\delta} \\
U_{n1} &= R_{n1}I_{n1} + L_{n1\sigma}dl_{n1}/dt + (\omega_1 + \omega_2)I_{n1\sigma}l_{n1} + d\psi_{n1\delta}/dt + (\omega_1 + \omega_2)\psi_{k1\delta} \\
U_{k2} &= R_{k2}I_{k2} + L_{k2\sigma}dl_{k2}/dt - (\omega_1 + \omega_2)I_{k2\sigma}l_{k2} + d\psi_{k2\delta}/dt - (\omega_1 + \omega_2)\psi_{n2\delta} \\
U_{n2} &= R_{n2}I_{n2} + L_{n2\sigma}dl_{n2}/dt + (\omega_1 + \omega_2)I_{n2\sigma}l_{n2} + d\psi_{n2\delta}/dt + (\omega_1 + \omega_2)\psi_{k2\delta}
\end{align*}
\]

where \( \psi_{k1\delta} \) and \( \psi_{n1\delta} \) are the K and N axis stator air-gap flux, \( R_1 \) and \( R_2 \) are the stator and rotor resistance, \( \omega_1 \) is the stator angular velocity, \( \omega_2 \) is the angular velocity of the air-gap flux, \( \psi_{k2\delta} \) and \( \psi_{n2\delta} \) are the K and N axis rotor air-gap flux, \( L_{k\sigma} \) and \( L_{n\sigma} \) are the stator and rotor leakage inductance, \( \omega_3 \) is the slip angular velocity.

These equations are transformed by using the relationships \( \psi_{n1\delta} = \psi_{n2\delta} \), \( \psi_{k1\delta} = \psi_{k2\delta} \) and \( \omega_6 = \omega_1 - \omega_2 \), the following expressions are derived:

\[
\begin{align*}
U_{k2} &= R_{k2}I_{k2} + L_{k2\sigma}dl_{k2}/dt - (\omega_1 + \omega_2)I_{k2\sigma}l_{k2} + d\psi_{k2\delta}/dt - (\omega_1 + \omega_2)\psi_{n2\delta} \\
U_{n2} &= R_{n2}I_{n2} + L_{n2\sigma}dl_{n2}/dt + (\omega_1 + \omega_2)I_{n2\sigma}l_{n2} + d\psi_{n2\delta}/dt + (\omega_1 + \omega_2)\psi_{k2\delta} \\
U_{k2} &= R_{k2}I_{k2} + L_{k2\sigma}dl_{k2}/dt - (\omega_1 + \omega_2)I_{k2\sigma}l_{k2} + d\psi_{k2\delta}/dt - (\omega_1 + \omega_2)\psi_{n2\delta} \\
U_{n2} &= R_{n2}I_{n2} + L_{n2\sigma}dl_{n2}/dt + (\omega_1 + \omega_2)I_{n2\sigma}l_{n2} + d\psi_{n2\delta}/dt + (\omega_1 + \omega_2)\psi_{k2\delta}
\end{align*}
\]

where \( \omega_3 \) is the rotor angular velocity.

When the equations (22), (23), (24) and (25) are transformed by the rotor current \( I_{k2} \) and \( I_{n2} \), (26) and (27) are given,

\[
\begin{align*}
I_{k2} &= (U_{k2} - (\omega_1 + \omega_2)I_{k2\sigma}l_{k2} - U_{k1\delta} - R_{k2} + pL_{k2\sigma})/(R_{k2} + pL_{k2\sigma}) \\
I_{n2} &= (U_{n2} - (\omega_1 + \omega_2)I_{n2\sigma}l_{n2} - U_{n1\delta} - (\omega_1 + \omega_2)\psi_{n2\delta})/(R_{n2} + pL_{n2\sigma})
\end{align*}
\]

where \( p \) is the differential operator.

The stator winding is directly connected to the power system. Therefore, stator voltage becomes constant in the normal state, leading to the conditions \( U_{k1\delta} = 0 \) and \( U_{n1\delta} = \) constant. And \( L_{2\sigma} \) is negligible because it is generally small (Yamamoto & Motoyoshi, 1991). Thus, (26) and (27) become as follows.

\[
\begin{align*}
I_{k2} &= U_{k2} / R_2 \\
I_{n2} &= (U_{n2} - U_{n1\delta} + \omega_2\psi_{n2\delta}) / R_2
\end{align*}
\]

Equations (28) and (29) show that rotor voltages along the K and N axes respectively depend only on the rotor currents along the K and N axes. In other words, the relationships between the currents and voltages along the K and N axes are linear. Consequently, the rotor currents \( I_{k2} \) and \( I_{n2} \) can be controlled independently by regulating the rotor voltages \( U_{k2} \) and \( U_{n2} \).

**Composition of the control system**

Fig. 4 shows the block diagram of the control system. From the results of this analysis, the active and the reactive power control system can be composed independently by using K-N frame. This control system is separated into six parts.
The first part is the power control loop. The active power proportional integral (PI) regulator (APR) regulates the rotor current reference $I_{N2}^*$ from the deviation between the stator active power detection $P_1$ and the stator active power reference $P_{1^*}$. The reactive power proportional integral (PI) regulator (AQR) regulates the rotor current reference $I_{K2}^*$ from the deviation between the stator reactive power detection $Q_1$ and the stator reactive power reference $Q_{1^*}$.

The second part contains the current proportional integral (PI) regulator (ACR) for rotor currents $I_{K2}$ and $I_{N2}$. The current regulators regulate the rotor voltages references $U_{K2}^*$ and $U_{N2}^*$ from the deviation between the rotor current detection $I_{K2}$ and $I_{N2}$ and the rotor current reference $I_{K2}^*$ and $I_{N2}^*$. The third part is the air-gap flux calculator, which provides the K-N standard frame by using the stator currents, voltages, and the signals of the position sensor. The fourth part is $P_1$ and $Q_1$ detector, which calculate the stator active and reactive power from the stator currents and voltages. The fifth part is the detector of the rotor current, which is in two phases corresponding to the vector values of K-N axis. This part calculate the two phase rotor currents by using the following equation:

$$
\begin{bmatrix}
I_{K2} \\
I_{N2}
\end{bmatrix} =
\begin{bmatrix}
\cos(\lambda + \gamma) & \sin(\lambda + \gamma) \\
-\sin(\lambda + \gamma) & \cos(\lambda + \gamma)
\end{bmatrix}
\begin{bmatrix}
-t/2 \\
t/2
\end{bmatrix}
\begin{bmatrix}
I_{a2} \\
I_{b2} \\
I_{c2}
\end{bmatrix}
$$

(30)

The sixth part is coordinate transformer. Here the three phase voltage references are calculated from K-N axis voltage references by using the following equation (Yamamoto&Motoyoshi, 1991).

$$
\begin{bmatrix}
U_{a2} \\
U_{b2} \\
U_{c2}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
-1/2 & \sqrt{3}/2 & 0 \\
-1/2 & -\sqrt{3}/2 & 0
\end{bmatrix}
\begin{bmatrix}
\cos(\lambda + \gamma) & -\sin(\lambda + \gamma) & U_{K2}^* \\
\sin(\lambda + \gamma) & \cos(\lambda + \gamma) & U_{N2}^*
\end{bmatrix}
$$

(31)

**Power reference generation**

The first of the key components of the algorithm mentioned previously is the Power Reference Generation (PRG). Oddly, this turns out to be the part of the algorithm that is dependent on knowledge of parameters. Of the two references the easiest one to generate is the active power reference, since this is directly connected to the torque one wishes to produce from the machine. However, even with the active power reference there are a few traps one can easily fall into.

The most obvious way to generate the active power reference one desires from the machine is Betz&Cook, 2001:

$$
P_{\text{ref}} = T_{\text{ref}} \omega_{m2} = T_{\text{ref}} (2\pi n_2)
$$

(32)

where $T_{\text{ref}}$ is supplied from some outer loop such as a speed control loop, and $n_2$ is the actual mechanical shaft speed at a particular instant of time.

Equation (32) works to some extent, but it gives values of active power which are insufficient to generate the torque $T_{\text{ref}}$. This is due to the fact that not all the active power at the input to the machine contributes to the production of output power. Clearly some power is lost in the stator resistance and
iron losses of the machine. However, in addition to this there is a significant amount of power that is lost in the rotor resistance. In fact the power lost here is dependent on the slip of the machine. Schematic demonstration of the power flows under motoring and generating for an induction machine are shown in Fig. 5.

![Fig. 5. Schematic demonstration of the power flows in an induction machine under (a) motoring and (b) generating (P_i = input power (taken from supply in motor mode, given from shaft in generator mode), P_m = mechanical power, P_a = air-gap power (transferred from stator to rotor under motoring and from rotor to stator under generating), P_l = power loss, P_fe = iron loss, P_cu = copper loss, P_a = additional losses produced by harmonics, P_fw = friction and windage losses, P_e = effective electrical power taken from rotor circuit, P_o = output power (shaft power in motor mode, electrical power in generation mode) (1 subscript means stator, 2 subscript means rotor)

As seen in literature, whilst some researchers can assume that the stator resistance power and the iron losses can be ignored (under many practical situations), the power in the rotor resistance cannot be ignored, especially under heavy load conditions when the slip of the machine can be large (Betz&Cook, 2001).

As can be seen from this diagram, under the motoring condition the input power divides into two, some of it going into the stator resistance losses, iron losses and additional losses produced by harmonics, some of it going into the rotating field power (air-gap power).

Similarly, under generating the input shaft power divides between the friction and windage losses and mechanical power. To make the shaft power equal to the desired shaft power we must compensate for the power that is being diverted away from the shaft. This implicitly means that we must have some knowledge of the slip then we can compensate the power expressions as follows for the motoring/generating situation (if the friction and windage losses are neglected):

\[
P_{\text{ref}} = \frac{P_{\text{shaft}}}{1-s} = \frac{T_{\text{ref}} \omega_{m2}}{(1-s)}
\]

(33)

where \(P_{\text{shaft}}\) is the desired shaft power, and \(P_{\text{ref}}\) is the terminal reference power as defined previously.

To generate the slip for compensation we firstly need to consider the reactive power reference generation, as the two are related. Consider Fig. 2 which shows an approximate vector diagram of the voltages, currents and fluxes of an induction machine. We know that the reactive power is the emf voltage \(E\) in one axis of the machine multiplied by the current in the other axis. If the axes are \(dr, qr\) in Fig. 2, we can write:

\[
|Q| = I_{nr} E = I_{nr} \omega_t \psi_m
\]

(34)

\[
(35)
\]

where \(\psi_m\) is the flux magnitude, \(I_{nr}\) is the magnetising current, and \(\omega_t\) is the stator angular velocity related with electrical frequency.
Rearranging (35) one can write:

$$\omega_{s\ ref} = - \left( \frac{\mid Q_{ref} \mid}{(I_{mr\ ref} \psi_{m\ ref})} \right) - \omega_2$$  \hspace{1cm} (36)

realising that:

$$f_2 = p_P \omega_2$$
$$\omega_2 = p_P \omega_{m2}$$
$$\omega_1 = \omega_2 + \omega_s$$
$$\omega_s = \text{slip angular velocity related with slip frequency}$$
$$\omega_{s\ ref} = \text{the desired slip angular velocity related with slip frequency}$$
$$I_{mr\ ref} = \text{the desired magnetizing current}$$
$$p_P = \text{the pole pairs}$$
$$\mid Q_{ref} \mid = \text{the desired reactive power}$$

Note that the negative sign in (36) results from the sign of $Q_{ref}$, the reference reactive power, derived later in the paper.

Given (36) we can now write the expression for the slip:

$$s = \frac{\omega_s}{(\omega_2 + \omega_s)} = 1 + \frac{\omega_2 I_{mr\ ref} \psi_{m\ ref}}{Q_{ref}} = 1 + \frac{\omega_2 L_m I_{mr\ ref}^2}{Q_{ref}}$$  \hspace{1cm} (37)

This expression can be substituted into the active power slip compensation term $1/(1-s)$. The $I_{mr\ ref}$ and $\psi_{m\ ref}$ terms in this expression are reference values. Clearly $I_{mr}$ and $\psi_m$ for an induction machine are related - i.e. $\psi_m = L_m I_m$. Hence we have written the numerator of (37) as $L_m I_{mr\ ref}^2$. This means that knowledge of the magnetising inductance of the machine is required.

Now let us consider the $Q_{ref}$ used in (37). The reactive power is the crucial variable to maintain the flux in the machine. It is also required to prevent the active power positive feedback situation that can occur in generation.

As can be seen from (35), the reactive power expression can be written as:

$$\mid Q_{ref} \mid = I_{mr} \omega_1 \psi_m = I_{mr} \psi_m (\omega_2 + \omega_s)$$  \hspace{1cm} (38)

Therefore one concludes that the reactive power is crucially dependent on the slip frequency of the machine. One implication of the dependence is that the reactive power can undergo step changes, since the slip frequency changes as a step when there is a sudden torque demand.

The slip frequency of the machine is intimately related to the torque of the machine. The logical extension to this is that the desired slip frequency is related to the desired torque. The torque $T$ and $\omega_s$ expressions of an induction machine can be written as (using the standard expression from Field Oriented Control):

$$T = 1.5 p_P L_m^2 \mid I_{mr} \mid I_p / L_2$$  \hspace{1cm} (39)
$$\omega_s = I_p / (\tau_2 \mid I_{mr} \mid)$$  \hspace{1cm} (40)

where $\tau_2 = L_2 / R_2$, $L_2 = \text{the rotor inductance}$, and $R_2 = \text{the rotor resistance}$. Therefore $\tau_2$ is the rotor time constant.

Rearranging (39) one can write:

$$I_p = \frac{T L_2}{(1.5 p_P L_m^2 \mid I_{mr} \mid)}$$  \hspace{1cm} (41)

Substituting (41) into (40) gives:

$$\omega_s = \frac{T L_2}{(1.5 p_P L_m^2 \mid I_{mr} \mid^2 \tau_2)}$$  \hspace{1cm} (42)

The denominator in (42) can be simplified by assuming that the leakage inductance of the machine is very small in relation to $L_2$, and hence $L_2 = L_m$. Therefore (42) can be written as:

$$\omega_s = \frac{2T}{(3 p_P L_m \mid I_{mr} \mid^2 \tau_2)} = \frac{2T}{(3 p_P \psi_m \mid I_{mr} \mid \tau_2)}$$  \hspace{1cm} (43)
We are now in a position to write an expression for the reference reactive power. Substituting (43) into (38) and simplifying we get [6]:

$$Q_{ref} = - \left( |I_{mr}|_{ref} \omega \psi_{m ref} \right) + (2T_{ref} / 3p \tau_2) = - [L_m (|I_{mr}|_{ref})^2 \omega_2 + (2T_{ref} / 3p \tau_2)]$$ (44)

**Experimental setups**

By using the computer, the experimental setups to control active and reactive power of the wound rotor induction generator independently and stably are shown in Fig. 6 and 7. Also, schematic diagram of cyclo-converter used in experimental setups is shown in Fig. 8.

![Fig. 6. Schematic block diagram of the experimental setup for computer aided power control of wound rotor induction generator.](image)

![Fig. 7. Another schematic block diagram of the experimental setup for computer aided power control of wound rotor induction generator.](image)

![Fig. 8. Schematic diagram of cyclo-converter [16].](image)
CONCLUSION

A new power control system for the doubly fed wound rotor induction generator has been developed. This power control system has applied a control method using a rotating reference frame fixed on the air-gap flux of the generator. By using this control system, the active and reactive power of generator can be controlled independently and stably. To realize this purpose, power and current control which are fundamental subjects have been analyzed and as a result a computer aided circuit is given to realize the power and current control.

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