電流形 인버어터로 驅動되는 誘導電動機의 磁束制御에 의한 效率개선에 관한 研究

論 文
31~8~3

Improvement in Efficiency of CSI fed Induction Motor by Means of Flux Control

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(Min-Ho Park · Heung-Geun Kim)

Abstract

When an induction motor is lightly loaded, the efficiency can be very substantially improved by controlling the air gap flux. Thus in the system which requires constant speed under either normal load or light load, it is possible to save energy by means of controlling the air gap flux. In this paper, the required relationships between stator current and rotor slip frequency for optimal efficiency control is derived and the improved control loop is suggested.

1. Introduction

The squirrel cage induction motor has many inherent advantages for industrial applications. When compared to dc or synchronous machine, it is lighter, more robust, less expensive, has lower inertia rotor, and is capable of much higher speeds. However induction motors have not been used whenever adjustable speed is needed due to the difficulty of controlling the speed. Development in static power controllers has made it possible to use induction motors in high performance variable speed drives.

The current source inverter (CSI) drive shown in Fig. 1 has many advantages. The CSI is a very rugged supply capable of recovery from short circuits or commutation faults. It offers inherent overcurrent protection when current feedback is used. It is a simple circuit which does not require fast turn off thyristors. The CSI is capable of full regeneration with only 12 SCR's and 6 diodes. While it produces a square wave current supply, the motor voltage and hence flux is quasi-sinusoidal. These numerous advantages have resulted in increasing use of the CSI for motor drives.

It is shown that, when a current source inverter is used in conjunction with an induction motor, open-loop operation is unstable for most operating conditions.[3, 5, 6] Therefore closed-loop control is essential for satisfactory operation.

In order to improve performance of the drive, the use of motor flux control is suggested by a number of authors.[15, 16] In this control, the air gap flux is maintained constant throughout the speed range. But it is possible to save energy in lightly loaded induction motor by means of variable flux control. Therefore in this paper the air gap flux for maximum efficiency is derived and the relationship required for this flux between rotor slip frequency and stator current is also derived.

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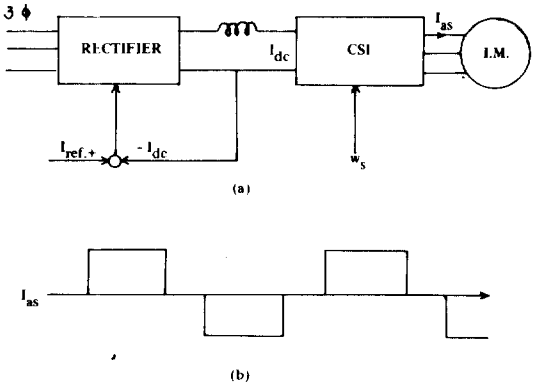

Fig. 1. Current source inverter
(a) block diagram (b) typical phase current waveform

2. Steady-State Characteristics

The torque speed curves for the voltage source and the current source at a given frequency can be obtained, and the results are given in Fig. 2.

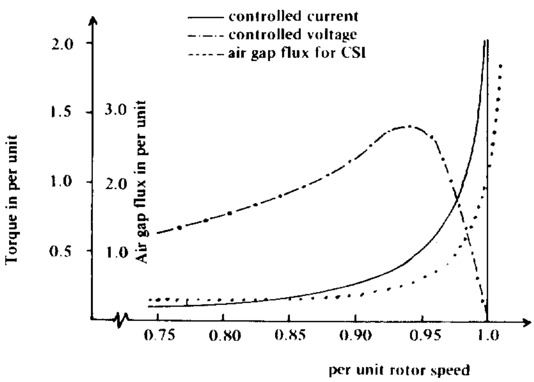

Fig. 2. Steady state torque speed characteristics

It can be noted that in the case of CSI, the torque remains very small until the motor approaches synchronous speed, then rises rapidly. Also it can be noted that the peak torque for the CSI is considerably higher than the voltage source suggesting that operation from a current source may be superior to operation from a voltage source. However further investigation reveals that this is not the case. In the case of CSI, the air gap flux for different speeds at a given frequency is also plotted in Fig. 2. As the slip approaches zero, the air gap flux rises rapidly. This results in saturation and high losses in a practical machine. Thus in the case of CSI fed induction motor drives, most operating points are statically unstable and feedback control is essential.

3. Constant Flux Control

If the stator current and supply frequency are controlled independently, closed loop control of speed would not stabilize the system. Therefore slip speed control is added in order to stabilize the system as shown in Fig. 3.

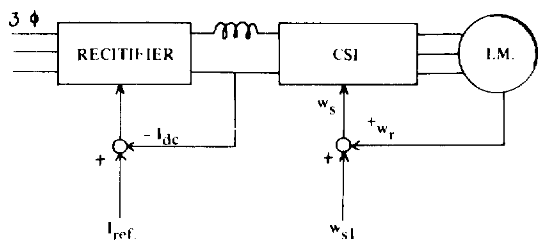

Fig. 3. Independent current and slip speed control

The use of motor flux control (constant flux control) is suggested by a number of authors as a method of improving perfermance of the drive. There are several methods: direct flux sensing, voltage sensing, and current-slip speed control. The last method is most suited for this application because both current and slip speed are already controlled.

The required relationships between current and slip speed can be obtained by referring to the steady-state characteristics. If the iron loss is ignored in Fig. 1, an approximate equivalent circuit considered only the mutual inductance is obtained. From the approximate equivalent circuit the following torque equation can be derived.

$$T = 2\pi p m_1 R_2 L_m^2 \frac{f_2}{[R_2^2 + \{2\pi(L_2 + L_m)\}^2 f_2^2]} (I_1)^2$$

$$= F_1(f_2, I_1) \qquad (1)$$

When the air gap flux is maintained constant, the torque eq. is obtained as follows; (from eq. 2 and eq. 15)

$$T = \frac{pm_1}{2\pi}\left[\frac{E_1}{f_1}\right]^2 \frac{R_2 f_2}{[R_2^2+(2\pi f_2 L_2)^2]}$$

$$= F_2(f_2) \quad (2)$$

Since the air gap flux is proportional to(E_1/f_1), the electro-magnetic torque is proportional to the square of the air gap flux at a given rotor slip frequency, f_2. Consequently, if the air gap flux is maintained constant under all operating conditions, the induction motor torque is determined solely by the rotor slip frequency, f_2, and is independent of the supply frequency, f_1.

Therefore from the eq. (1), the torque speed curves for several current levels can be plotted as in Fig. 4. From the eq. (2) the torque speed curve at constant flux operation is also plotted in Fig. 4 by the broken line. The points on each curve where the broken line meets are marked. The current and slip frequency for each point are plotted in Fig. 5. This is the required relationship between current and slip speed to maintain constant flux in the motor.

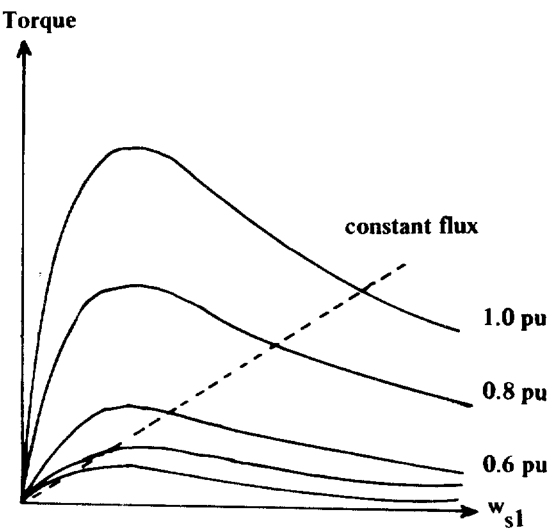

Fig. 4 Torque speed curves for different currents

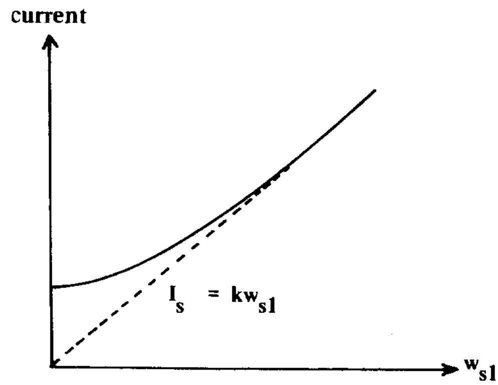

Fig. 5. Current slip curve resulting from constant flux

4. Optimal Efficiency Control

The torque equation (A–17) is a function of supply frequency f_1, the stator current I_1, and slip s. But if the speed that we want is determined, f_m, since $f_1 = f_2 + f_m$, $s = f_2/f_1$ the eq. (A–17) becomes a function of rotor slip frequency f_2, and stator current I_1. Thus it can be expressed as follows.

$$T = F_1(f_2,\ I_1) \quad (3)$$

Also the input power is

$$P_{in} = F_2(f_2,\ I_1) \quad (4)$$

If the speed that we want is controlled to be constant, the out-put power is proportional to the torque. Therefore, for a certain torque $T = T_0$, the output power is

$$P_{out} = wT_0 = \frac{2\pi f_m}{p}\ T_0 \quad (5)$$

In the case of constant flux operation, the rotor slip frequency required for this torque, T_0, can be calculated from eq. (2)

$$f_{20} = G_2(T_0) \quad (6)$$

And the stator current at this slip frequency is from eq. (3)

$$I_{10} = G_1(f_{20},\ T_0) \tag{7}$$

The input power at this operating point is also calculated from eq. (4)

$$P_{in} = F_2(f_{20},\ I_{10}) \tag{8}$$

By the way, if the load factor is decreased, then the efficiency of induction motor can be improved by decreasing the air gap flux. Therefore, for the same torque (same output), the maximum efficiency point will exist in the non-saturation region in Fig. 6.

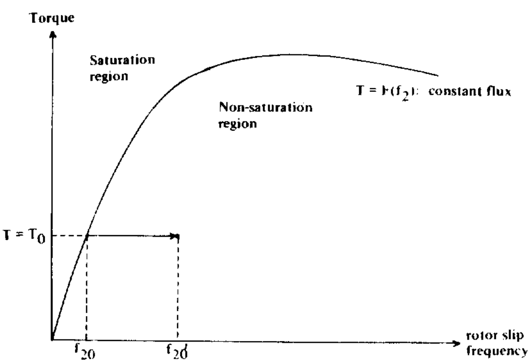

Fig. 6. Operating region for a certain load

To obtain the required relationships for maximum efficiency between the stator current and rotor slip frequency, the algorithm shown in Fig. 7. is applied and the results are plotted in Fig. 8.

As shown in Fig. 8, the operating points are moved (A A′, B B′) below a certain current. But above this current, the maximum efficiency points coincide with the rated flux points. This can be explained by considering the saturation effects. According to the previous publication[12], the slip at which the efficiency is maximum is determined and unique. Therefore, if the operating points are below this slip, the efficiency can be improved by maintaining the slip constant. But above this slip, the air gap flux must be controlled to be con-

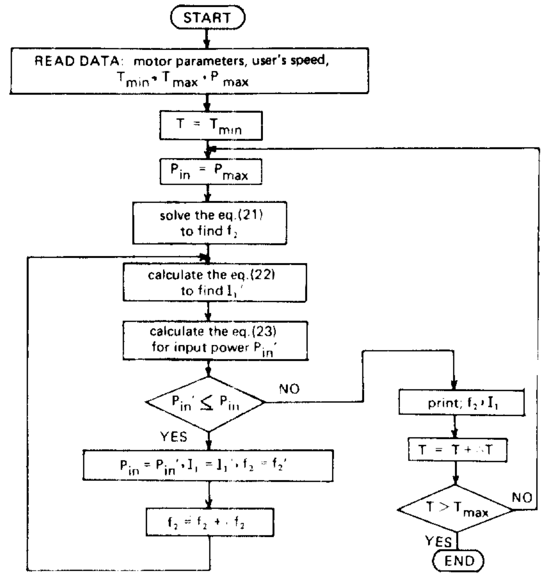

Fig. 7. The algorithm for maximum efficiency control

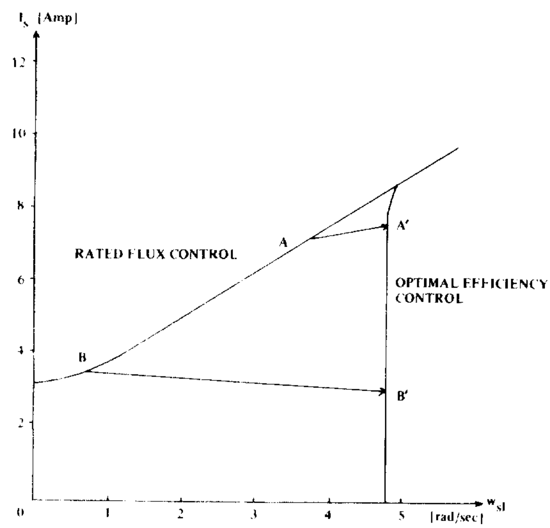

Fig. 8. Current slip curve for optimal efficiency

stant because the motor is saturated.

The maximum efficiency curves for different speeds can be obtained from the above algorithm, and the results are shown in Fig. 9.

The constant flux operation can be obtained in two ways. The slip speed can be used to control

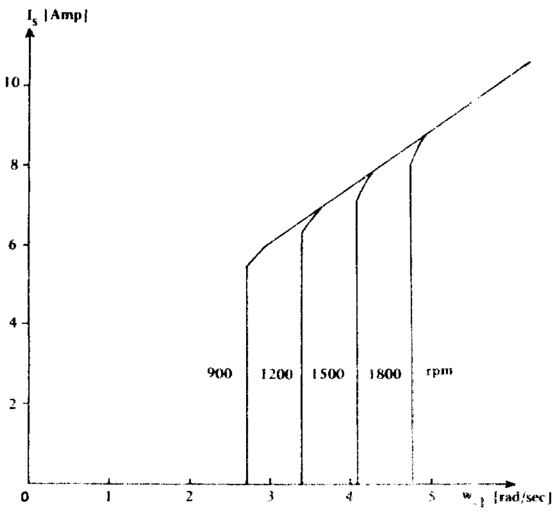

Fig. 9. Maximum efficiency curves for different speeds

the current reference as suggested by Phillips and Maag, and shown in Fig. 10-a. The second method is to control the slip speed with the measured current level as proposed by Cornell and Lipo, and shown in Fig. 10-b.

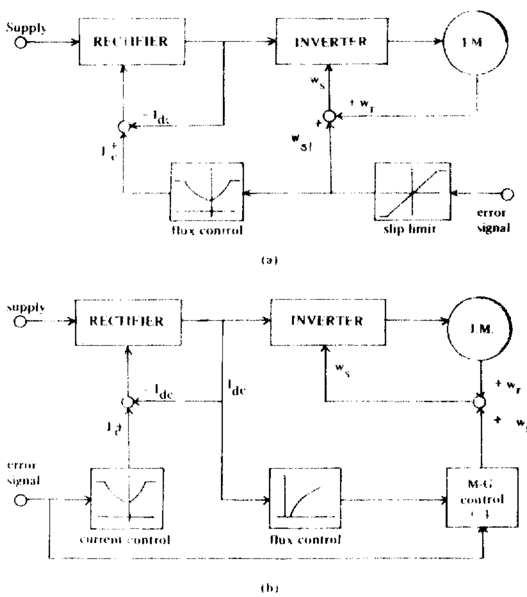

Fig. 10. Flux control diagram
(a) Slip speed controls current reference
(b) Current controls slip speed

The first method can be used for maximum efficiency control by amending slightly. If the output of slip limit is lower than the specified value, the rotor speed must be maintained at the specified value and the stator current must be controlled with the value which the load demands.

For example, when the user's speed is 1800 rpm, the control method can be explained as follows;

$$w_{sl} = \begin{cases} 4.8\ , & w_{sl}^* < 4.8 \\ w_{sl}^*\ , & w_{sl}^* \geq 4.8 \end{cases}$$

$$I_1 = \begin{cases} I_1^{*\prime}\ , & w_{sl}^* < 4.8 \\ I_1^*\ , & w_{sl}^* \geq 4.8 \end{cases}$$

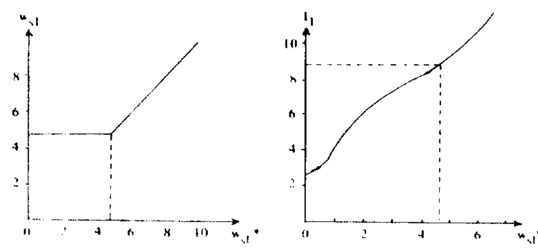

Fig. 11. Control method

Such operation can be obtained with following control loop;

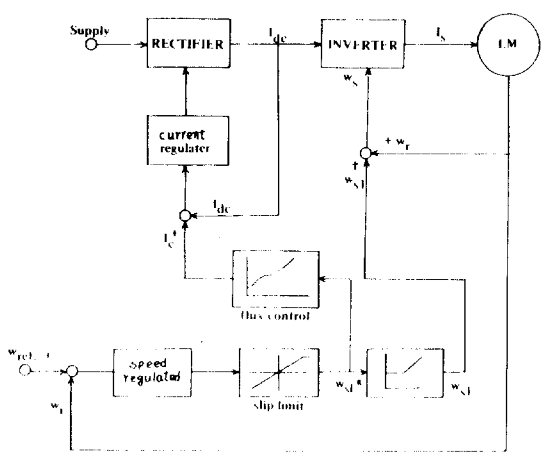

Fig. 12. Optimal efficiency control block diagram

5. Results

The improvement in efficiency at 48% load is shown in Fig. 13. Also the improvement in efficiency of induction motor according to load variation is shown in Fig. 14.

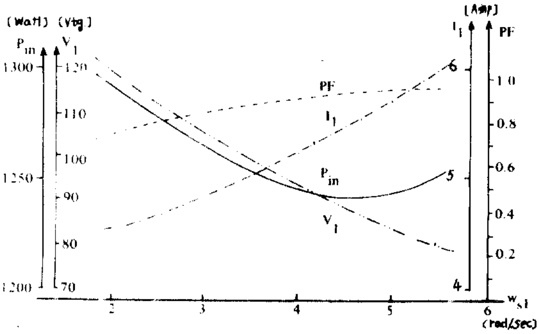

Fig. 13. Improvement in efficiency at 48% load

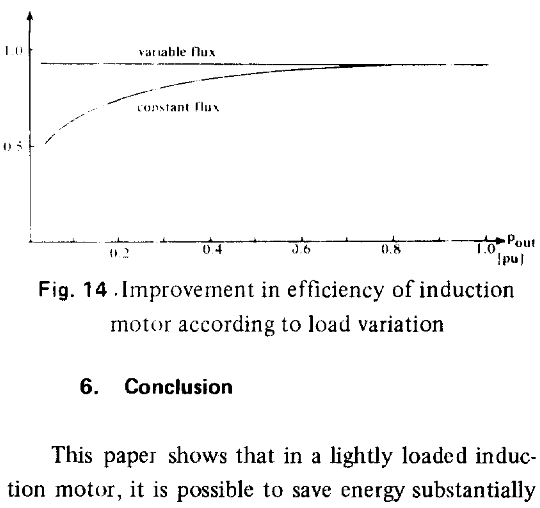

Fig. 14. Improvement in efficiency of induction motor according to load variation

6. Conclusion

This paper shows that in a lightly loaded induction motor, it is possible to save energy substantially by controlling the air gap flux. In order to improve the efficiency of induction motor, two ways were suggested [11, 12, 14]. The one is voltage control and the other is VVVF (variable voltage variable frequency) control. But nowadays, the current source inverter is widely used for induction motor drives due to its advantages. Therefore the algorithm suggested in this paper can be easily applied to practical application. This optimal efficiency control can be implemented by using microprocessor. According to previous publication [5], the constant flux operation may not be the best method for good dynamic response at low currents. The author thinks that this optimal efficiency control may also improve the dynamic response in lightly loaded induction motor.

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Nomenclature

The squirrel cage induction motor used in this study is 3 phase, 4 pole, 3 h.p., and the parameters are ;

stator leakage inductance,	L_1		1.7	mH
rotor leakage inductance,	L_2	(referred to stator)	1.7	mH
mutual inductance,	L_m		109.6	mH
conductance,	G_o		0.0035	ohm
stator resistance,	R_1		0.65	ohm
rotor resistance,	R_2	(referred to stator)	0.43	ohm
speed			1750	rpm
frequency			60	Hz
current			7.75	Amp
Voltage			208	Vol

Appendix: Induction Motor Equivalent Circuit

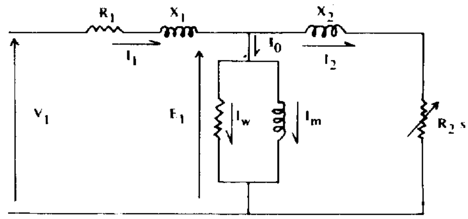

Fig. A—1. Induction motor equivalent circuit per phase

From the above equivalent circuit, the following equations are derived. At standstill, the induced *e.m.f.* per phase in the equivalent rotor is equal to the stator *e. m·f·* E_1 and the rotor frequency equals the supply frequency, f_1. When the motor runs with a slip s, the rotor *e. m. f.* $E_2 = sE_1$ and the rotor frequency $f_2 = sf_1$. *If* R_2 is the equivalent rotor resistance per phase at standstill, then the rotor current is given by

$$I_2 = \frac{E_2}{R_2 + jsX_2} = \frac{sE_1}{R_2 + jsX_2} \qquad \text{(A-1)}$$

and hence

$$I_2 = \frac{E_1}{(R_2/s) + jX_2} \qquad \text{(A-2)}$$

In equation (A—1), all rotor quantities are at slip frequency but in equation (A—2) they are at supply frequency. This shows that the rotor current I_2 is unaltered in magnitude if the rotor is brought to standstill and the resistance increased from R_2 to R_2/s.

Input Power Equation

If E_1 is the induced *e. m. f.* per phase in the stator, and E_2' is the induced *e. m. f.* at standstill in the rotor (referred to stator) then

$E_1 = E_2'$

and the induced *e. m. f.* per phase in the rotor at slip s, E_2 is $E_2 = sE_1$

and also the magnetizing current, rotor current, and stator current is given as follows;

$$\bar{I}_0 = \bar{E}_1 Y_0 = \bar{E}_1 (G_0 - jB_0) \quad \text{(A–3)}$$

$$\bar{I}_2 = \frac{s\bar{E}_1}{R_2 + jsX_2} = \bar{E}_1 (a_1 - ja_2) \quad \text{(A–4)}$$

where; $a_1 = \frac{sR_2}{R_2^2 + s^2 X_2^2}$, $a_2 = \frac{s^2 X_2}{R_2^2 + s^2 X_2^2}$

$$\bar{I}_1 = \bar{I}_0 + \bar{I}_2 = \bar{E}_1\left(G_0 - jB_0 + \frac{s}{R_2 + jsX_2}\right) \quad \text{(A–5)}$$

$$= \bar{E}_1 (b_1 - jb_2)$$

where; $b_1 = G_0 + a_1$, $b_2 = B_0 + a_2$

The terminal voltage, $\bar{V}_1$, is the sum of stator leakage impedance drop and induced *e.m.f.* in the stator; $\bar{V}_1 = \bar{E}_1 + \bar{I}_1 (R_1 + jX_1)$

$$= \bar{E}_1 (c_1 - jc_2) \quad \text{(A–6)}$$

where; $c_1 = 1 + R_1 b_1 + X_1 b_2$, $c_2 = R_1 b_2 - X_1 b_1$

$$\bar{E}_1 = \frac{\bar{V}_1}{(c_1 - jc_2)} \quad \text{(A–7)}$$

If eq. (A–7) is substituted in eq. (A–5), then the stator current is expressed as

$$\bar{I}_1 = \bar{V}_1 \frac{b_1 - jb_2}{c_1 - jc_2} = \bar{V}_1 (d_1 - jd_2) \quad \text{(A–8)}$$

where; $d_1 = \frac{b_1 c_1 + b_2 c_2}{c_1^2 + c_2^2}$, $d_2 = \frac{b_2 c_1 - b_1 c_2}{c_1^2 + c_2^2}$

The power factor becomes

$$\cos\theta = \frac{d_1}{\sqrt{d_1^2 + d_2^2}} \quad \text{(A–9)}$$

The total electrical input power is given by

$$P_{in} = m_1 I_1 V_1 \cos\theta = m_1 \frac{[b_1 c_1 + b_2 c_2]}{b_1^2 + b_2^2} (I_1)^2 \quad \text{(A–10)}$$

Torque Equation

At a slip s, the rotor power loss in the equivalent circuit is $I_2^2 R_2 / s$ watts per phase, whereas in the actual machine the rotor copper loss is $I_2^2 R_2$ watts per phase. The additional power loss in the equivalent circuit is the electrical equivalent of the mechancial power output of the motor. If P_{mech} denotes the gross mechanical power output including windage and friction losses, then

$$P_{mech} = m_1[(I_2^2 R_2 / s) - (I_2^2 R_2)]$$
$$= m_1 I_2^2 R_2 (1 - s)/s \quad \text{(A–11)}$$

where m1 is the number of stator phases.

If w is the mechanical angular velocity of the rotor and T is the electromagnetic torque

$$T_w = m_1 I_2^2 R_2 (1 - s)/s \quad \text{(A–12)}$$

and

$$T = [m_1 I_2^2 R_2 (1 - s)/s]/w \quad \text{(A–13)}$$

This is the internal motor torque which is greater than the useful shaft torque by the amount required to overcome the windage and friction torques.

Since the synchronous angular velocity is given by $w_1 = w/(1 - s) = 2\pi f_1 / p$

the torque equation can be rewritten as

$$T = \frac{m_1 I_2^2 R_2}{s w_1} \quad \text{(A–14)}$$

or

$$T = \frac{p m_1}{2\pi f_1} (I_2)^2 \frac{R_2}{s} \quad \text{(A–15)}$$

From eq. (A–4), (A–5), the rotor current is rewritten as

$$I_2 = \frac{\sqrt{a_1^2 + a_2^2}}{\sqrt{b_1^2 + b_2^2}} I_1 \quad \text{(A–16)}$$

If eq. (A–16) is substituted in eq. (A–15), then the electromagnetic torque is given by

$$T = \frac{p m_1}{2\pi f_1} \frac{[a_1^2 + a_2^2]}{[b_1^2 + b_2^2]} \frac{R_2}{s} (I_1)^2 \quad \text{(A–17)}$$