

JPE 2-1-8

Vector Control of Induction Motors using Optimal Efficiency Control

¹Sang-uk Kim*, ²Jin-ho Choi, and ³Young-seok Kim

¹Dept of Electrical Engineering, Inha Tech Col., Incheon, Korea

²Analog Team, Fairchild Semiconductor, Korea

³Dept of Electrical Engineering, Inha Univ, Incheon, Korea

ABSTRACT

This paper presents the control algorithm for maximum efficiency drives of an induction motor system with the high dynamic performance. This system uses a simple model of the induction motor that includes equations of the iron losses. The model, which only requires the parameters of the induction motor, is referred to a field-oriented frame. The minimum point of the input power can be obtained at the steady state condition. The proposed optimal efficiency control algorithm calculates the reference torque and flux currents for the vector control of the induction motors. A 32 bit floating point TMS320C32 DSP chip implements the drive system with the efficiency optimization controller. The results show the effectiveness of the control strategy proposed for the induction motor drive.

Key Words: induction motor, optimal efficiency control, iron loss, input power

1. Introduction

Vector control has been accepted as one of the most effective methods for the control of the induction motor drives. Specially, the induction motors are designed and controlled with optimal conditions for the purpose of the energy saving. To get the high efficiency, the conventional control algorithms have been widely studied in the vector control of the induction motors. The conventional optimal control method, which was to reduce the iron loss by regulating the flux currents at the light-load condition, was proposed [1]. This control method has a disadvantage. It is only possible to apply to the light-load case. The control algorithm based on the optimal reference of the slip frequency was proposed [2].

The reference of the slip frequency to get the minimal input power was calculated by measuring the input power under on-line time. The slip frequency was profiled for the vector control. However, the profiled slip frequency is sensible for the parameter variation on the hostile environments. It is difficult to use the servo control because of the lower response for the reference. This control scheme has also a defect that the stability of the system is not performed because the curve of the input power has too wide range for the minimization. The conventional adaptive control was studied for high efficiency drives [3]. This controller had optimal flux currents to reduce the input power by measuring the inverter input power. This adaptive control has good performance for the variation of the parameter; the point of minimum input power is not exact. The conventional control method by the profiled optimal ratio between the flux and torque currents was proposed [4]. Although this method has stability by using the optimal reference of flux currents, it is sensitive for the parameter variation.

Manuscript received September 24, 2001, revised February 19, 2002

Corresponding Author sanguk@inhac.ac.kr, Tel +82-32-870-2197, Fax +82-32-870-2507

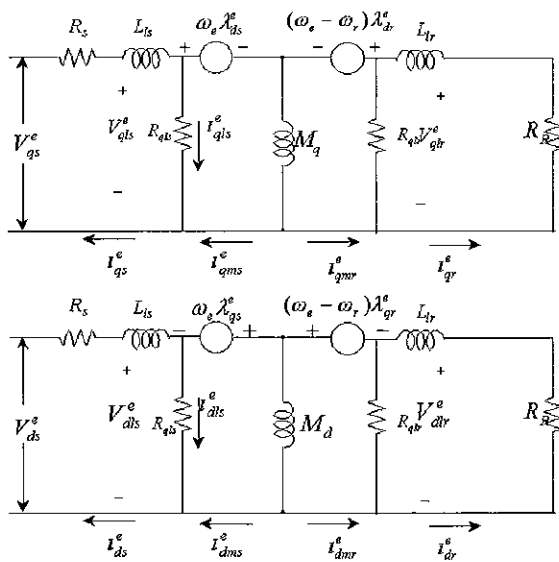


Fig 1 Equivalent circuits of IM in arbitrary reference frame

This paper proposes an optimal efficiency control for the vector control of the induction motors. To obtain the optimal reference of flux currents, the optimal ratio between the torque and flux currents is calculated by means of the model, including the iron loss for the indirect vector-controlled induction motor drives. A 32 bit floating POINT TMS320C32 DSP chip has implemented the efficiency optimization controller in this paper. Furthermore, the results of this experiment show the effectiveness of the control strategy proposed for the induction motor drive.

2. The model of induction motors

To solve the optimal efficiency problem of the induction motors, it is important to obtain the optimal balanced point of both the iron and copper losses. The reference of torque and flux currents can adjust the optimal balanced point to the high efficiency. Equivalent circuits of the induction motors considering the iron loss in the arbitrary reference frame are illustrated in Fig 1. If the torque and flux currents are controlled independently for the optimal balanced point with these circuits, shown in Fig. 1, we may find out the optimal balanced point. However, this model potentially has the following problems: difficult equations, de-coupled parameters, the huge amount of calculations, the non-linearity of the rotor flux, and parameter variations due to external factors.

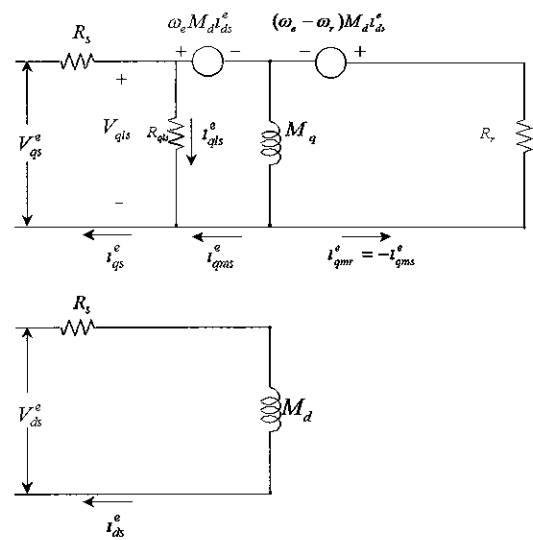


Fig 2 Brief equivalent circuits of IM at the steady state in field-oriented frame

The electrical constant is lower than the mechanical constant in the servo motor system. For that reason, the optimal efficiency method relies on the model of the induction motor in the steady state, because the steady state is more effective than the transient state. For the brief equivalent circuits, a model of the induction motors can be remodeled such as Fig 2. Here, R_{qis} , R_{dis} , R_{qir} , and R_{dir} are the stator and rotor resistances of the iron loss. The remodeled equivalent circuits can be obtained by the following assumptions:

- 1) The model is based on the steady state in the field-oriented frame
- 2) The leakage flux is too small in comparison with the flux to be considered
- 3) All parameters of the induction motor are regarded as constants because all parameters are not taken into account of the flux saturation and the temperature
- 4) The rotor resistance of the iron loss is regarded as part of the rotor resistance ($R_r = R_R \parallel R_{qir}$)

With the above assumption, the following equations are acquired from the equivalent circuits in the steady state:

$$\lambda_{qr}^e = 0 = \lambda_{qs}^e = M_q (i_{qms}^e + i_{qmr}^e) \tag{1}$$

$$i_{qms}^e = -i_{qmr}^e \tag{2}$$

$$v_{ds}^e = 0 = v_{dr}^e \quad (3)$$

$$i_{dms}^e = i_{ds}^e \quad (4)$$

$$i_{dr}^e = 0 = i_{dmr}^e \quad (5)$$

$$\lambda_{ds}^e = \lambda_{dr}^e = M_d (i_{dms}^e + i_{dmr}^e) \quad (6)$$

$$\lambda_{ds}^e = \lambda_{dr}^e = M_d i_{ds}^e \quad (7)$$

From the equation in (4), the iron loss of the d-axis is zero; R_{ds} in Fig. 2 is also zero. Therefore, the total iron loss is equal only to the one of the q-axis. The circuits of the q-axis in Fig. 2 are formulated as the following

$$(\omega_e - \omega_r) M_d i_{ds}^e = R_r i_{qms}^e \quad (8)$$

From the equation (8) and Fig. 2,

$$i_{qms}^e = i_{qs}^e - \frac{v_{qis}}{R_{qis}} = i_{qs}^e - \left(\frac{R_r}{M_d} \frac{i_{qms}^e}{i_{ds}^e} + \omega_r \right) \left(\frac{M_d}{R_{qis}} i_{ds}^e \right) \quad (9)$$

In sum,

$$i_{qms}^e = \left(\frac{R_{qis}}{R_{qis} + R_r} \right) i_{qs}^e - \left(\frac{M_d}{R_{qis} + R_r} \right) \omega_r i_{ds}^e \quad (10)$$

Based on the above equations, the iron and copper losses of the induction motor are illustrated as

$$P_{cus} = R_s \left((i_{ds}^e)^2 + (i_{qs}^e)^2 \right) \quad (11)$$

$$P_{cur} = R_r (i_{qms}^e)^2 \quad (12)$$

$$P_{fe} = R_{qis} (i_{qs}^e - i_{qms}^e)^2 \quad (13)$$

$$P_t = P_{cus} + P_{fe} + P_{cur} = R_q (i_{qs}^e)^2 + R_d \omega_r (i_{ds}^e)^2 \quad (14)$$

where,

$$R_q \equiv R_s + \frac{R_{qis} R_r}{R_{qis} + R_r}, \quad R_d \equiv R_s + \frac{M_d^2}{R_{qis} + R_r} \omega_r^2$$

P_{cus} : stator copper loss, P_{cur} : rotor copper loss

P_{fe} : iron loss, P_t : total loss

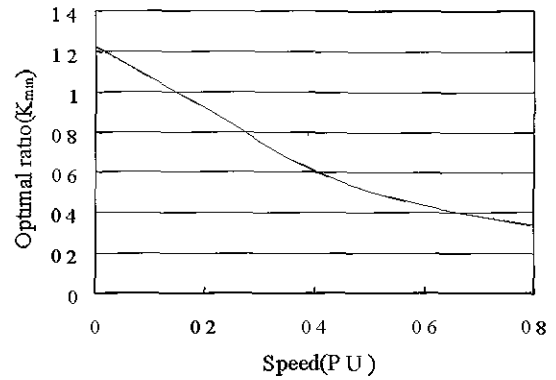


Fig 3 Relations between loss-minimization factor and speed

The torque of the induction motor is represented by the following equations

$$T_d = p (\lambda_{qr}^e i_{dmr}^e - \lambda_{dr}^e i_{qmr}^e) \quad (15)$$

$$T_d = p \left(\frac{M_d i_{ds}^e}{R_{qis} + R_r} (R_{qis} i_{qs}^e - M_d \omega_r i_{ds}^e) \right) \quad (16)$$

$$T_d \approx p M_d i_{ds}^e i_{qs}^e \quad (17)$$

where, $R_{qis} \gg R_r$, $R_{qis} \gg (M_d)^2 \omega_r (i_{ds}^e)^2$

3. Optimal efficiency control algorithm

We are able to achieve the optimal ratio ($K_{min(\omega)}$) that minimizes the loss in the model. When the speed and torque are regarded as constants on the steady state, the first derivative for the time with relation to the speed and torque in (14) is

$$i_{ds}^e = K_{min(\omega)} | i_{qs}^e | \quad (18)$$

where,

$$K_{min(\omega)} = \sqrt{\frac{R_q}{R_d}} = \sqrt{\frac{R_s (R_{qis} + R_r) + R_{qis} R_r}{R_s (R_{qis} + R_r) + M_d^2 \omega_r^2}} \quad (19)$$

Fig 3 shows relations between the loss-minimization factor and the speed. It is impossible to apply the optimal efficiency algorithm in case of the low speed region because an optimal ratio exceeds 1.

From (14)-(17), the efficiency of the induction motor can be obtained as follows.

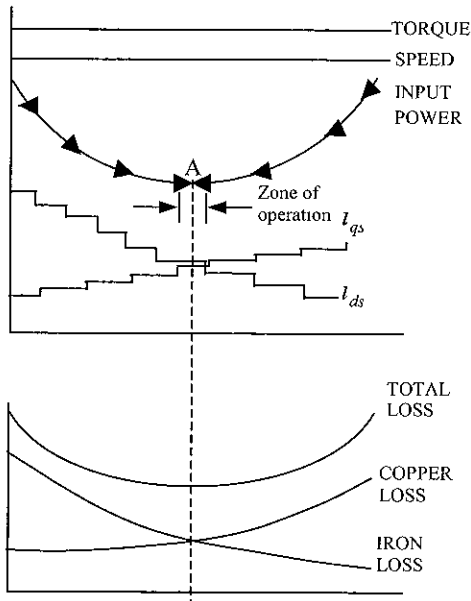


Fig 4 Principle of efficiency optimization control

$$\eta = \frac{T_d \omega_r}{T_d \omega_r + P_t} \tag{20}$$

where,

$$T_d \omega_r = M_d i_{qs}^e i_{ds}^e \omega_r$$

$$P_t = (R_s + \frac{R_{qls} R_r}{R_{qls} + R_r})(i_{qs}^e)^2 + (R_s + \frac{M_d^2 \omega_r^2}{R_{qls} + R_r})(i_{ds}^e)^2$$

As the rotor flux becomes smaller, the flux current is reduced, but the torque current increases through the speed controller. Consequently, the torque of the motor remains

constant. The reduction of the flux brings in the increase of the copper loss and the reduction of the iron loss. It results in the reduction of the DC link input power.

This paper proposes the equation to obtain the minimal of the input power. At the steady state, the minimum point of input power, point A, can be obtained as shown in Fig. 4. Based on the Fig. 4, the value of total loss is the lowest when the copper corresponds the iron loss. We can also obtain the lowest input power by inspecting that time. On the supposition that the torque is constant in the steady state, when the flux and torque currents optionally control the torque, the value of the optimal point A from Eq. (17)-(20) can be calculated by Eq. (21)

$$\hat{T}_d = K_t i_{ds}^* i_{qs}^* = K_t i_{ds}^{\omega_r} i_{qs}^{\omega_r} \tag{21}$$

where,

\hat{T}_d : constant torque in the steady state

i_{ds}^* : flux current in the steady state

i_{qs}^* : torque current in the steady state

4. Computer simulations and experimental results

As a consequence, we can get the lowest value of the loss with the flux and torque currents derived from the optimal ratio. Along with this, the optimal efficiency control is established. However, this algorithm has a disadvantage.

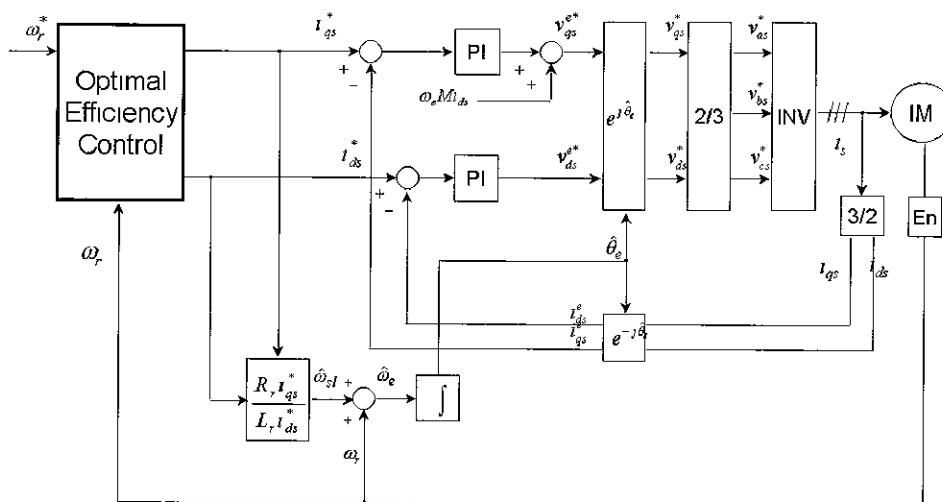


Fig 5 Block diagram of the proposed system

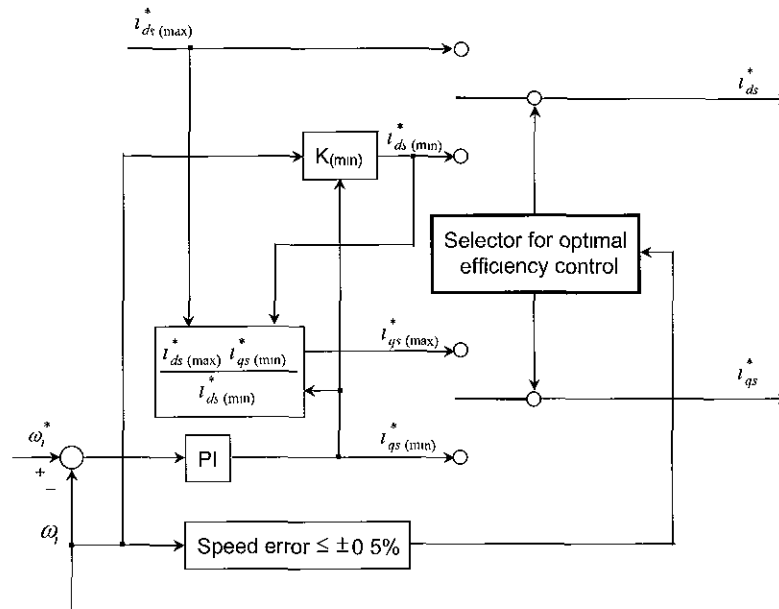


Fig 6 Block diagram of the optimal efficiency controller

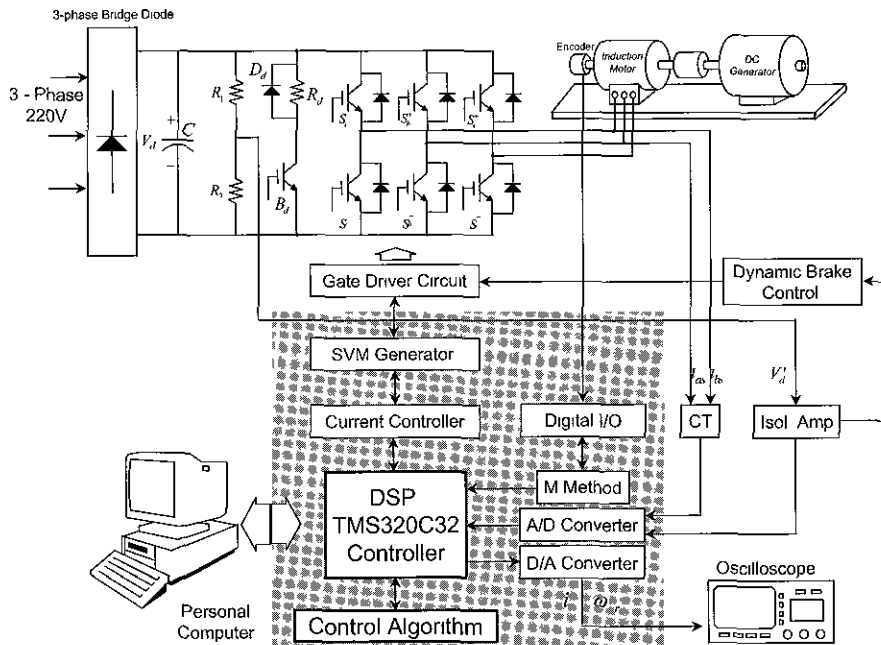


Fig 7 Hardware block diagrams of IM

The transient state, characterized as the load torque variations, requires a lot of time. It is caused by the fact that the only flux current, acquired by the proposed control method, fails to get the plenty of torque within the short time. Therefore, to solve this problem, the enough torque can be applied to this system in the transient state. This system can be used only under the steady state, defined as the state in which the speed error is within 0.5%

Therefore, the nominal flux current should be applied in the transient state. The block diagram for the optimal efficiency control of the induction motor is shown in Fig 5. Fig 6 shows the block diagram of the proposed controller. As Fig 6, the optimal method should be adapted to the time that the real speed is within 0.5% of the reference speed. Otherwise, the constant flux current should be permitted in the system.

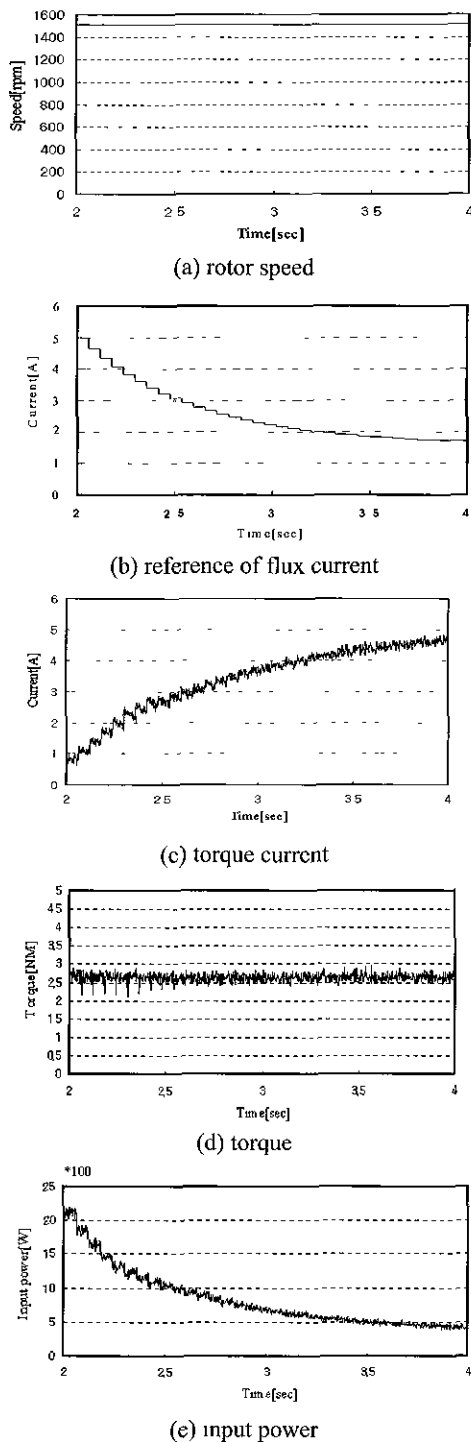


Fig 8 Computer simulation results with optimal efficiency controller (1500rpm)

The overall block diagram for the induction motor drives is shown in Fig. 7. The actual parameters of the induction motor used for the experiments are listed in the appendix.

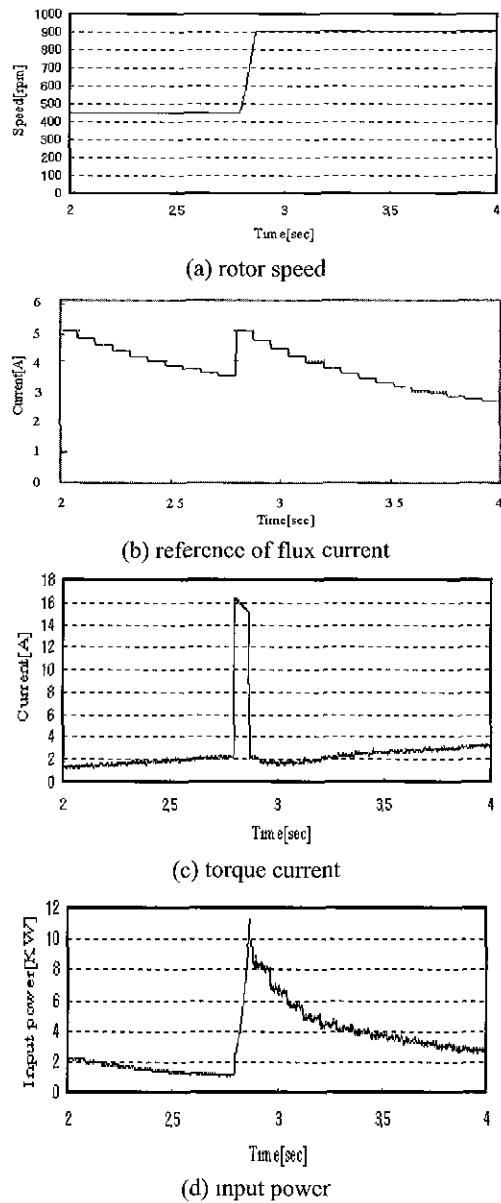


Fig 9 Computer simulation results with optimal efficiency controller (450-900rpm)

The rotor shaft of the induction motor is connected to the loaded DC generator. A 3.3(KW) DC generator has been applied for the loads. A 32 bit floating point TMS320C32 DSP implements the hardware of the experimental system. The calculations except for the motion controller (ADMC201 IC) are performed by DSP with the sampling time of 100[μsec]. The space vector PWM controller is performed by about 10[KHz] switching frequency of the IGBT inverter. An optical encoder installed at the motor shaft measures the motor speed.

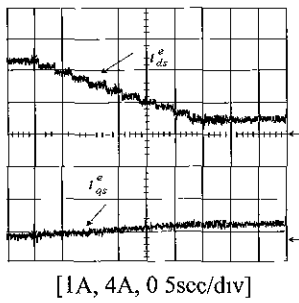


Fig 10 Flux and torque current (500rpm, 0 1PU)

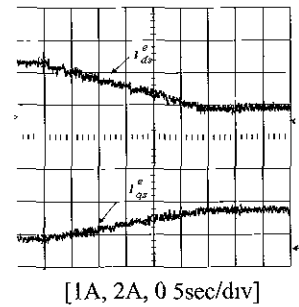


Fig 13 Flux and torque current (1000rpm, 0 4PU)

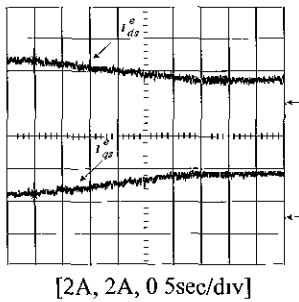


Fig 11 Flux and torque current (500rpm, 0 5PU)

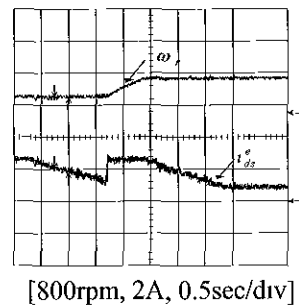


Fig 14 Flux and torque current (500-1000rpm)

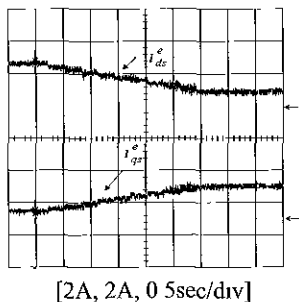


Fig 12 Flux and torque current (1000rpm, 0 2PU).

The encoder pulses that generate 6000 pulses per revolution are increased to 24000 pulses per revolution by using a multiply-by-four logic circuit

Because the proposed controller is only operated in the steady state, the steady state is considered to be within 0.5% of the reference speed. That is, when the real speed reaches to be within 0.5% of the reference speed, the optimal efficiency control algorithm is operated. But, even if the real speed reaches to the considered steady state, the optimal reference of the torque and flux currents does not control the system just at the moment. It is the reason that the drive condition of the induction motors can be an unstable due to the sudden reference variations. To avoid the unstable drive condition, the calculated optimal values divide into 20 steps during 1.2 second

From the process, we can get the maximum efficiency point within 1.2 second

To verify the effectiveness of the proposed control schemes, speed references of 1500rpm are enforced at 0.1 times with a rating load. Fig. 8 shows the rotor speed, the reference of flux current, the torque current, torque, and input power by the computer simulations. Under the same torque condition, we can show the waveforms of the minimum input power.

To verify the motor performance by the proposed control schemes in the transient state, the reference of rotor speed gives from 500 to 1000[rpm]. In Fig. 9, even if the torque and speed are varied, we can see the good performance

Experimental results show the performance of the proposed controller in Fig. 10-14. The characteristic waveforms in Fig. 10-14 are the flux and torque reference current at the speed of 500rpm, 1000rpm, and 500-1000rpm. These waveforms are obtained by the proposed algorithm such as the computer simulations. We can also see that all goes well. Fig. 15 shows the efficiency characteristic curve. The figures show the capacities of the proposed control scheme when the speed reference and the load are varied

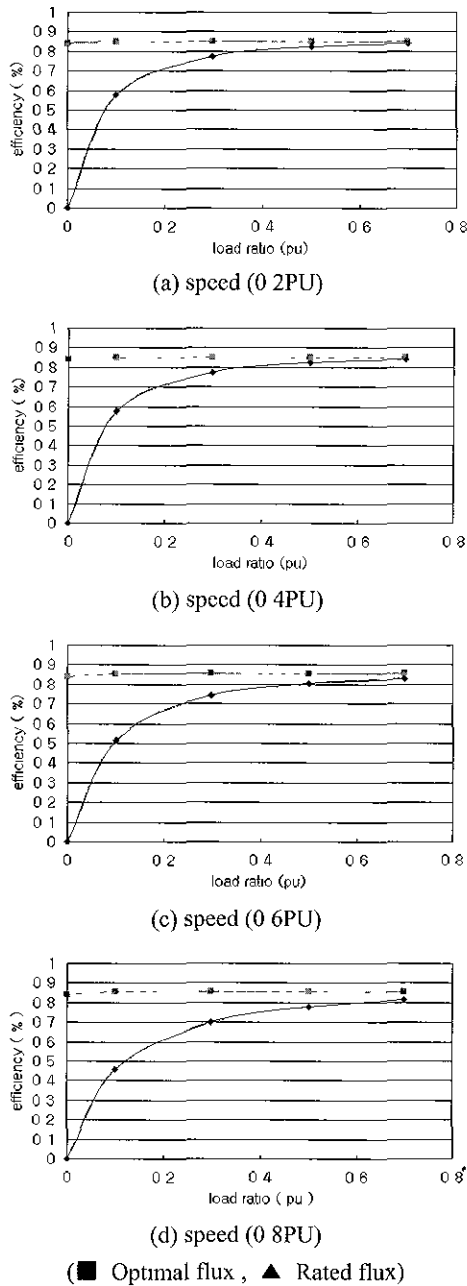


Fig 15 Efficiency curve according to the speed and load

It has high efficiency for the induction motor drives. In case of the proposed optimal efficiency control, it works in the higher speed and lower load very well.

5. Conclusions

In this paper, the control algorithm for maximum efficiency drives of the induction motor system with the

high dynamic performance is presented. We design the simple model that includes equations of the iron loss under the several assumptions. For the high efficiency, we may find out the optimal balanced point with this model. To reduce the input power of the induction motor, the flux and torque currents are controlled independently. The proposed controller is only operated in the steady state. According to the proposed optimal efficiency control algorithm, we come to know that the efficiency of the motor is higher at the higher speed and the lower load. Simulations and experiments, through the drive system with the proposed efficiency optimization controller, show the good performance for the vector control of the induction motor.

Appendix

Experiments have been realized using the following actual parameters of an induction motor:

2KW, 220/380V, 8 3/4 A, 4poles, 1720rpm

$$\begin{aligned}
 R_r &= 0.52 [\Omega] & R_s &= 1 [\Omega] \\
 L_r &= 103 [mH] & L_s &= 110 [mH] \\
 M &= 103 [mH]
 \end{aligned}$$

Acknowledgment

This research was supported by Inha University under Grant 21449(2000'), for which authors would like to express their thanks.

References

- [1] Dal Y. Ohm, Yuri Kheisonky and James R. Kimzey, "Rotor Time Constant Adaptation Method For Induction Motors Using DC Link Power Measurement", IEEE Trans Ind App, pp 588~593, 1989
- [2] P. Famouri and J.J. Cathy, "Loss minimization control of an induction motor drive" IEEE Trans Ind App Vol 27, No 1, pp 33~37, Jan/Feb 1991
- [3] G. O. Garcia, J. C. Mendes Luis, R. M. Stephan, and E. H. Watanabe, "An Efficient Controller for an Adjustable Speed Induction Motor Drive", IEEE Trans Ind Elec, Vol 41, No 5, pp 533~539, Oct 1994
- [4] Gilberto C. D. Sousa, member, IEEE, Bimal K. Bose, and John G. Cleland, "Fuzzy Logic Based On-Line Efficiency

Optimization Control of an Indirect Vector-Controlled Induction Motor Drive", IEEE, Trans. Ind. Elec., Vol. 42, No. 2, pp. 192~198, April 1995.

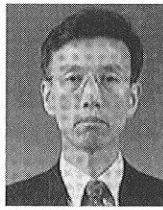
- [5] B. K. Bose, Power Electronics and AC drives, Englewood cliff, NJ: Prentice hall, 1986.
- [6] Duck-yong Yoon, Gyu-Ha Choe, Soon-chan Hong, Woo-Hyun Baek, and Eun-woong Lee, "Maximum Efficiency Drive of Vector-controlled Induction Motors", KIEE, Vol. 1, pp. 27~37, Nov. 1996.



Sang-uk Kim received the B.S., M.S. and PH.D. degrees in 1992, 1995 and 1998 in electrical engineering from the Inha University, respectively. Since 1998, he has been with the Department of Electrical Engineering of Inha Technical College, where he is presently Assistant Professor. His current interests are in motor design, motor drives and power electronics.



Jin-ho Choi received the B.S. degree and M.S. degree in 1999 and 2001, respectively, in electrical engineering from the Inha University. Since 2001, he has been application engineer of the Analog Team at Fairchild Semiconductor. His research interests are motor drives, power device design and power conversion system.



Young-seok Kim received the B.S. degree in electrical engineering from Inha University and the M.S. and PH.D. degrees from Nagoya University, Japan, in 1977, 1984, and 1987, respectively. From 1987 to 1989 he was a Senior Researcher of the Power Electronics Research Department at Korea Electro technology Research Institute. Since 1989, he has been with the Department of Electrical Engineering of Inha University, where he is presently Professor. His research interests are in the areas of Power Electronics.