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# Vector Control of Induction Motors using Optimal Efficiency Control

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## 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.

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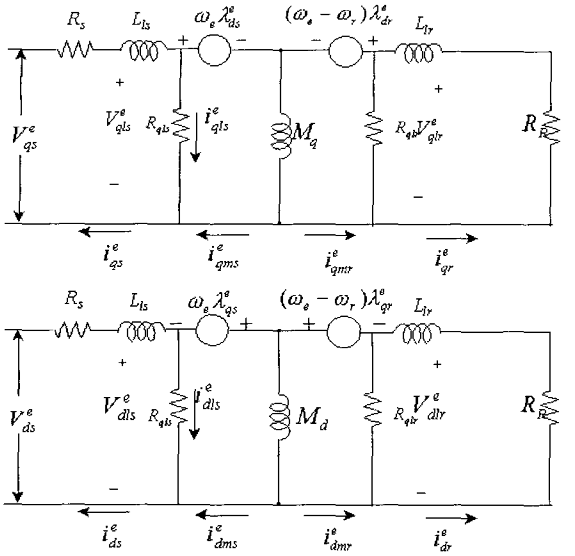


Fig. 1. Equivalent circuits of IM in arbitrary reference frame.

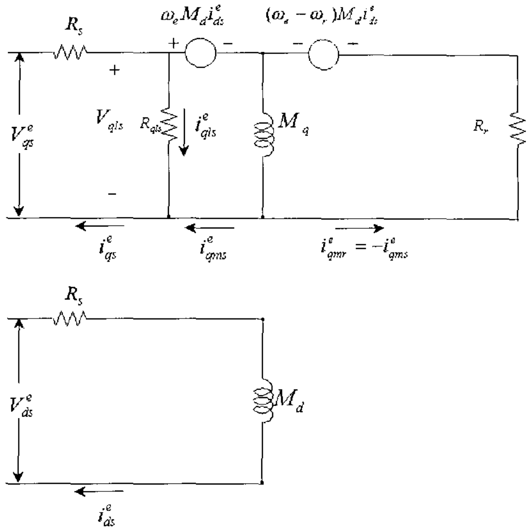


Fig. 2. Brief equivalent circuits of IM at the steady state in field oriented frame.

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.

The electrical constant is lower than the mechanica constant in the servo motor system. For that reason, th optimal efficiency method relies on the model of th induction motor in the steady state, because the stead state is more effective than the transient state. For the brie equivalent circuits, a model of the induction motors can b remodeled such as Fig. 2. Here, $R_{qls}$ , $R_{dls}$ , $R_{qlr}$ ,and $R_{dl}$ are the stator and rotor resistances of the iron loss. Th remodeled equivalent circuits can be obtained by th 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 wit the flux to be considered.
3) All parameters of the induction motor are regarde as constants because all parameters are not take into account of the flux saturation and th temperature.
4) The rotor resistance of the iron loss is regarded a part of the rotor resistance.( $R_r = R_R \,\|\, R_{qlr}$ )

With the above assumption, the following equations ar aquired from the equivalent circuits in the steady state.

$$\lambda^e_{qr} = 0 = \lambda^e_{qs} = M_q\,(i^e_{qms} + i^e_{qmr}) \qquad (1$$

$$i^e_{qms} = -\,i^e_{qmr} \qquad (2$$

$$v^e_{dls} = 0 = v^e_{dlr} \tag{3}$$

$$i^e_{dms} = i^e_{ds} \tag{4}$$

$$i^e_{dls} = 0 = i^e_{dmr} \tag{5}$$

$$\lambda^e_{ds} = \lambda^e_{dr} = M_d (i^e_{dms} + i^e_{dmr}) \tag{6}$$

$$\lambda^e_{ds} = \lambda^e_{dr} = M_d\, i^e_{ds} \tag{7}$$

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

$$(\omega_e - \omega_r) M_d i^e_{ds} = R_r i^e_{qms} \tag{8}$$

rom the equation (8) and Fig. 2,

$$i^e_{qms} = i^e_{qs} - \frac{v_{qls}}{R_{qls}} = i^e_{qs} - \left(\frac{R_r}{M_d}\frac{i^e_{qms}}{i^e_{ds}} + \omega_r\right)\left(\frac{M_d}{R_{qls}} i^e_{ds}\right) \tag{9}$$

n sum,

$$i^e_{qms} = \left(\frac{R_{qls}}{R_{qls} + R_r}\right) i^e_{qs} - \left(\frac{M_d}{R_{qls} + R_r}\right) \omega_r i^e_{ds}\,. \tag{10}$$

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

$$P_{cus} = R_s \left( (i^e_{ds})^2 + (i^e_{qs})^2 \right) \tag{11}$$

$$P_{cur} = R_r (i^e_{qmr})^2 \tag{12}$$

$$P_{fe} = R_{qls} (i_{qs} - i^e_{qms})^2 \tag{13}$$

$$P_t = P_{cus} + P_{fe} + P_{cur} = R_q (i^e_{qs})^2 + R_d \omega_r (i^e_{ds})^2 \tag{14}$$

where,

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

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

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

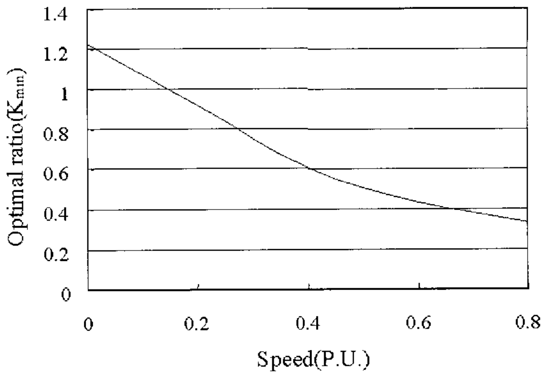


Fig. 3. Relations between loss-minimization factor and speed.

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

$$T_d = p(\lambda^e_{qr} i^e_{dmr} - \lambda^e_{dr} i^e_{qmr}) \tag{15}$$

$$T_d = p\left( \frac{M_d i^e_{ds}}{R_{qls} + R_r} (R_{qls} i^e_{qs} - M_d \omega_r i^e_{ds}) \right) \tag{16}$$

$$T_d \cong p M_d i^e_{ds} i^e_{qs} \tag{17}$$

where, $R_{qls} \rangle\rangle R_r$, $R_{qls} \rangle\rangle (M_d)^2 \omega_r (i^e_{ds})^2$

## 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

$$i^e_{ds} = K_{\min(\omega)} \left| \; i^e_{qs} \; \right| \tag{18}$$

where,

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

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:

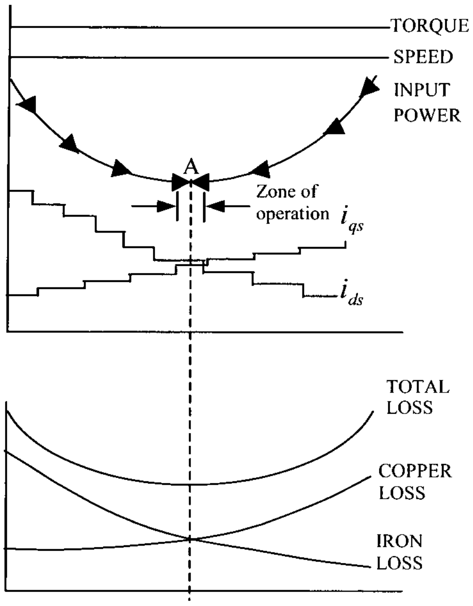


Fig. 4. Principle of efficiency optimization control.

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

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 increas of the copper loss and the reduction of the iron loss. results in the reduction of the DC link input power.

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

$$\hat{T}_d = K_t i_{ds} i_{qs} = K_t i_{ds}^{e*} i_{qs}^{e*} \qquad \text{(21}$$

where,

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

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

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

## 4. Computer simulations and experimental results

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

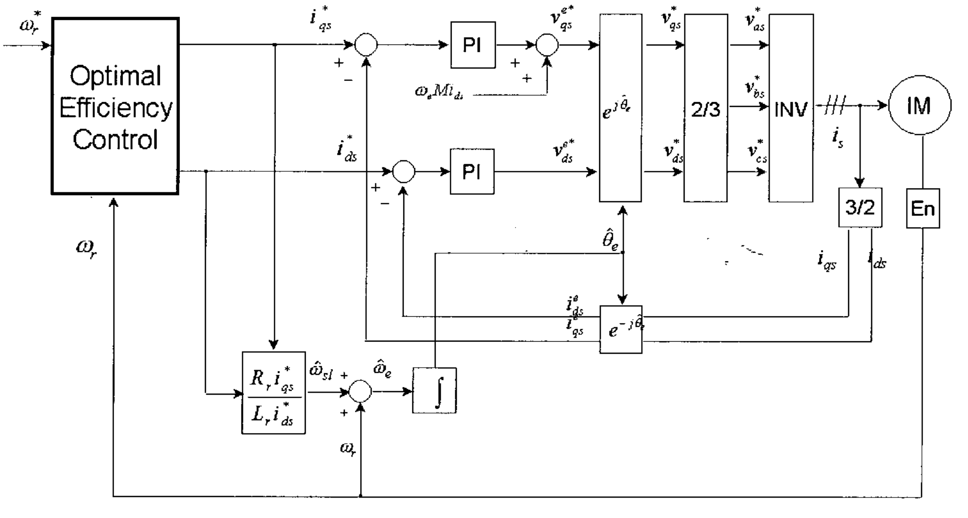
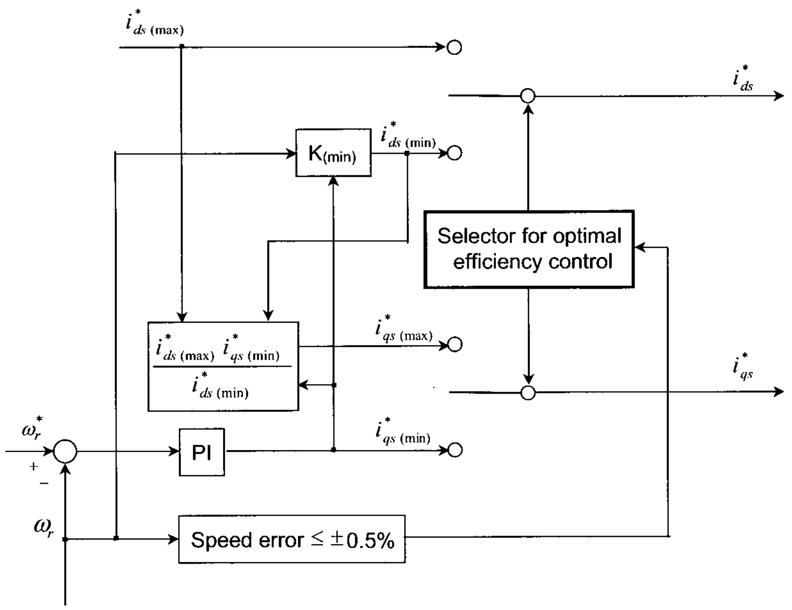
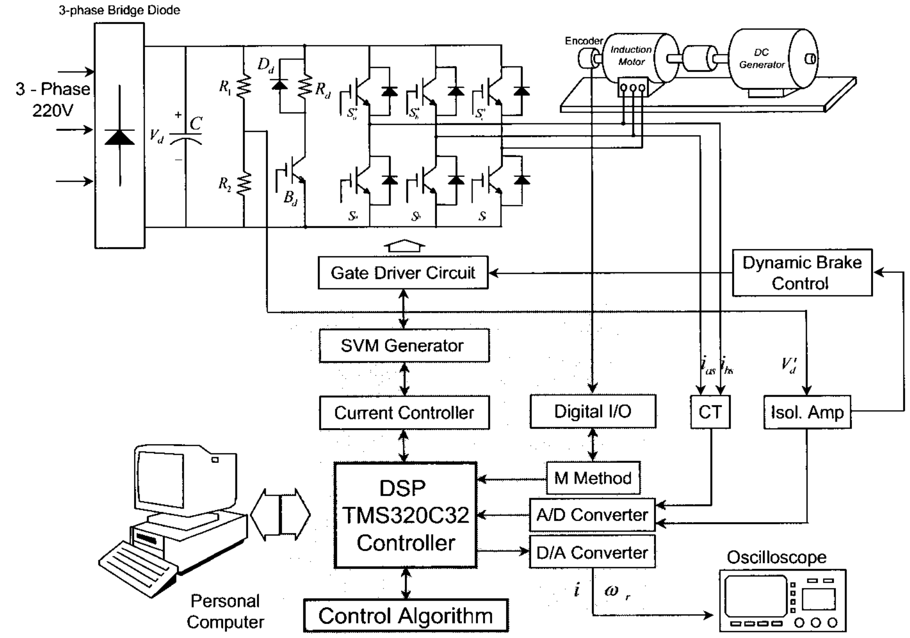


Fig. 5. Block diagram of the proposed system.

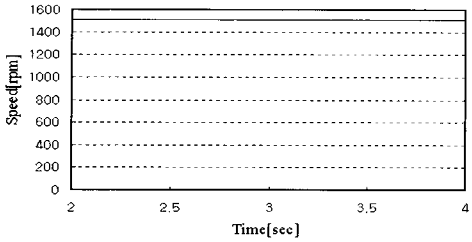


ig. 6. Block diagram of the optimal efficiency controller.

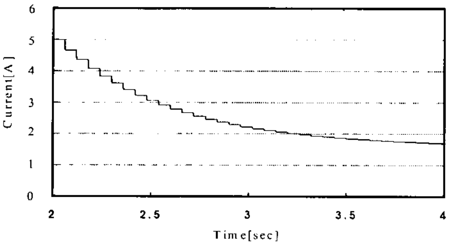


ig. 7. Hardware block diagrams of IM.

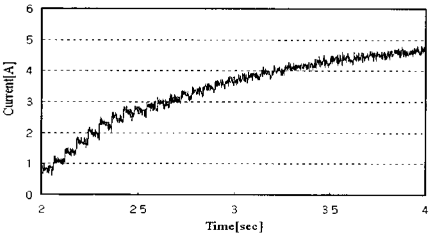
The transient state, characterized as the load torque variations, requires a lot of time. It is caused by the fact that the only flux current, acquired by the proposed control method, fails to get the plenty of torque within the short time. Therefore, to solve this problem, the enough orque can be applied 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.



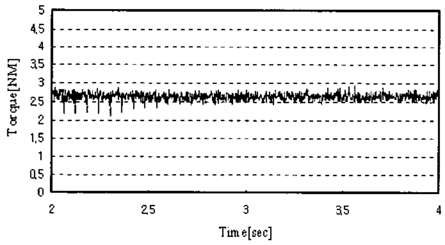
(a) rotor speed



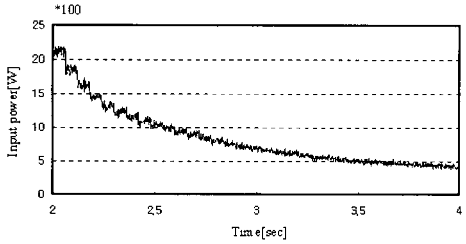
(b) reference of flux current



(c) torque current



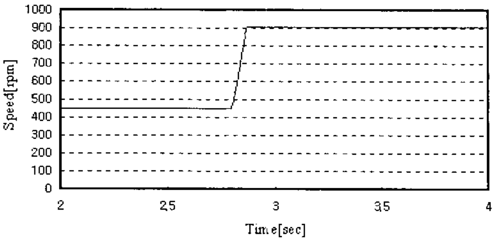
(d) torque



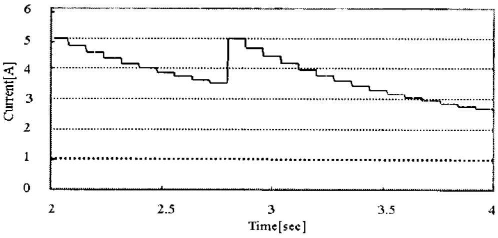
(e) input power

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

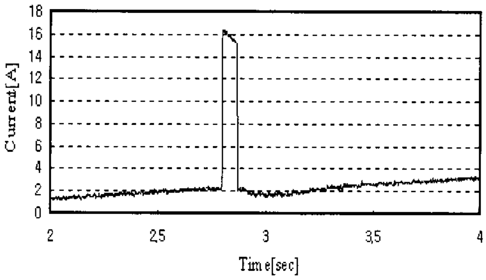
The overall block diagram for the induction motor drives is shown in Fig. 7. The actual parameters of the induction motor used for the experiments are listed in the appendix.



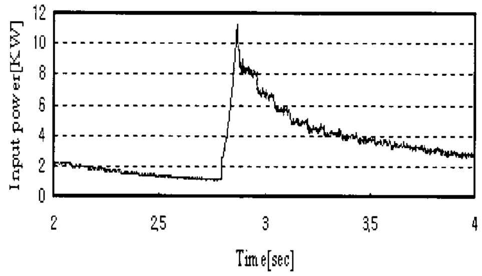
(a) rotor speed



(b) reference of flux current



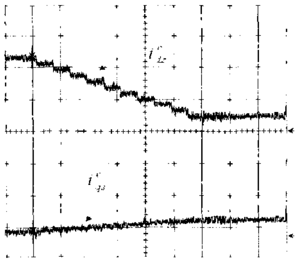
(c) torque current



(d) input power

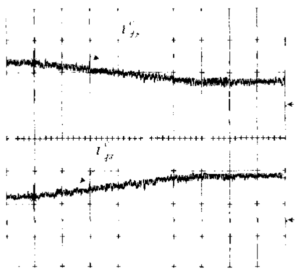
Fig. 9. Computer simulation results with optimal efficienc controller (450-900rpm).

The rotor shaft of the induction motor is connected to th loaded DC generator. A 3.3(KW) DC generator has bee applied for the loads. A 32 bit floating point TMS320C3 DSP implements the hardware of the experimental systen The calculations except for the motion controlle (ADMC201 IC) are performed by DSP with the samplin time of $100[\mu\text{sec}]$. The space vector PWM controller i performed by about 10[KHz] switching frequency of th IGBT inverter. An optical encoder installed at the moto shaft measures the motor speed.



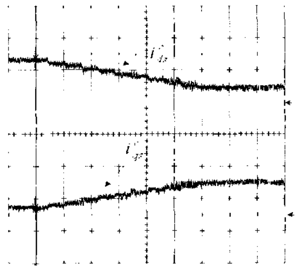
[1A, 4A, 0.5sec/div]

Fig. 10. Flux and torque current (500rpm, 0.1PU).



[2A, 2A, 0.5sec/div]

Fig. 11. Flux and torque current (500rpm, 0.5PU).

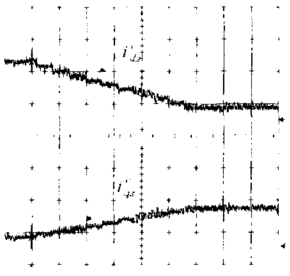


[2A, 2A, 0.5sec/div]

Fig. 12. Flux and torque current (1000rpm, 0.2PU).

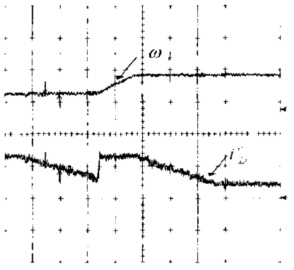
The encoder pulses that generate 6000 pulses per revolution are increased to 24000 pulses per revolution by using a multiply-by-four logic circuit.

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 f 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 he drive condition of the induction motors can be an unstable due to the sudden reference variations. To avoid he unstable drive condition, the calculated optimal values divide into 20 steps during 1.2 second.



[1A, 2A, 0.5sec/div]

Fig. 13. Flux and torque current (1000rpm, 0.4PU).



[800rpm, 2A, 0.5sec/div]

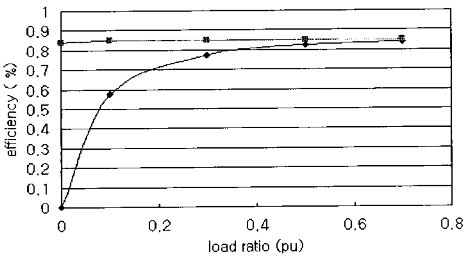
Fig. 14. Flux and torque current (500-1000rpm).

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

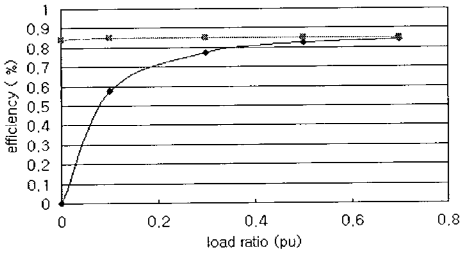
To verify the effectiveness of the proposed control schemes, speed references of 1500rpm are enforced at 0.1 times with a rating load. Fig. 8 shows the rotor speed, the reference of flux current, the torque current, torque, and input power by the computer simulations. Under the same torque condition,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

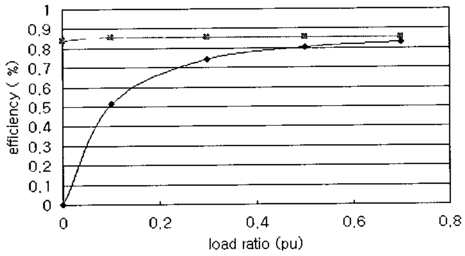
Experimental results show the performance of the proposed controller in Fig. 10-14. The characteristic waveforms in Fig. 10-14 are the flux and torque reference current at the speed of 500rpm, 1000rpm, and 500→1000rpm. These waveforms are obtained by the proposed algorithm such as the computer simulations. 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.



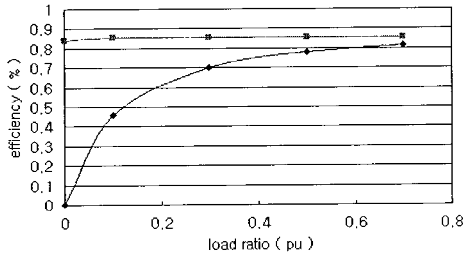
(a) speed (0.2PU)



(b) speed (0.4PU)



(c) speed (0.6PU)



(d) speed (0.8PU)

(■: Optimal flux , ▲: Rated flux)

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 th simple model that includes equations of the iron loss unde the several assumptions. For the high efficiency, we ma find out the optimal balanced point with this model. T reduce the input power of the induction motor, the flu and torque currents are controlled independently. Th proposed controller is only operated in the steady stat According to the proposed optimal efficiency contr algorithm, we come to know that the efficiency of th motor is higher at the higher speed and the lower loa Simulations and experiments, through the drive syste with the proposed efficiency optimization controller, sho the good performance for the vector control of th induction motor.

## Appendix

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

2KW, 220/380V, 8.3/4.8A, 4poles, 1720rpm

$R_r = 0.52\,[\Omega]$ $R_s = 1\ [\Omega]$

$L_r = 103\ [mH]$ $L_s = 110[mH]$

$M = 103\ [mH]$

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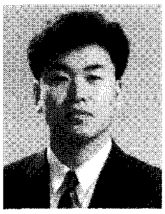

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