Optimal Efficiency Control for Induction Motor Drives

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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 iron losses. The model, which only requires the parameters of 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 reference torque and flux currents for the vector control of induction motors are calculated by the optimal efficiency control algorithm. The drive system with the proposed efficiency optimization controller has been implemented by a 32 bit floating point TMS320C32 DSP chip. The results show the effectiveness of the control strategy proposed for the induction motor drive.

1. Introduction

Vector control has been accepted as one of the most effective methods for the control of 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 induction motors. The conventional optimal control method, which was to reduce 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.

This paper proposes an optimal efficiency control for the vector control of 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 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 iron and copper losses. The reference of torque and flux currents can adjust the optimal balanced point to the high efficiency. Equivalent circuits of induction motors considering 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 this equivalent 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.

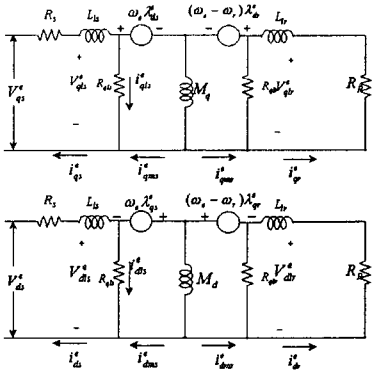


Fig 1. Equivalent circuits of IM in arbitrary reference frame.

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 induction motors can be remodeled such as Fig. 2. Here, R_{qls}, R_{dls}, R_{qlr}, and R_{dlr} 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.($R_r = R_R \parallel R_{qlr}$)

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

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

$$i^e_{qms} = -i^e_{qmr} \quad (2)$$

$$v^e_{dls} = 0 = v^e_{dlr} \quad (3)$$

$$i^e_{dms} = i^e_{ds} \quad (4)$$

$$i^e_{dls} = 0 = i^e_{dmr} \quad (5)$$

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

$$\lambda^e_{ds} = \lambda^e_{dr} = M_d\, i^e_{ds} \quad (7)$$

From the equation in (4), the iron loss of the d-axis is zero; R_{dls} 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 is formulated as the following.

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

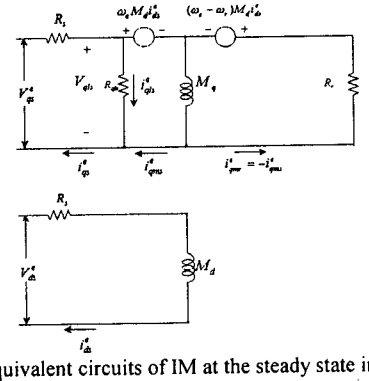


Fig 2. Brief equivalent circuits of IM at the steady state in field-oriented frame

From the equation (8) and Fig. 2,

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

In sum,

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

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

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

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

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

$$P_t = P_{cus} + P_{fe} + P_{cur} \quad (14)$$

$$= R_q (i^e_{qs})^2 + R_d \omega_r (i^e_{ds})^2$$

where,

$$R_q \equiv R_s + \frac{R_{qls} R_r}{R_{qls} + R_r}$$

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

P_{cus} : stator copper loss

P_{cur} : rotor copper loss

P_{fe} : iron loss

P_t : total loss.

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

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

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

$$T_d \cong= p M_d i^e_{ds} i^e_{qs} \quad (17)$$

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($K_{\min(\omega)}$) which minimizes the loss in the model. The derivative for the time in (14) is

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

where,

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

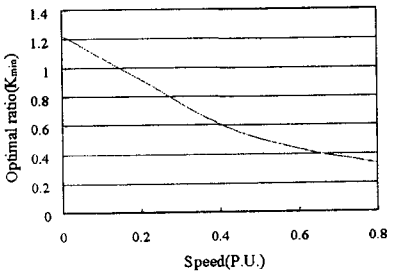


Fig.3 Relations between loss-minimization factor and speed

Figure 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

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

where,

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

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

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.

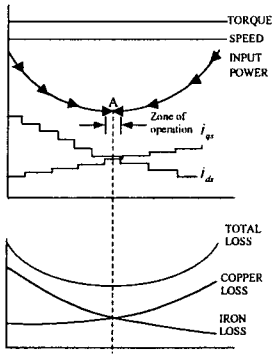


Fig. 4 Principle of efficiency optimization control

This paper proposes the equation to obtain the minimal of the input power. At the steady state, the minimum point of input power 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 iron loss. 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 point from (17)-(20) can be calculated by (21)

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

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

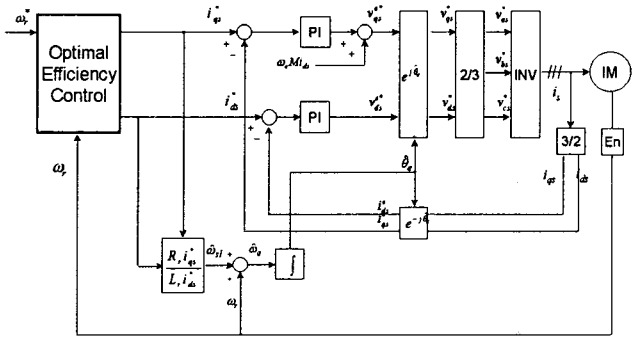


Fig. 5 Block diagram of the proposed system

As a consequence, we can get the lowest value of loss with the flux and torque currents derived from the optimal ratio. Along with this, the optimal efficiency control is estabilished. However, this algorithm has a disadvantage. 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 facilitated by the nominal flux current 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. Figure 6 shows the block diagram of the proposed controller. As Fig. 6, the optimal method should be adapted if the real speed is within 0.5% of the reference speed. Otherwise, the constant flux current should be permitted in the system.

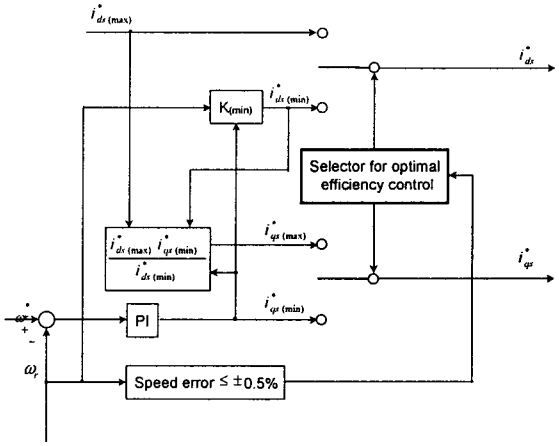


Fig.6. Block diagram of the optimal efficiency controller

4. Computer simulations and experimental results

The overall block diagram for the induction motor drives is shown in Fig.7. The actual parameters of an induction motor used for the experiments are listed in the appendix. 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. The hardware of the experimental system has been implemented by a 32 bit floating point TMS320C32 DSP. 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. The motor speed is measured by an optical encoder installed at the motor shaft. The encoder pulses which 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. When 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. To avoid an unstable drive condition of induction motors given rise to sudden reference variations, optimal values divide into 20 steps per 0.06 second from the reference currents of the transient state to the reference

currents of the steady state. From the process, we can get the maximum efficiency point within 1.2 second.

To verify the capacities of the proposed control schemes, speed references of 1500rpm are enforced at 0.1 times rating load. Figure 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.

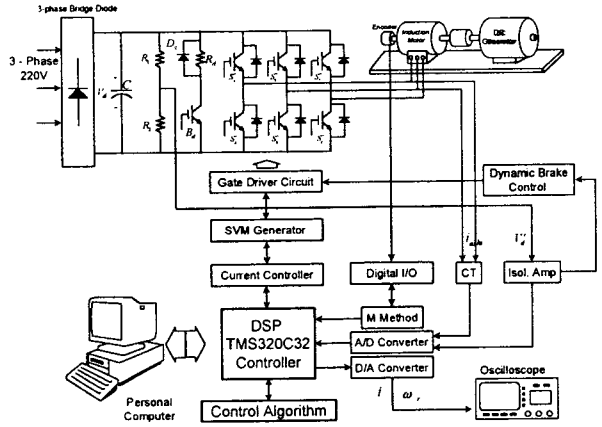
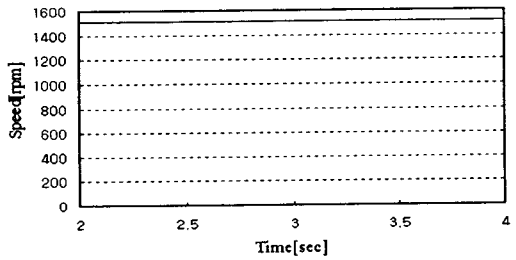
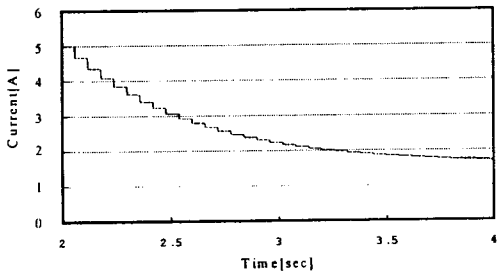


Fig. 7 Hardware block diagrams of IM

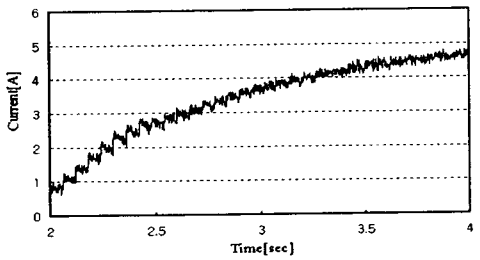
To verify the motor performance by the proposed control schemes in the transient state, the reference of rotor speed gives from 500 to 1000[rpm]. In Fig. 9, even the torque and speed are varied, we can see the good performance.



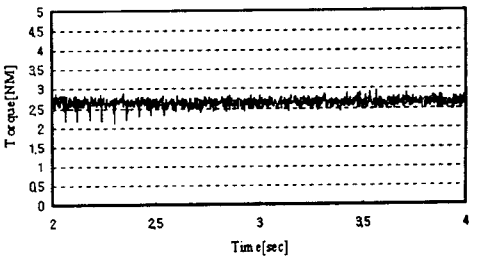
(a) rotor speed



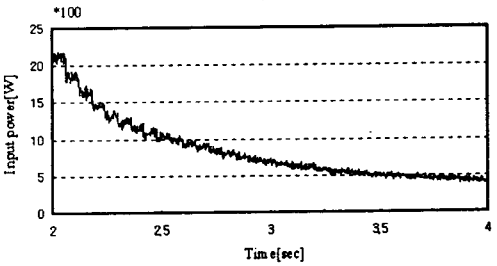
(b) reference of flux current



(c) torque current

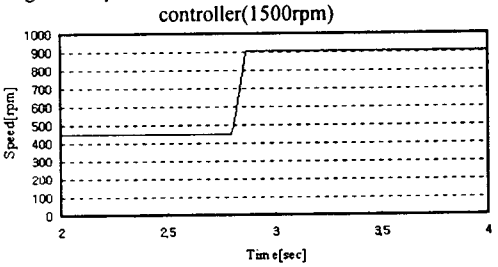


(d) torque

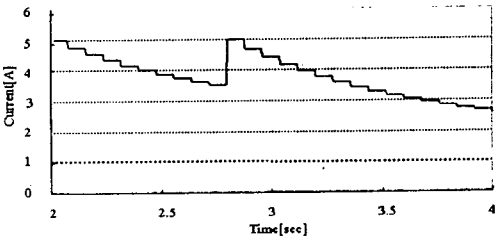


(e) input power

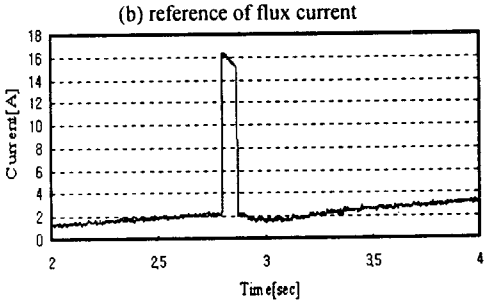
Fig. 8 Computer simulation results with optimal efficiency controller(1500rpm)



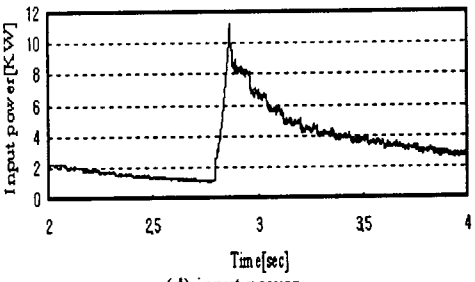
(a) rotor speed



(b) reference of flux current

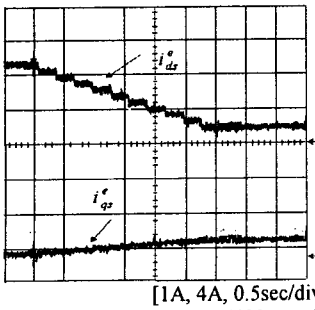


(c) torque current



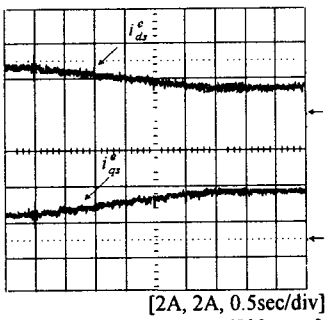
(d) input power

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



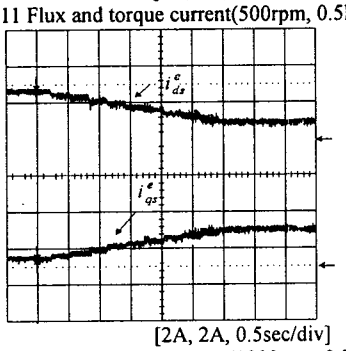
[1A, 4A, 0.5sec/div]

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



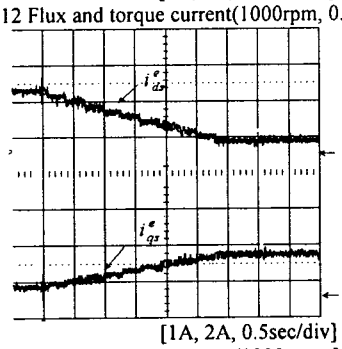
[2A, 2A, 0.5sec/div]

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



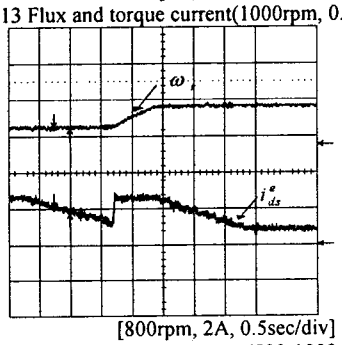
[2A, 2A, 0.5sec/div]

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



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

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

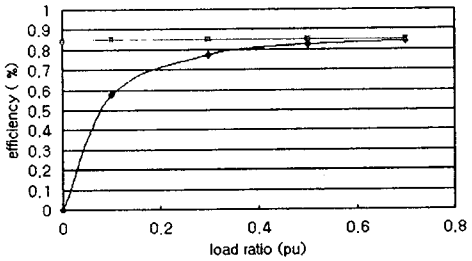


[800rpm, 2A, 0.5sec/div]

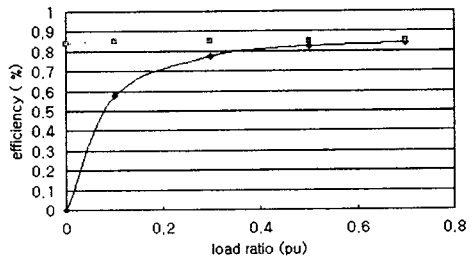
Fig. 14 Flux and torque current(500-1000rpm)

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.

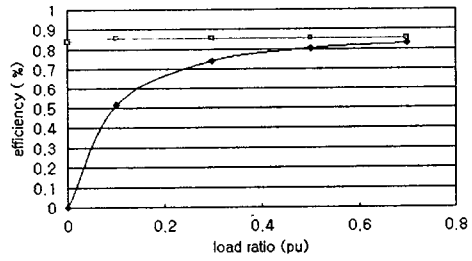
Experimental results show the performance of the proposed controller in Fig. 10-14. The characteristic waveforms in Fig. 10-14 are the flux and torque reference current at the speed of 500rpm, 1000rpm, and 500→ 1000rpm. These waveforms are obtained by the proposed algorithm such as the computer simulations. We can also see that all goes well. Figure 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. It has high efficiency for induction motor drives. The higher the speed is and the lower the load is, the higher the efficiency of the motor is.



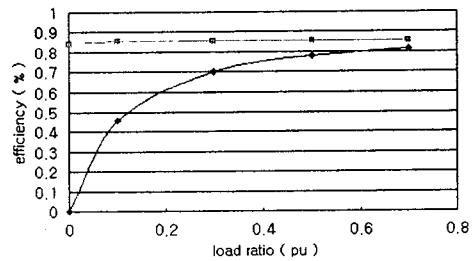
(a) speed (0.2PU)



(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

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 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.

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APPENDIX

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

2KW, 220/320V, 4.8/8.3A, 4poles, 1720rpm

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

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

$M = 103\ [mH]$