On-line Copper Loss Minimization Control Method of Induction and PM Motors with Periodic Fluctuation Load

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Keywords

«Permanent magnet motor», «Induction motor», «Vector control»

Abstract

This paper discusses the efficiency of permanent magnet motors (PM motors) and induction motors when periodic fluctuation occurs in the load. PM motors generate magnet torque by permanent magnet in the rotor. The magnet torque of PM motor is independent to d-axis current. However, if d-axis current of PM motor change rapidly in order to achieve high efficiency control, output torque also change rapidly without transient current because the reluctance torque is proportional to d-axis current. Thus, the torque response is quick according to electric time constant of the PM motor. On the other hand, induction motors generate output torque by the secondary flux. There is a relationship of first order lag between the secondary flux and the excitation current in the induction motors. Consequently, the secondary flux cannot be rapidly changed by the load torque. When the load torque varies in faster speed, the high efficiency control method increases the copper loss because the transient current flows in the excitation current. This paper clarifies the minimum copper loss control method for induction motors with torque fluctuation. When the load fluctuation is faster than the secondary flux of the induction motor, the high efficiency control method using the effective value of the load torque is used. The copper loss in the load fluctuation condition is analyzed in order to derive the boundary condition that copper loss is minimized. The validity of the boundary condition is confirmed by the experimental results using 3.7-kW induction motor.

I. Introduction

Electric motors are widely applied to industry applications. Permanent magnet synchronous motors (PM motors) have some advantages such as high efficiency, high power factor compared with induction motors. In contrast, induction motors have some advantages such as low cost and high reliability in electric motors. In order to improve the efficiency of the electric motor, high efficiency control methods have been proposed based on the vector control [1-4]. Basically, the high efficiency control methods for the electric motor are discussed under constant torque or step torque conditions [5][6].

However, the load torque is not just constant value depending on applications. Some loads have torque fluctuations such as belt conveyors, compression machines, and so on [7][8]. In copper loss minimization control methods for PM motor, the armature current is controlled depending on the load [5]. In contrast, in the copper loss minimization control methods for the induction motor, the magnetic flux is controlled by the excitation current depending on the load torque [6]. PM motor generates output torque by permanent magnet in the rotor. The magnet torque of PM motor is independent to d-axis current. However, if d-axis current of PM motor change rapidly in order to achieve high efficiency control, output torque also change rapidly because the reluctance torque is proportional to d-axis current. On the other hand, induction motor generates output torque by secondary flux. There is a relationship of first order lag between the secondary flux and the excitation current. Consequently, the secondary flux cannot be rapidly changed by the load torque. When the copper loss minimization control method is applied to the induction motor in which the load torque fluctuation occurs, the copper loss increases. This is because the transient current of the excitation current increases the copper loss when the load torque varies faster than the rotor time constant. In order to compensate for the secondary flux using excitation current, the torque current is drastically increased by the high efficiency control in case of the torque fluctuation. As a result, the copper loss increases because the effective value of the torque current is increased. In order to solve this problem, an average high efficiency control method has been proposed [9]. Consequently, in order to achieve high efficiency, different kinds of high efficiency control methods should be used from the relationship between the time period of the load torque fluctuation and the rotor time constant. However, the boundary condition depends on the relationship has not been reported in past works.

In this paper, the boundary condition which achieves minimum copper loss is derived in order to achieve high efficiency for induction and PM motors. The copper loss by each condition is analyzed in order to obtain the boundary condition which achieves minimum copper loss. If it is assumed that the load fluctuation is sinusoidal wave, then the boundary condition is decided from the relationship among the fluctuation frequency, the rotor time constant, the torque amplitude and its average. The remainder of this paper is organized as follows; first, the high efficiency control is introduced based on the vector control. Second, the copper losses in the constant torque and the fluctuation torque are analyzed in order to derive the boundary condition. Finally, the experimental results are shown in order to confirm the validity of the designed boundary condition.

II. Copper loss minimization control method

A. Periodic fluctuation load

Figure 1 shows a periodic fluctuation of the load torque. As first step, the torque is fluctuated at a single frequency without harmonic components in this paper. Note that a is the ratio between the torque amplitude T_m and the average torque T_0. There are two methods to achieve high efficiency in the periodic fluctuation load as follows; the high efficiency control by controlling the excitation current based on instantaneous value or constant value.

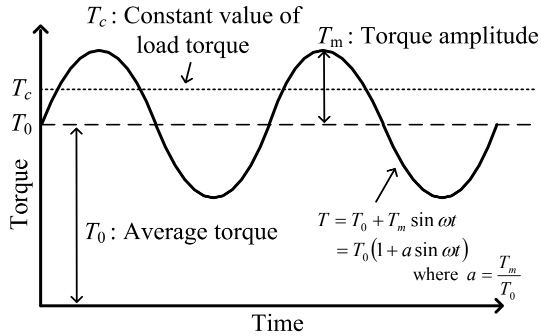


Figure 1. Fluctuating load torque. The fluctuation of load torque can be analyzed as sinusoidal functions. Note that, a is the ratio between the torque amplitude T_m and the average torque T_0.

B. Copper loss minimization control for PM motors

Figure 2 shows the equivalent circuit of PM motor. In the copper loss minimization control method of PM motor, the armature current is adjusted by the load torque. When the excitation current is decreased, the copper loss can be decreased at same time. In this paper, the iron loss is not taken into consideration for simplicity. Note that, the iron loss minimization is an important challenge for the high efficiency control. However, in heavy load, the copper loss is dominant compared to the iron loss. Therefore, this paper considers the copper loss minimization in order to improve the efficiency in the heavy load. The instantaneous copper loss p_{c_PM} in Figure 2 is given by (1).

$$p_{c\_PM} = 3R_a I_a^2 = \frac{3}{2} R_a \left(i_d^2 + i_q^2 \right) \tag{1}$$

where, R_a is the armature winding resistance, i_d and i_q are the d- and q-axis components of the armature current. The q-axis current is given by (2).

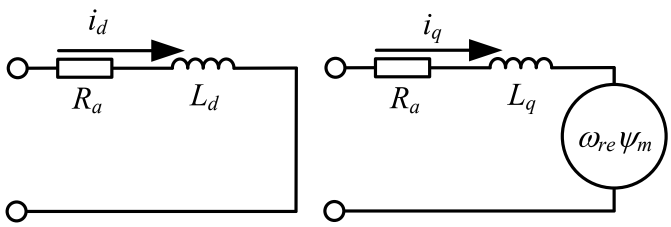
$$i_q = \frac{T}{P_f \{ \psi_m + (L_d - L_q) i_d \}} \tag{2}$$

where, P_f is the number of pole pairs, L_d and L_q are the d- and q-axis components of the armature self-inductance, and ψ_m is the flux linkage of the permanent magnet. It is noted that p_{c_PM} is calculated by substituting (2) into (1). The condition of minimizing copper loss can be derived by differentiating p_{c_PM} with respect to i_d and equating the derivatives to zero. As a result, the copper loss minimization condition is given by (3).

$$i_d = \frac{T^2}{P_f^2} \frac{L_d - L_q}{\{ \psi_m + (L_d - L_q) i_d \}^3} \tag{3}$$

When the torque T is given, the current which achieves minimum copper loss can be derived from (3). If PM motor has not saliency, the current i_d is zero.

The current i_q is decided by substituting the derived optimal current i_d. If the current i_d is derived by instantaneous torque, the copper loss is not changed transiently. This is because there is no relationship of first order lag. Therefore, in case that the load torque fluctuation frequency is slower than natural angular frequency of ACR, the high efficiency control method for PM motors is achieved by d-axis current control according to load torque fluctuation.



(a) d-axis equivalent circuit (b) q-axis equivalent circuit

Figure 2. Equivalent circuit of PM motor. In this paper, the iron loss is not taken into consideration for simplicity.

C. Copper loss minimization control method for induction motors

Figure 3 shows the equivalent circuit of induction motor. In the high efficiency control method, the excitation current is adjusted by the load torque. When the excitation current is decreased, the copper loss can be decreased at same time. The instantaneous copper loss p_{c_IM} in Figure 3 is given by (4).

$$p_{c\_IM} = \frac{3}{2} \{ (R_1 + R_2) i_q^2 + R_1 i_d^2 \} \tag{4}$$

where R_1 is the primary winding resistance, R_2 is the secondary winding resistance and i_d is the excitation current. where L_2 is the self-inductance, P_f is the number of pole pairs, M is the mutual inductance, and ϕ_{2d} is the magnetic flux at secondary side.

The torque current is given by (5).

$$i_q = \frac{L_2}{P_f M} \frac{T}{\phi_{2d}} = \frac{L_2}{P_f M^2} \frac{T}{i_d} \tag{5}$$

It is noted that p_{c_IM} is calculated by substituting (5) into (4). In addition, the excitation current i_d is obtained by differentiating P_c. Further, the zero point of the differential value is calculated. As a result, i_{d_min} at the minimum loss is expressed as (6).

$$i_{d\_\min} = \sqrt[4]{\frac{R_1 + R_2}{R_1}} \sqrt{\frac{L_2 T}{P_f M^2}} \tag{6}$$

According to (6), the excitation current at the minimum loss, which depends on the load torque, is controlled by the copper loss minimization control method.

The excitation current using the instantaneous torque $T(t)$ is given by (7).

$$i_d = \frac{1}{M} \sqrt[4]{\frac{R_1 + R_2}{R_1}} \sqrt{\frac{L_2 T_0 (1 + a \sin \omega t)}{P_f}} \tag{7}$$

Further, there is a relationship of first order lag between the excitation current i_d and the secondary flux $\phi_{2d.}$ According to (7), the relationship of i_d and ϕ_{2d} is expressed as (8).

$$\tau_2 \frac{d}{dt} \phi_{2d} + \phi_{2d} = M i_d = \sqrt[4]{\frac{R_1 + R_2}{R_1}} \sqrt{\frac{L_2 T_0 (1 + a \sin \omega t)}{P_f}} \tag{8}$$

where, τ_2 is the rotor time constant. When it is defined as non-dimensional time function $k(t)$, the secondary flux ϕ_{2d} is obtained by (10).

$$\tau_2 \frac{d}{dt} k(t) + k(t) = \sqrt{1 + a \sin \omega t} \tag{9}$$

$$\phi_{2d} = k(t) \sqrt[4]{\frac{R_1 + R_2}{R_1}} \sqrt{\frac{T_0 L_2}{P_f}} \tag{10}$$

In order to solve for $k(t)$, it is necessary to calculate the right formulas in (9) by Fourier transform. Additionally, $k(t)$ is solved by calculating the frequency response, that the amplitude of each frequency component is used. Thus, the torque current i_q is expressed (11).

$$i_q = \frac{L_2}{P_f M} \frac{T}{\phi_{2d}} = \frac{k_{iq}}{M} \sqrt[4]{\frac{R_1}{R_1 + R_2}} \sqrt{\frac{T_0 L_2}{P_f}} \tag{11}$$

$$k_{iq} = \frac{1 + a \sin \omega t}{k(t)} \tag{12}$$

where k_{iq} is the non-dimensional time function. In addition k_{iq} is depending on $\omega\tau_2$. As a result, the copper loss by copper loss minimization control method which considers the instantaneous value of the load torque, P_{c_ins} can be expressed as (13).

$$P_{c\_ins} = \sqrt{R_1 (R_1 + R_2)} \frac{L_2 T_0}{p M^2} \left(1 + k_{iq\_rms}{}^2\right) \tag{13}$$

It is noted that k_{iq_rms} is the effective value of k_{iq}. Therefore, the copper loss by the copper loss minimization control method, which uses the instantaneous torque, is calculated by the motor parameters and k_{iq_rms}.

Figure 4 shows the relationship between $\omega\tau_2$ and non-dimensional parameter k_{iq_rms}. The non-dimensional parameter k_{iq_rms} is a function of $\omega\tau_2$ and a. Therefore, the copper loss P_{c_ins} depends on $\omega\tau_2$ and a because P_{c_ins} depends on k_{iq_rms}.

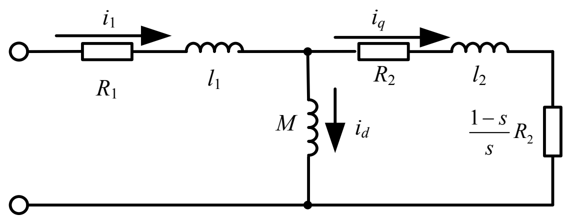


Figure 3. Equivalent circuit of induction motor. In this paper,the iron loss is not taken into consideration for simplicity.

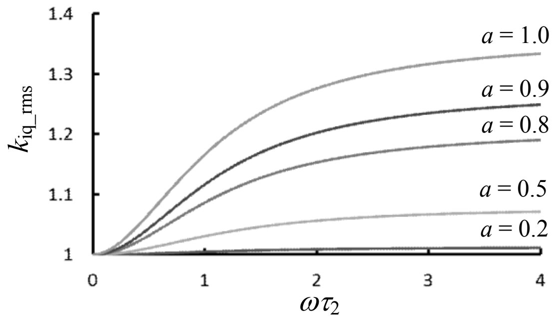


Figure 4. Relationship between $\omega\tau_2$ and non-dimensional parameter k_{iq_rms}. The copper loss P_{c_ins} is depending on $\omega\tau_2$ and a because P_{c_ins} is depending on k_{iq_rm}.

D. Copper loss minimization control method based on constant value of instantaneous torque for induction motors

The excitation current by using a constant torque T_c and the torque current are expressed as (14) and (15), respectively.

$$i_d = \frac{1}{M}\sqrt[4]{\frac{R_1+R_2}{R_1}}\sqrt{\frac{L_2 T_c}{P_f}} \tag{14}$$

$$i_q = \frac{1}{M}\sqrt[4]{\frac{R_1}{R_1+R_2}}\sqrt{\frac{T_0 L_2}{P_f}}\left(1 + a\sin\omega t\right) \tag{15}$$

In addition, the copper loss of the copper loss minimization control based on the constant value of the instantaneous torque P_{c_const} can be expressed as (16).

$$\begin{aligned} P_{c\_const} &= R_1\sqrt{\frac{1}{2\pi}\int_0^{2\pi} {i_d}^2 dt} + \left(R_1 + R_2\right)\sqrt{\frac{1}{2\pi}\int_0^{2\pi} {i_q}^2 dt} \\ &= \sqrt{R_1\left(R_1+R_2\right)}\frac{L_2}{P_f M^2}\left(T_c + \frac{{T_{rms}}^2}{T_c}\right) \end{aligned} \tag{16}$$

where T_{rms} is the effective value of the load torque $T(t)$. The effective value is defined by (17).

$$T_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} T(t)^2 dt} = \sqrt{{T_o}^2 + \frac{{T_m}^2}{2}} \tag{17}$$

Figure 5 shows the relationship between the copper loss of the copper loss minimization control P_c and the ratio between the constant torque Tc and the average torque T_0. The average torque T_0 is set to 0.2, whereas the load characteristic a is set to 0.6. The function of the copper loss is concave up. In addition, the point where T_c equals to T_m does not achieve the minimum copper loss. The constant torque is obtained by differentiating P_c. Furthermore, the zero point of the differential value is calculated. Consequently, the constant torque value that can be achieved the minimum copper loss is expressed as (18) and (19).

$$\frac{dp_c}{dT_c} = 0 \tag{18}$$

$$T_c = T_{rms} \tag{19}$$

According to (19), the constant value achieve the minimum copper loss is the effective value of the load torque. The minimum copper loss using the effective value of the load torque is can be expressed as (20).

$$P_{c\_rms} = 2\sqrt{R_1(R_1+R_2)}\frac{L_2}{P_f M^2}T_{rms} \tag{20}$$

The minimum copper loss using the effective value of the load torque is independent from $\omega\tau_2$. Hence, the copper loss is suppressed when the load torque is varied faster than the rotor time constant.

The minimum copper loss control of the induction motor is more effective than that of the PM motor. Therefore, this paper proposes on-line copper loss minimization method for the induction motor. In addition, this paper conducts experiments in order to confirm the utility of proposed method.

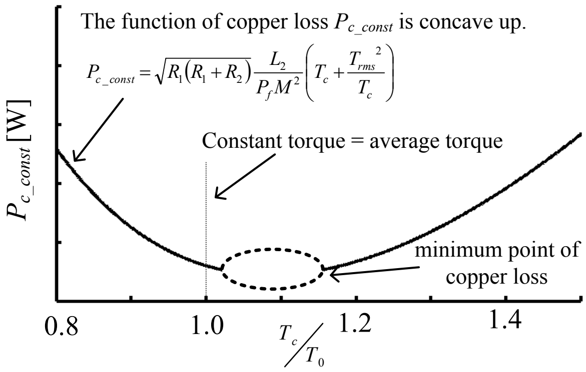


Figure 5. Relationship between the copper loss of the copper loss minimization control and the ratio between the constant torque and average torque. Note that the point that T_c equivalent to T_m is not minimum copper loss.

III. Proposed copper loss minimization method for periodic fluctuation load

According to (20), P_{c_rms} is constant value. In contrast, according to (13), P_{c_ins} depends on the relationship between the rotor time constant τ_2 and the angular frequency of the load torque fluctuation ω. Therefore, the boundary condition of the minimum copper loss based on the relationship between τ_2 and ω is calculated from the intersection pint between the function of P_{c_rms} and the function of P_{c_ins}. From (20) and (13), the boundary condition is given by (21).

$$k_{iq\_rms}^2 = 2\sqrt{1+\frac{a^2}{2}} - 1 \tag{21}$$

From (21), in the periodic fluctuation load, the torque characteristic a and $\omega\tau_2$ determine the excitation current which achieves the minimum copper loss.

However, it is necessary to clarify the load characteristic of the induction motor in order to control the flux by the load torque characteristic. In other words, the real load characteristic of the induction motor should be measured. In order to solve this problem, an on-line control method is proposed in order to control the excitation current. This method can decide the excitation current by calculation the frequency of load torque.

Figure 6 shows the calculation method of load torque frequency. First, the average torque is calculated by the integration value of the instantaneous torque. Second, subtract the average torque from the instantaneous torque. Then, the load frequency is calculated by counting the number of zero cross points N. The load frequency is calculated by (22).

$$f = \frac{N}{t_2 - t_1} \tag{22}$$

Figure 7 shows the block diagram of the proposed copper loss minimization control method. The online excitation current control block calculates the load torque frequency according to figure 6. In addition, the online excitation current control block determines the excitation current which achieves the minimum copper loss according to (21).

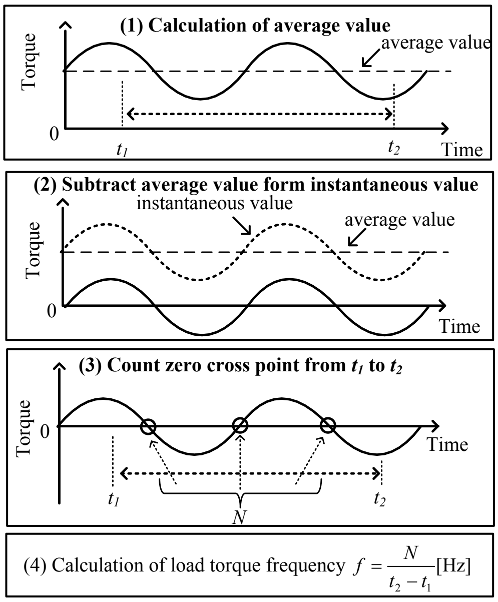


Figure 6. Calculation method of load torque frequency. (1) Average torque is calculated by the integration value of the instantaneous torque. (2) Subtract the average torque from the instantaneous torque. (3)Count zero-crossing points. (4) Load frequency is calculated by *N*.

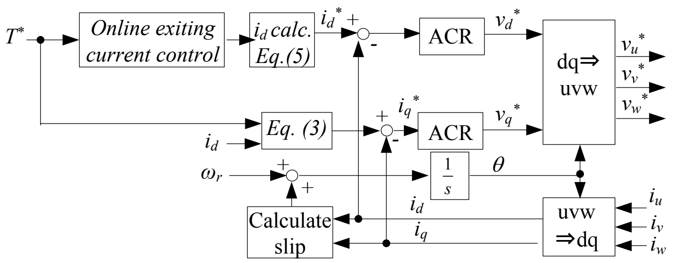


Figure 7. Block diagram of the proposed copper loss minimization control method. The online exiting current control block determines the exciting current which achieves minimum copper loss according to (19).

IV. Experimental results

Figure 8 shows the schematic of the experimental system. It is noted that the induction motor is driven by a 2-level inverter and the switching frequency is 10 kHz. In addition, the load motor is used as load machine to supply periodic fluctuation loads. Table 1 lists the motor parameters.

Figure 9 shows the copper loss based on experimental results. Note that the ratio between the constant torque and the average torque a is 0.6. The copper loss of the copper loss minimization control method using the instantaneous torque depends on the load frequency. On the other hand, the copper loss of the copper loss minimization control method using the effective value of load torque is constant. The error between the calculation boundary condition is 6.7%. The excitation current is changed by the on-line excitation current control considering the load torque condition.

Figure 10 shows the boundary condition of minimum copper loss based on the calculation result and experimental result. Note that $\omega\tau_2 = 1$ means the angular frequency of the load torque fluctuation ω is same as the rotor time constant τ_2. The error between calculation result and experimental result is 7.3%. The area achieves minimum copper loss using the instantaneous torque narrow by $\omega\tau_2$.

Figure 11 shows the waveforms of each copper loss minimization control at operation point A shown in figure 10 (a = 0.2, $\omega\tau_2$ = 1.1). Figure 11 (a) shows the copper loss minimization control method using the instantaneous torque, and (b) shows the copper loss minimization control method using the effective value of the load torque. In Figure 11 (a), the excitation current is changed in according to the torque current. In addition, the phase of the excitation current is as same as the phase of the torque current. In this condition, the copper loss is 86.8 W. On the other hand, in Figure 11 (b), the excitation current is constant. In this condition, the copper loss is 87.9 W.

Figure 12 shows the waveforms of the each copper loss minimization control at operation point B shown in figure 10. (a = 0.2, $\omega\tau_2$ = 2.6). Figure 12 (a) shows the copper loss minimization control method using the instantaneous torque, and (b) shows the copper loss minimization control method using the effective value of the load torque. In addition, in Figure 12 (a), the copper loss is 88.7, and in (b), the copper loss is 88.1 W. In Figure 12 (a), the excitation current is ahead of the torque current. The fluctuation frequency is higher two times than the rotor time constant. As a result, the copper loss increases because the root mean square value of the torque current is increased by the flux fluctuation.

Figure 13 shows the waveforms of the each copper loss minimization control at operation point C shown in figure 10. (a = 0.8, $\omega\tau_2$ = 2.6). Figure 13 (a) shows the copper loss minimization control method using the instantaneous torque, and (b) shows the copper loss minimization control method using the effective value of load torque. In Figure 13 (a), the transitional torque current increases compared to point B. The transitional torque current is due to an increase of a. As a result, the boundary becomes narrow shown in Figure 10.

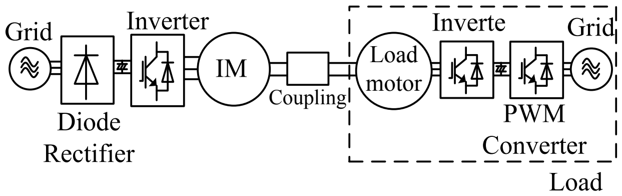


Figure 8. Experimental system. The induction motor is driven by a 2-level inverter and the switching frequency is 10 kHz

Table 1. Motor parameters.

Parameter	Value
Poles	4
Rated power	3.7 kW
Rated voltage	188 V
Rated current	18.0 A
Rated speed	1500 r/min
Primary resistance R_1	0.414 Ω
Secondary resistance R_2	0.423 Ω
Primary leakage inductance l_1	1.24 mH
Secondary leakage inductance l_2	1.24 mH
Mutual inductance M	34.3 mH
Time constant τ_2	0.528 sec

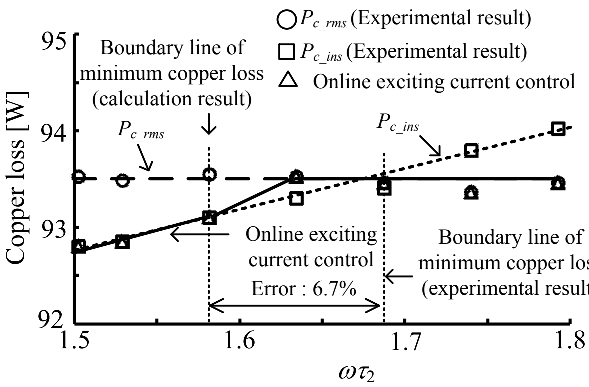


Figure 9. Copper loss of the on-line minimum copper loss control method based on experimental result. The error between calculation boundary condition is 6.7%. The exiting current is changed by on-line exiting current control considering the load torque condition.

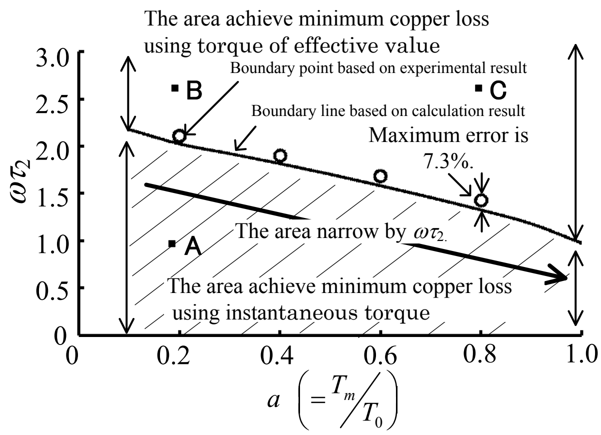
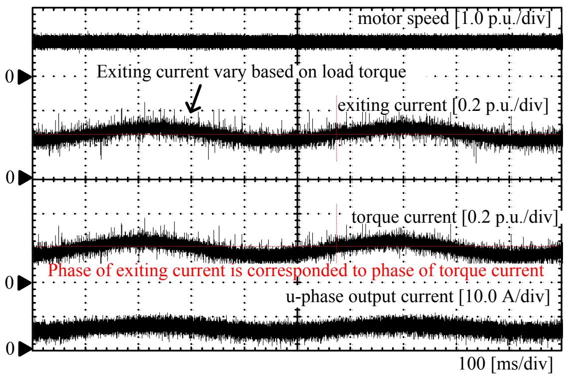
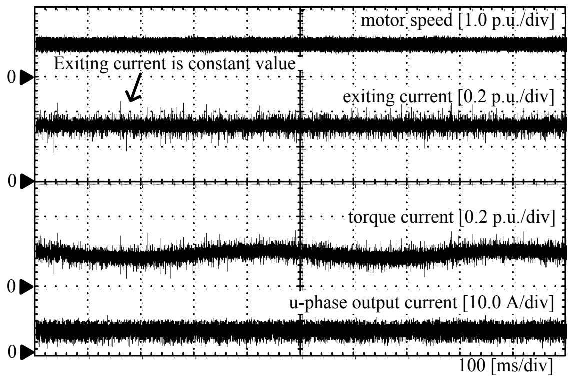


Figure 10. Boundary condition of minimum copper loss based on the calculation and experimental results. The area achieves minimum copper loss using instantaneous torque narrow by $\omega\tau_2$.

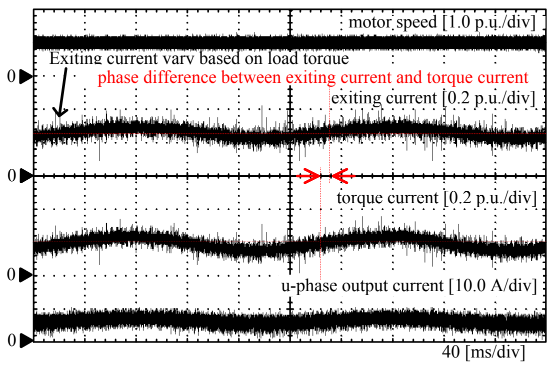


(a) Using the instantaneous torque.

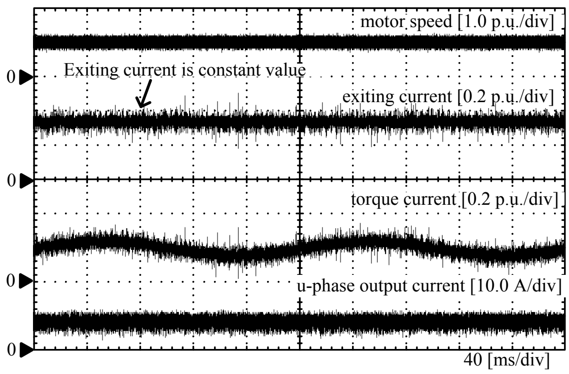


(b) Using effective value of torque.

Figure 11. Waveforms of each copper loss minimization control at operation point A shown in figure 10.(a = 0.2, $\omega\tau_2$ = 1.1). In (a), the excitation current is changed in according to the torque current. In addition, the phase of exiting current is as same as the phase of torque current. On the other hand, in (b), the exiting current is constant.

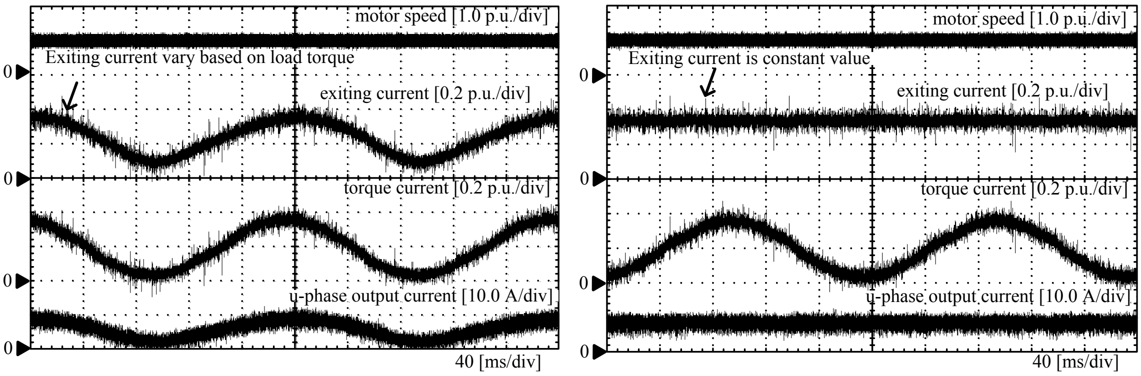


(a) Using the instantaneous torque.



(b) Using effective value of torque.

Figure 12. Waveforms of each copper loss minimization control at operation point B shown in figure 10.(a = 0.2, $\omega\tau_2$ = 2.6). In (a), the exiting current is ahead of the torque current. As a result, the copper loss increases because the root mean square value of the torque current is increased by flux fluctuation.



(a) Using the instantaneous torque. (b) Using effective value of torque.

Figure 13. Waveforms of each copper loss minimization control at operation point C.
(a = 0.8, $\omega\tau_2$ = 2.6). The transitional torque current increases compared to figure 12.
The transitional torque current is due to an increase of a. Therefore, the boundary becomes narrow.

V. Conclusion

This paper discusses the on-line copper loss minimization control by the excitation current control when the periodic fluctuation occurs in the load. The high efficiency control of PM motors, if the load torque fluctuation frequency is slower than natural angular frequency of ACR, the high efficiency control of PM motors is achieved by d-axis current control independently of load torque fluctuation frequency. Besides, the high efficiency control of induction motors has two control methods according to the relationship between the load torque fluctuation frequency and the rotor time constant. In this paper, the copper loss by each control method is theoretically calculated in order to design the boundary, where the copper loss is minimized. The error between calculation result and experimental result is 7.3%. From the experimental result, the trend of the boundary is confirmed. In addition, the on-line control method is proposed in order to control the excitation current. This method can decide the excitation current by calculation the frequency of the load torque. The error between the calculation boundary condition and the experimental boundary condition is 6.7%.The proposed method achieves the copper loss minimization by calculation the excitation current depends on the torque fluctuation.

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