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Current commands for high-efficiency torque control of DC shunt motor

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Abstract: The current commands for a high-efficiency torque control of a DC shunt motor is described. In the proposed control method, the effect of a magnetic saturation and an armature reaction are taken into account by representing the coefficients of an electromotive force and a torque as a function of the field current, the armature current and the revolving speed. The current commands at which the loss of the motor drive system becomes a minimum are calculated as an optimal problem. The proposed control technique of a motor is implemented on the microprocessor-based control system. The effect of the consideration of the magnetic saturation and the armature reaction on the produced torque and the minimisation of the loss are discussed analytically and experimentally.

List of symbols

E_1 = a battery (24 V)
E_0 = an electromotive force
I_a = an armature current
I_f = a field current
ω = a revolving speed of motor
$K_E(I_f, I_a)$ = a coefficient of electromotive force
k_{e1}, k_{e2}, k_{e3} and k_a = constants
τ = a produced torque
$K_T(I_f, I_a)$ = a coefficient of torque
τ_f = a torque due to iron loss, mechanical loss and stray-load loss
$\tau_{fi}(I_a, I_f, \omega)$ = a torque due to iron loss
$\tau_{fm}(I_a, \omega)$ = a torque due to mechanical loss and stray-load loss
$K'_T(I_f, I_a, \omega)$ = a coefficient of output torque
$k_{N1}, k_{N2}, k_{M1}, k_{M2}$ and k_F = constants
P_{loss} = a motor loss
k_{a1}, k_{a2} and k_{f1} = constants
P'_{loss} = a loss of motor drive system
$k'_{a1}(m_a), k'_{a2}(m_a), k'_{f1}(m_f)$ and $k'_{f2}(m_f)$ = coefficients
m_a and m_f = time ratios in armature chopper and field chopper
R_a, R_f = resistances of armature and field
V_b = a voltage drop of brush
V_{d1}, V_{d2} = voltage drops of diodes in armature chopper and field chopper
R_{FET1}, R_{FET2} = resistances of FETs in armature chopper and field chopper
V_{sa}, V_{sf} = voltage coefficients corresponding to switching loss of armature and field chopper
$k_1(I_a, I_f)$, $k_2(I_a, I_f)$, k_3, k_4, $k_5(I_f)$, $k_6(I_f)$, k_7, k_8 and k_9 = coefficients
I_a^* = a command of armature current
I_f^* = a command of field current
$I_{a\,max}$ and $I_{f\,max}$ = maximum values of armature and field current
N = the number of revolution
PG = a pulse generator
CT = a current transformer
E_2 = a DC supply voltage
R_1 = a load resistance
$u(k)$ = an output of digital PI controller at kth period
$d(t)$ = an incremental output of digital PI controller
K_p and K_i = gains of digital PI controller
$y(k)$ = an output of controller in kth control period
$r(k)$ = a reference of controller in kth control period
τ^* = a torque command

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1 Introduction

In an application of the DC motor to the drive system, it is desirable to operate the motor drive system at high-efficiency in addition to the control of the revolving speed and the torque. This proposition can be achieved by controlling both the armature current and the field current so that the efficiency becomes maximum at every operating point [1]. The microcomputer-based control system are proposed to regulate the ratio of the armature current to the field current to minimise the loss of motor [2, 3]. The control method is proposed based on the optimal regulator theory with an evaluating function of the efficiency and the system response [4].

The produced torque of the motor is in proportion to the product of the armature current and the magnetic flux. The magnetic saturation and the armature reaction affect the magnetic flux in the motor. Therefore, the relation between the field current and the magnetic flux is nonlinear. Then, the relation between the torque, the armature current and the field current also has nonlinear characteristics. In this case, the deviation exists between the torque command and the produced torque. Consequently, it is impossible to operate the motor at high efficiency without consideration of these effects [5].

In this paper, the current commands for the high-efficiency torque control of a DC shunt motor, taking account of the magnetic saturation and the armature reaction [6], is described. The produced torque and the loss of the motor drive system are expressed as a function of the armature current, the field current and the revolving speed of the motor. The effect of the magnetic saturation and the armature reaction are taken into account by representing the coefficients of the electromotive force and the torque as a function of the field current, the armature current and the revolving speed. Then, the current commands at which the loss of the motor drive system becomes a minimum can be solved as a solution of an optimal problem. The proposed control of the motor is implemented on the microprocessor-based control system. The effects of the consideration of the magnetic saturation and the armature reaction on the produced torque and the minimisation of the loss are discussed by the calculation and the experiment.

2 Motor drive circuit

Fig. 1 shows the drive circuit of a DC shunt motor. Fig. 2 shows the configuration of the chopper circuit. The drive

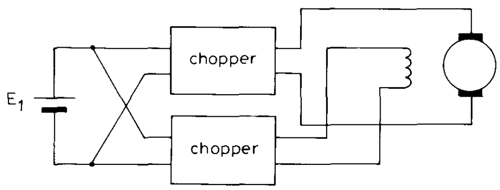

Fig. 1 *DC shunt motor drive circuit*

circuit is composed of a battery ($E_1 = 24$ V) and two chopper circuits with a MOSFET and a diode shown in Fig. 2. The armature current and the field current are

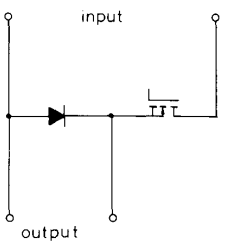

Fig. 2 *Configuration of chopper circuit*

regulated by two chopper circuits, respectively. The circuit for a regeneration is omitted in this Figure because the power running is dealt with in this paper. The tested motor in this paper has the ratings of the output 250 W and the revolving speed 1800 RPM.

3 Consideration of magnetic saturation and armature reaction

3.1 Electromotive force

A magnetic flux in a DC motor is affected by a magnetic saturation (MS) and an armature reaction (AR). Therefore, it is desirable to take them into account for a high-efficiency motor drive. Then, the electromotive force of the motor is expressed by

$$E_0 = K_E(I_f, I_a)\omega \tag{1}$$

The effect of MS and AR in eqn. 1 can be considered by the coefficient of the electromotive force. The circles shown in Fig. 3 shows the no-load characteristic curve of the tested motor gained by experiment. The coefficient of the electromotive force of the tested motor is indicated by curve *a* in Fig. 3. Then, this curve is approximated by the next expression taking account of AR.

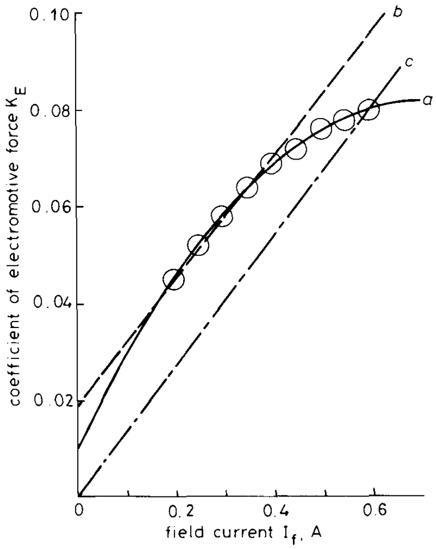

Fig. 3 *Coefficient of electromotive force*
○ measured

$$K_E(I_f, I_a) = k_{e1} I_f^2 + k_{e2} I_f + k_{e3} - k_a I_a \tag{2}$$

The term of $k_a I_a$ in eqn. 2 represents AR. The lines *b* and line *c* are for the coefficients without consideration of MS and AR. The line *c* is the straight one drawn through the rated value and the origin. The line *b* is selected to be approximately a line tangent to the curve *a* with almost the same slope as the line *c*. The residual flux offset k_{c3} is set to zero in the case of line *c*. The two curves *b* and *c* are used for the comparison of the proposed control method taking account of MS and AR with the control method without consideration of them.

3.2 Torque

As the torque produced by the motor is denoted as the torque transmitted to the load, it is expressed by [7]

$$\begin{aligned}\tau &= K'_T(I_f, I_a, \omega)I_a \\ &= K_T(I_f, I_a)I_a - \tau_f\end{aligned} \tag{3}$$

Namely, the torque transmitted to the load is defined as the electrically produced torque minus the torque due to the iron loss, the mechanical loss and the stray-load loss. Then, the torque for these losses is expressed by

$$\tau_f = \tau_{fi}(I_a, I_f, \omega) + \tau_{fm}(I_a, \omega) \tag{4}$$

The torque due to the iron loss is expressed as a function of the field current and the revolving speed because the hysteresis loss is in proportion to the product of the frequency and the square of flux, and the eddy current loss is in proportion to the product of the square of frequency and the square of flux. The torque due to the mechanical loss and the stray-load loss is as a function of the armature current and the revolving speed because the mechanical loss is a function of the revolving speed and the stray-load loss is in proportion to the product of the revolving speed and the square of armature current. They are, thus, expressed as follows:

$$\tau_{fi}(I_a, I_f, \omega) = (k_{N1}\omega + k_{N2}) \times (k_{e1}I_f^2 + k_{e2}I_f + k_{e3} - k_a I_a)^2 \quad (5)$$
$$\tau_{fm}(I_a, \omega) = k_{M1}\omega^2 + k_{M2}\omega + k_{M3} + k_F I_a^2 \omega$$

The second bracketed term of the τ_{fi} equation represents flux, the coefficients being found by curve-fitting to the measured magnetic curve, and the I_a term allows for the slight reduction in net flux that occurs with armature reaction.

4 Minimisation of loss and current commands

4.1 Loss of motor drive system

The motor loss is composed of the copper loss, the brush loss, the iron loss, the mechanical loss and the stray-load loss. The last three losses are the product of the revolving speed and the torque τ_{fi} and τ_{fm}. They are expressed by using the state variables, that is the armature current, the field current and the revolving speed.

$$P_{loss} = k_{a1}I_a^2 + k_{a2}I_a + k_{f1}I_f^2 + k_{f2}I_f + (k_{N1}\omega^2 + k_{N2}\omega)(k_{e1}I_f^2 + k_{e2}I_f + k_{e3} - k_a I_a)^2 + k_{M1}\omega^3 + k_{M2}\omega^2 + k_{M3}\omega + k_F I_a^2 \omega^2 \quad (6)$$

The iron, mechanical and stray loss terms correspond to the relevant torque terms discussed in Section 3.2, multiplied by ω. In eqn. 6, the term of $(k_{a1}I_a^2 + k_{a2}I_a + k_{f1}I_f^2)$ expresses the copper loss in the armature circuit and the field circuit, and the brush loss. The terms of $(k_{N1}\omega^2 + k_{N2}\omega)(k_{e1}I_f^2 + k_{e2}I_f + k_{e3} - k_a I_a)^2$ and $(k_{M1}\omega^2 + k_{M2}\omega)$ show the iron loss and the mechanical loss, respectively. $k_F I_a^2 \omega^2$ indicates the stray-load loss.

Fig. 4 shows the loss of the motor with $I_f = 0.6$ and 0.4 A. The k values in eqn. 6 and Table 1 are chosen by curve fitting to the experimental results. The coefficients in eqn. 6 are shown in the (*a*) column in Table 1.

Table 1: Coefficient of loss expression

	a	*b*	*c*	*d*
k_{a1}	2.75×10^{-1}	2.75×10^{-1}	2.75×10^{-1}	2.75×10^{-1}
k_{a2}	3.85×10^{-1}	3.85×10^{-1}	3.85×10^{-1}	3.85×10^{-1}
k_{f1}	3.74×10	3.74×10	3.74×10	3.74×10
k_{N1}	1.75×10^{-2}	1.68×10^{-2}	1.32×10^{-2}	1.78×10^{-2}
k_{N2}	2.50	2.46	1.72	2.22
k_a	3.36×10^{-4}	0	0	0
k_{e1}	-1.43×10^{-1}	-1.43×10^{-1}	0	0
k_{e2}	2.02×10^{-1}	2.02×10^{-1}	1.28×10^{-1}	1.33×10^{-1}
k_{e3}	1.05×10^{-2}	1.05×10^{-1}	1.89×10^{-2}	0
k_{M1}	3.90×10^{-5}	3.90×10^{-5}	6.20×10^{-5}	8.00×10^{-5}
k_{M2}	4.20×10^{-2}	4.20×10^{-2}	3.97×10^{-2}	3.95×10^{-2}
k_F	8.93×10^{-7}	8.22×10^{-7}	1.73×10^{-6}	2.57×10^{-6}

Table 1 lists the k values used later for performance and loss predictions. The k values in the first two columns of the Table correspond to the analysis incorporating MS (line *a* on Fig. 3) with and without AR taken into account, respectively. The 3rd and 4th columns correspond to lines *b* and *c*, respectively, of Fig. 3 which neglect AR and MS.

In a practical motor drive system, the loss due to the power convertors for regulating the armature current and the field current must be taken into account. Then, eqn. 6 is rewritten by the next expression.

$$P'_{loss} = k'_{a1}(m_a)I_a^2 + k'_{a2}(m_a)I_a + k'_{f1}(m_f)I_f^2 + k'_{f2}(m_f)I_f + (k_{N1}\omega^2 + k_{N2}\omega) \times (k_{e1}I_f^2 + k_{e2}I_f + k_{e3} - k_a I_a)^2 + k_{M1}\omega^2 + k_{M2}\omega + k_F I_a^2 \omega^2 \quad (7)$$

where,

$$k'_{a1}(m_a) = R_a + R_{FET1}m_a$$
$$k'_{a2}(m_a) = V_b + (1 - m_a)V_{d1} + V_{sa}$$
$$k'_{f1}(m_f) = R_f + R_{FET2}m_f$$
$$k'_{f2}(m_f) = (1 - m_f)V_{d2} + V_{sf}$$
$$m_a = (R_a I_a + V_b + E_0)/E_1$$
$$m_f = R_f I_f / E_1$$
$$R_a = k_{a1} \quad R_f = k_{f1} \quad V_b = k_{a2}$$

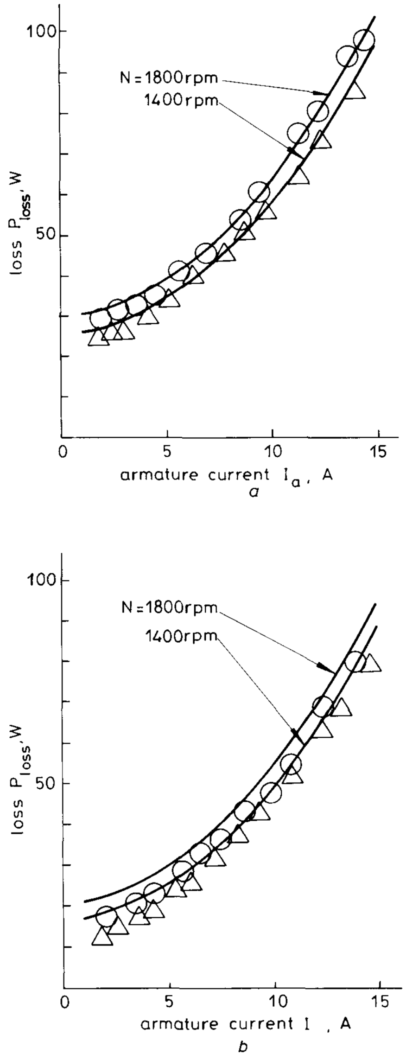

Fig. 4 *Loss of motor*
a $I_f = 0.6$ A
b $I_f = 0.4$ A
○ N = 1800 RPM (measured)
△ N = 1400 RPM (measured)

When a MOSFET and a diode are conducting, a MOSFET is assumed to be at a constant resistance and a diode has a characteristic of constant voltage drop. On the other hand, they have an infinite resistance in the period of nonconduction. Furthermore, the switching loss

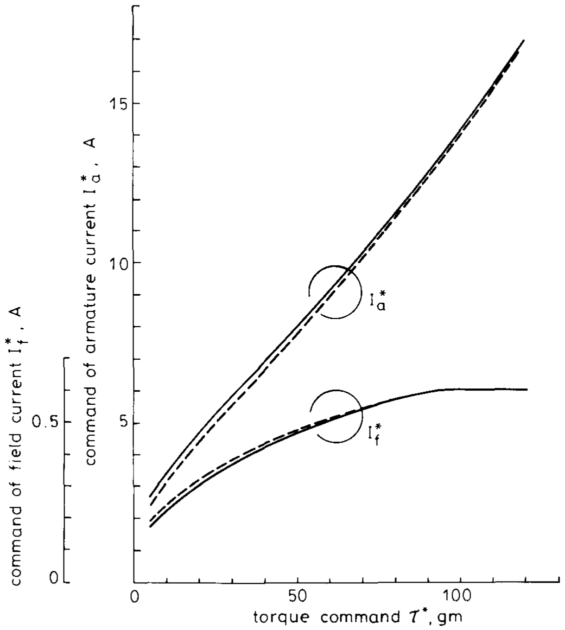

Fig. 5 *Current command in proposed control method*
——— $N = 1728$ RPM
- - - - $N = 960$ RPM

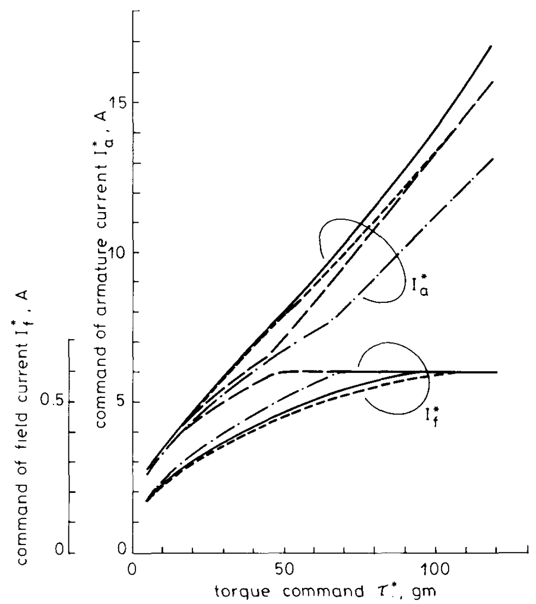

Fig. 6 *Comparison of current command*
——— *a* with AR
.... *a* without AR
—·—·— *b* without AR
- - - - *c* without AR

of the switches can be contained in the coefficients $k'_{a2}(m_a)$ and $k'_{f2}(m_f)$ because it is expressed as a function of each current.

The coefficients $k'_{a1}(m_a)$ and $k'_{a2}(m_a)$ are expressed as a function of time ratio of the armature chopper. Then, m_a is a function of armature current, field current and revolving speed. The coefficients $k'_{f1}(m_f)$ and $k'_{f2}(m_f)$ are expressed as a function of time ratio of the field chopper. Then, m_f is a function of field current. Therefore, these coefficients vary with the operating state of the drive system.

4.2 Current commands

The total loss of the motor and the drive system is expressed by using the armature current, the field current and the revolving speed in eqn. 7. It is unfortunately not possible to formulate a general expression for the current commands to minimise the total loss given by eqn. 7. However, it is possible to use eqn. 7 to evaluate P'_{loss} for a set of speed and current values for a specific scheme, and then to search for the pair of current values that minimise P'_{loss} at each speed. The controllable loss with the constant revolving speed is expressed by

$$P'_{loss} = k_1(I_a, I_f)I_a^2 + k_2(I_a, I_f)I_a + k_3 I_f^4 + k_4 I_f^3 + k_5(I_f)I_f^2 + k_6(I_f)I_f + k_7 I_a I_f^2 + k_8 I_a I_f + k_9 \quad (8)$$

Further, the armature current and the field current must satisfy the following requirement

$$0 \leqslant I_a \leqslant I_{a\,max}$$
$$0 \leqslant I_f \leqslant I_{f\,max} \quad (9)$$

Therefore, the maximum efficiency drive of the DC shunt motor is regarded as the optimal problem to solve a set of current command to satisfy the requirements expressed by eqns. 3 and 9 and then minimise the loss expressed by eqn. 8. Then, the solution in the optimal problem is a set of the current commands, I_a^* and I_f^* for a set of the revolving speed and the torque command. For the tested motor, the torque is divided by 1 gm and the revolving speed is divided by 128 RPM. The evaluation of optimal current commands is carried out by searching the minimum value in the losses which are calculated under the restriction of eqns. 9 and 3. In the experiment, $V_{d1} = V_{d2} = 1.0$ V and $R_{FET1} = R_{FET2} = 0.05\ \Omega$ in eqn. 7.

Fig. 5 shows the obtained current command against the torque command at $N = 960$ and 1728 RPM. As the torque command becomes larger, the commands of the armature current and the field current increase. The field current command is limited to the maximum value of the field current in the torque command greater than $\tau^* = 95$ gm. As the revolving speed becomes larger, the field current command becomes smaller so as not to increase the iron loss. That is because the variable loss equals the no-load loss at the maximum efficiency.

Fig. 6 shows the current commands corresponding to Table 1 at $N = 1728$ RPM. For the curves *b* and *c*, the field current command becomes the limit value in the small value of the torque command. The armature current command for the curve *b* is smaller than those of the others in the range of the large torque command.

5 Experimental system

5.1 Experimental circuit

Fig. 7 shows the experimental system. The control circuit is composed of a CPU board, an A/D convertor board and a counter board. They are connected through the multibus.

A 16 bit microprocessor 8086, a ROM, a RAM and a serial interface RS-232C are installed on the CPU board. The development of the program is carried out on the personal computer NEC PC-9801.

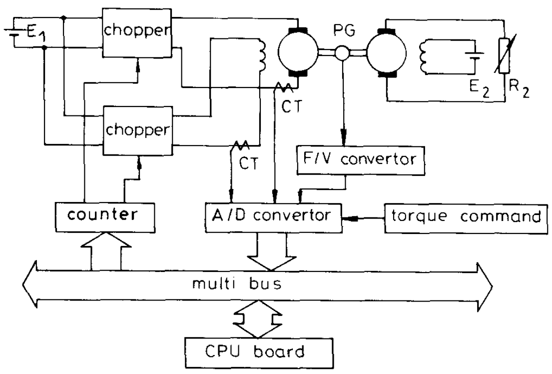

Fig. 7 *Experimental system*
PG = pulse generator

The torque command, the revolving speed, the armature current and the field current are detected and converted into the digital values on the A/D convertor board. The resolution of the A/D convertor is 12 bits and the converting time is 5 μs.

The counter board has a 16 bit counter (8253) and generates the pulses according to the chopper period and the on-time of the chopper. The clock frequency of the counter is 2 MHz.

5.2 Control method

Fig. 8 shows the control block diagram. The current command for the minimum loss is calculated in advance

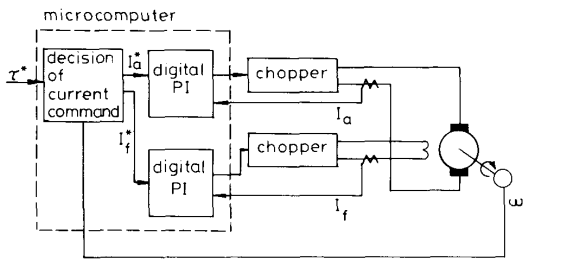

Fig. 8 *Block diagram of DC motor control*

and arranged in tabular form in the RAM. In the execution of this control, the current command corresponding to the torque command and the detected revolving speed is looked up from the table in the RAM. Then, the armature current and the field current are regulated by the corresponding digital PI controller, respectively.

The output of the digital PI controller is expressed by

$$u(k) = u(k-1) + d(k) \tag{10}$$

$d(k)$ in eqn. 10 is calculated as follows

$$d(k) = K_p\{y(k-1) - y(k)\} + K_i\{r(k) - y(k)\} \tag{11}$$

Therefore, the PI control is implemented by executing eqns. 10 and 11 for the armature current and the field current, respectively. The gains of the PI controller for the armature current and the field current are decided from the response and stability viewpoints by the simulation. The control period is 500 μs.

The memory used for the main program and the table of the current commands are 0.73 and 8.3 kB, respectively.

6 Experimental results

6.1 Output torque

The effect of the consideration of MS and AR on the torque control of the motor is discussed in this Section. Fig. 9 shows the characteristics of the produced torque

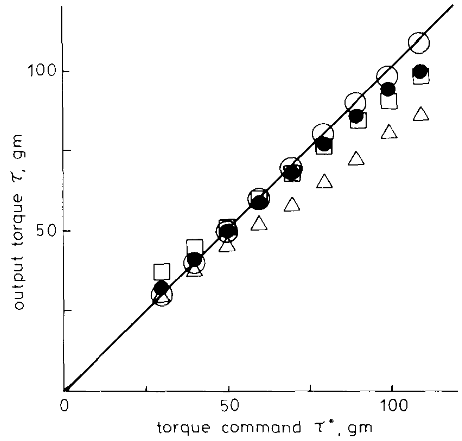

Fig. 9 *Characteristics of torque*
○ *a* with AR
● *a* without AR
△ *b* without AR
□ *c* without AR

against the torque command at the revolving speed of 1800 RPM. The solid line in this Figure indicates the theoretical value.

The measured net torque produced when the current command decision-making was done on the basis of line *b* analysis becomes significantly smaller than the demand torque. That is because the coefficient of electromotive force is estimated larger than the actual value when the field current is large. Then, the current command is calculated as a smaller value than the required one to produce the torque demanded.

The measured net torque produced when the current command decision-making was done on the basis of line *c* analysis becomes larger than the demand torque in the small torque command. The produced torque by using the coefficient of electromotive force of the line *c* is larger than the theoretical value when the torque command is small. Then, the produced torque is smaller than the theoretical value when the torque command is large. That is because the produced torque is reduced by the armature reaction when the torque command is large and the coefficient of electromotive force is estimated smaller than the actual value when the torque command is small.

The produced torque in the case of the line *a* without AR agrees with the theoretical value in the range of the small torque command. However, the torque is smaller than the theoretical value in the range of the large torque command. That is because the current command is estimated smaller due to the neglect of the armature reaction as shown in Fig. 6 and the increase in resistance because of the temperature change.

On the other hand, the produced torque by the proposed control method with the line *a* with AR agrees well with the theoretical torque in all of the range. Therefore, the consideration both of MS and AR in the torque control of motor is proved an important matter.

6.2 Effect on loss reduction

Fig. 10 shows the loss of the motor drive system in the proposed method and the conventional control method with a constant field current. From this Figure, a reduction of loss in the motor drive system is achieved, especially in the range of the small torque command. On the other hand, the losses of the motor drive system in the two control methods are the same in the range of the large torque command because the field current command in the proposed method is equal to the command in the constant field current control. The deviation between the calculated values and the experimental values is mainly due to the copper loss in the wiring, etc.

Fig. 11 shows the measured loss of the motor drive system with the coefficients of electromotive force expressed by the line *a* with AR and the line *c* without AR. In this Figure, the horizontal axis indicates the produced torque. From this Figure, it is proved that the consideration of MS and AR is effective in the reduction of loss in the motor drive system, especially in the range of the small torque. For example, the reduction of loss is 3.1% at the torque of 50 gm and 5.7% at the torque of 33 gm. On the other hand, the loss with the line *a* at the torque of 90 gm is almost the same as the loss with the line *c*. That is because the current command with the line *c* becomes equal to that with the line *a* as the torque becomes larger. Meanwhile, the loss of the motor drive system for the line *b* without AR is only a little large compared with the loss for the proposed control method. That is because the current command for the line *b* without AR is near to those for the proposed control method in the range of the small torque and almost the same in the range of the large torque.

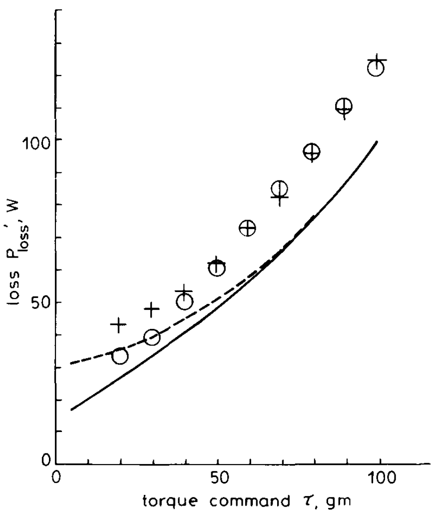

Fig. 10 *Loss of motor drive system with constant field current control and proposed control*
Calculated
—— proposed
---- constant field current $I_f = 0.6$ A
Measured
O proposed
+ constant field current $I_f = 0.6$ A

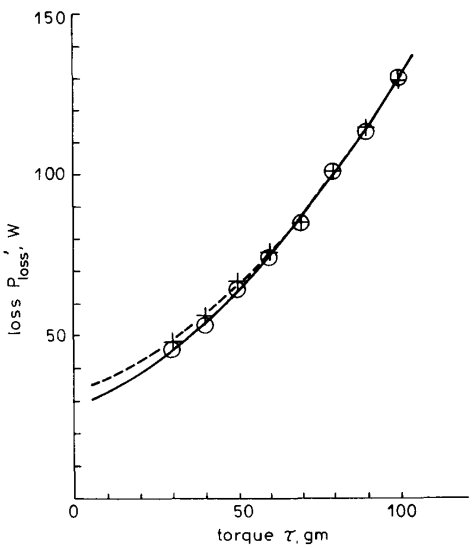

Fig. 11 *Loss of motor drive system against output torque*
—o— *a* with AR
-+- *c* without AR

7 Conclusions

The current command for the high-efficient torque control of DC shunt motor taking account of the magnetic saturation and the armature reaction is described. The effect of the magnetic saturation and the armature reaction are taken into account by representing the coefficients of the electromotive force and the torque as a function of the field current, the armature current and the revolving speed. The loss of the motor drive system in the proposed method becomes smaller than the loss in the constant field current control, especially in the range of the small torque command. The effect of the consideration of the MS and the AR on the torque control and the reduction of loss of the motor drive system are discussed experimentally. It is found that the consideration of the magnetic saturation and the armature reaction is effective in the torque control and the reduction of loss.

8 References

1 KUSKO, A., and GALLER, D.: 'Control means for minimization of losses in AC and DC motor drives', *IEEE Trans.*, 1983, **IA-19,** pp. 561–570
2 OHMAE, T., MARUMOTO, K., and NAITO, S.: 'Microprocessor based efficiency optimized speed control for DC shunt motor', *Trans. SICE*, 1982, **18,** pp. 628–634 (in Japanese)
3 HONG, S.C., and PARK, M.H.: 'Microprocessor-based high-efficiency drive of a DC motor', *IEEE Trans.*, 1987, **IE-34,** pp. 433–440
4 EGAMI, T., WANG, J., and TSUCHIYA, T.: 'Efficiency-optimized speed control system synthesis method based on improved optimal regulator theory — application to separately excited DC motor system', *IEEE Trans.*, 1985, **IE-32,** pp. 372–380
5 FUNABIKI, S., FUKUSHIMA, T., and HIMEI, T.: 'An effect of magnetic saturation on efficiency-optimized torque control of a DC shunt motor'. IEE of Japan, 1987, IAS National Conversion, pp. 423–428 (in Japanese)
6 FUNABIKI, S., and FUKUSHIMA, T.: 'High-efficient torque control of DC shunt motor taking account of magnetic saturation and armature reaction'. Int. PCIM, 1988, **1,** pp. 62–70
7 OKITSU, H., SUZUKI, S., and KIUCHI, Y.: 'A Measurement of friction torque', *J. SICE*, 1970, **9,** pp. 35–40 (in Japanese)