Transient Commutation Characteristics of Small-Sized DC Motor

By

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Abstract

In the recent direct current (dc) motor whose speed is precisely controlled, it is necessary to maintain a good commutation characteristic in the transient state where the armature current changes abruptly. In this paper, the authors clarify theoretically and experimentally the relations between the transient behavior of the commutating flux in a commutating zone in the interpole airgap and the commutation characteristics, where the experiment is done by using a small-sized dc motor. Also, they experimentally confirm that the initial delay of the transient response of the commutating flux to the abrupt change of the armature current deteriorates the transient commutation characteristics, and that the deteriorated initial commutation characteristics are improved by intensifying the interpole exciting magnetomotive force. Furthermore, the authors suggest that it is necessary to analyse experimentally and theoretically in detail the transient behaviors of the magnetic fluxes in the commutating zone, the yoke and so on, which relate closely to the transient commutation characteristics.

1. Introduction

In a direct current (dc) motor, the driving torque is efficiently generated by means of interaction between the main pole flux excited by the field current and the mechanically commutated armature current. Therefore, the dc motor has inherently a superior speed–torque characteristic and a strong starting torque, which can't be obtained by ac motors such as an induction motor or a synchronous one. The torque and the speed of the dc motor are accurately, widely and quickly controlled by using the thyristor rectifier or chopper circuits. Thus, the dc motors are widely applied as precise variable speed machines, such as mill motor, traction motor, industrial servomotor, etc.. However, in order to make the best use of the superior characteristic of the dc motor, it is essential to always maintain good commutation characteristics not only in the steady state where

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the armature current is constant, but also in the transient state where it abruptly changes.[1)~4)]

As is well known, to keep a good commutation, the ohmic and the reactive voltage drops in the commutated armature coils as well as the contact voltage drops betseen the brushes and the commutator segments must be immediately compensated by the speed electromotive forces (emf's) induced in the coils. This is called the commutating voltages. Here, the ohmic, the reactive and the contact voltage drops directly concern the armature current. On the oter hand, the commutating voltage concerns the so-called commutating magnetic flux in the commutating zone containing the interpole airgap. This is mainly governed by the interpole exciting magnetomotive force (mmf), the armature reaction mmf, the magnetic reluctances of the interpole, the armature and the yoke, and also the eddy currents induced in the yoke and the interpole liners.

Therefore, even when a good commutation is maintained in the steady state, it often deteriorates when an abrupt change of the armature current occurs because of the fluctuations of the motor speed or load. Hence, a regular distribution of the magnetic flux is disturbed. Especially, a serious commutation spark can occur when a large transitional delay of the response of the commutating flux to a change of the armature current is brought about by the transient eddy currents induced in the yoke, the interpole liner, etc..[5),6),7)] Because of the above delay of the commutating flux, the commutating voltage can't immediately compensate the voltage drops in the commutated coils.

Now, in large-sized and special small-sized dc motors, the laminated cores are used not only in the armature, the main poles and the interpoles, but also in the yoke. This is to decrease the eddy current which delays the transient response of the commutating flux. On the other hand, in usual small–sized dc motors, the yoke is made of a solid core for economical and industrial reasons. Therefore, it is very important to investigate the relation between the transient commutation characteristic and the transient response of the commutating flux of the usual small-sized dc motors, in whose yoke the large eddy current must be induced.

In this paper, there is first introduced theoretical commutation equations to clarify the close relations between the commutating flux in a commutating zone in the interpole airgap and the commutation characteristics. Next, by using a small–sized dc motor, the authors experimentally confirm that the initial delay of the transient response of the commutating flux density to the abrupt change of the armature current deteriorates the transient commutation characteristics. Then, the authors suggest that it is necessary to analyse experimentally and theoretically in detail the transient behaviors of the magnetic fluxes in the commutating zone, the yoke and so on, which relate closely to the commutating voltage.

2. DC Motor for Experiment

For the experimental and theoretical analyses of the commutation characteristic and the magnetic flux distribution of a dc motor in the case where the armature current changes abruptly, the authors made a small-sized dc motor, speeified as shown in Table 1.

Table 1 Specification of supplied dc motor.

Rating			
Power	: 3 kw	Speed	: 1800 rpm
Terminal voltage	: 220 V	Number of poles	: 4
Armature current	: 16 A	Field excitation	: external excitation
Armature			
Type of winding	: wave	Number of paraliel circuits	: 2
Number of coils	: 75	Number of slots	: 25
Number of turns of coil	: Nc = 5	Number of conductors/slot	: 30
Outside diameter of core	: Da = 170 mm	Inside diameter of core	: 60 mm
Axial length of core	: la = 90 mm	Cross-sectional area of conductor	: 28.3 mm
Material of core: silicon steel plate of thikness 0.5 mm			
Brush and Commutator			
Number of brushes	: 4	Number of commutator segments	: 75
Width of brush	: 12 mm	Width of segment	: 4 mm
Axial length of brush	: 25 mm	Width of insulating mica	: 0.4 mm
Outside diameter of commutator: 110 mm			
Main Pole			
Number of turns of coil/pole	: 1000	Height of core	: 66 mm
Width of core	: 50 mm	Height of liner	: 1 mm
Axial length of core	: lm = 90 mm	Ratio of pole arc	: 67%
Airgap under center of pole	: 3 mm	Cross-sectional area of conductor	: 3.14 mm^2
Material of core: cast iron plate of thickness 1 mm			
Interpole			

Number of turns of coil/pole	: 70	Number of turns of auxiliary coil/pole	: 10
Width of core	: 18 mm	Axial length of core	: li = 80 mm
Height of core	: 62.5 mm	Height of liner	: 2.5 mm
Airgap under center of interpole	: 3.5 mm	Cross-sectional area of conductor	: 28.3 mm²
Material of core: silicon steel plate of thickness 0.5 mm			
Yoke			
Outside diameter	: 347 mm	Inside diameter	: 312 mm
Axial length	: ly = 225 mm	Thickness	: ty = 17.5 mm
Material of yoke: solid cast iron			
Search coils		GaAs Hall cells	
Sc 1, Sc 2	: yoke	Ha 1, Ha 2	: airgap under center of main pole
Sc 3, Sc 4	: interpole core	Ha 3, Ha 4	: airgap under center of interpole
Number of turns of Sc 1 to Sc 4	: 4	Ha 5	: armature slot
C 1, C 2, C 3	: armature coil	Hall voltage	: 1.55 V/T

Next, the cross-sectional view perpendicular to an axial direction of this motor is shown in Fig. 1, where

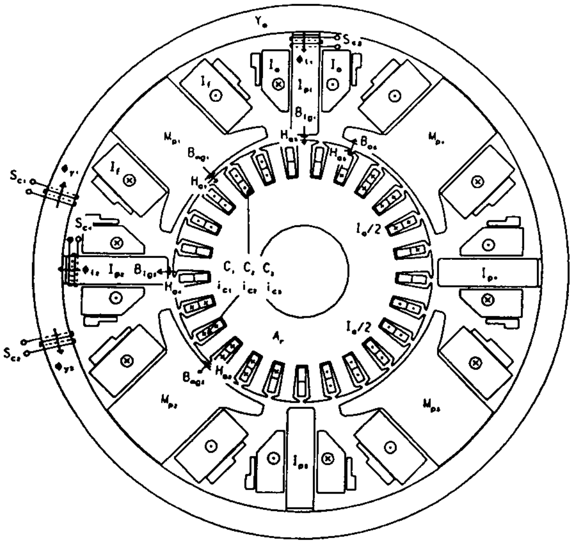

Fig. 1 Gross-sectional view of supplied dc motor.

A_r and Y_o :armature and yoke cores,

I_{p1}, I_{p2}, I_{p3} and I_{p4}: interpole cores

M_{p1}, M_{p2}, M_{p3}, and M_{p4}: main pole cores,

I_a: armature current equal to interpole exciting current,

$I_a/2$: armature coil current,

I_f: main pole exciting current,

B_{mg1}, B_{mg2}, B_{ig1}, B_{ig2}, and B_{as}: magnetic flux densities in main pole airgap, interpole airgap and armature slot, respectively,

H_{a1}, H_{a2}, H_{a3}, H_{a4} and H_{a5}: *GaAs Hall* cells to measure above flux densities,

i_{c1}, i_{c2}, and i_{c3}: currents in three coils whose sides are placed in top of one slot and bottom of another slot,

C_1, C_2, and C_3: search coils to measure i_{c1}, i_{c2} and i_{c3}, respectively,

Φ_{y1}, Φ_{y2}, Φ_{i1} and Φ_{i2}: magnetic fluxes through yoke and interpole cores neighbouring yoke,

S_{c1}, S_{c2}, S_{c3} and S_{c4}: search coils to measure Φ_{y1}, Φ_{y2}, Φ_{i1} and Φ_{i2}, respectively.

Here, the fluxes Φ_{y1} to Φ_{i2} are obtained by integrating the electromotive force (emf) induced in the respective search coils S_{c1} to S_{c4}. In this connection, we must think of the axial expansion of Φ_{y1} and Φ_{y2}, because the axial length l_y of Y_o is 2.5 times as long as l_a and l_m of A_r and M_{p1} to M_{p4}. Then, Φ_{y1} and Φ_{y2} in Fig. 1 are measured by using S_{cr} ($r=1$ and 2) which are divided into S_{cr1}, S_{cr2} and S_{cr3}, as shown in Fig. 2, where

$\Phi_{yr}=\Phi_{yr1}+\Phi_{yr2}+\Phi_{yr3}$, $r=1, 2$: flux through S_{cr} in Fig. 1,

Φ_{yr1}, Φ_{yr2} and Φ_{yr3}: fluxes through divided coils S_{cr1}, S_{cr2} and S_{cr3}.

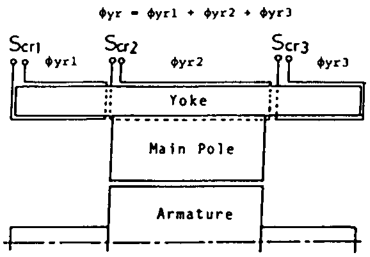

Fig. 2 Subdivision of search coil S_{cr} ($r=1$ and 2) due to axial expansion of yoke flux.

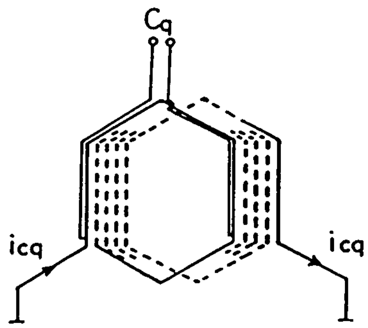

Fig. 3 Settlement of search coil C_q ($q=1, 2$ and 3) on armature coil.

The armature coil currents i_{c1}, i_{c2} and i_{c3} are obtained by measuring the respective ohmic voltage drops by C_1, C_2 and C_3, which are set on the armature coil, as shown in Fig. 3.

3. Commutation Mechanism

Commutation characteristics are the most important ones for the dc motor as well as the speed-torque one. Thus, we first describe the commutation mechanism in the dc motor. Especially, we touch upon the relation between the commutation characteristics and the magnetic flux or its density in an interpole airgap. Next, we try to do an experiment on the transient commutation characteristic by using the dc motor specified, as shown in Table 1 and Figs. 1 to 3.

When an armature slot passes the interpole airgap, which is called the commutating zone, the armature coils in the slot may be short-circuited by the brushes and the commutator segments. Then, the directions of the coil currents are reversed during a short-circuited period which is called the commutating period. This mechanism is well known as the commutation one.[1),4),8)]

In our dc motor introduced in the preceding Section 2, 13 coils out of 75 are short-circuited at the same time as shown in Fig. 4, where

A_{b1}, A_{b2}, A_{b3} and A_{b4}: brushes,
I_{ac1} and I_{ac2}: armature coil currents, and $I_{ac1} \fallingdotseq I_{ac2} \fallingdotseq I_a/2$,
I_{b1}, I_{b2}, I_{b3} and I_{b4}: direct currents in above brushes,
B_{igk}, $k=1, 2, 3, 4$: airgap flux density of I_{pk},
B_{mgk}, $k=1, 2, 3, 4$: airgap flux density of M_{pk},
N: revolution of armature per minute.

In the figure, the numbers of 1 to 13 are assigned to the short-circuited coils, and those of 1 to 15 to the commutator segments, which are connected with the coils and contact with the brushes. Also, the directions of the currents are shown by the arrows, where the dc motor is driven as a generator.

Now, we can find an electric circuit equation for each short-circuited coil in Fig. 4. For example, the equation for coil 1 is found by the closed-circuit of A_{b1}-segment 1-coil sides in the airgaps of I_{p3} and I_{p2}-segment 3-A_{b3}-A_{b1}. Ultimately, when the dc motor is driven in the steady state and the armature circuit current I_a is constant, we can obtain the following equations for the 1-st to the 13-th short-circuited armature coil currents i_1 to i_{13}:

$$N_c l_a u \begin{bmatrix} B_{i3,1}+B_{i2,1} \\ B_{i4,2}+B_{i3,2} \\ B_{i1,3}+B_{i4,3} \\ B_{i2,4}+B_{i1,4} \\ \cdot \\ \cdot \\ B_{i3,13}+B_{i2,13} \end{bmatrix} = \begin{bmatrix} L_{1,1} & L_{1,2} & L_{1,3} & \cdot\cdot & L_{1,13} \\ L_{2,1} & L_{2,2} & L_{2,3} & \cdot\cdot & L_{2,13} \\ L_{3,1} & L_{3,2} & L_{3,3} & \cdot\cdot & L_{3,13} \\ L_{4,1} & L_{4,2} & L_{4,3} & \cdot\cdot & L_{4,13} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ L_{13,1} & L_{13,2} & L_{13,3} & \cdot\cdot & L_{13,13} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ \cdot \\ \cdot \\ i_{13} \end{bmatrix}$$

$$+R_c \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ \cdot \\ \cdot \\ i_{13} \end{bmatrix} + R_b \begin{bmatrix} I_{b1}-I_{b3} \\ I_{b2}-I_{b4} \\ I_{b3}-I_{b1} \\ I_{b4}-I_{b2} \\ \cdot \\ \cdot \\ I_{b1}-I_{b3} \end{bmatrix} + \begin{bmatrix} V_{s1}-V_{s3} \\ V_{s2}-V_{s4} \\ V_{s3}-V_{s5} \\ V_{s4}-V_{s6} \\ \cdot \\ \cdot \\ V_{s13}-V_{s15} \end{bmatrix} \quad (1)$$

In the equations,

$B_{ik,r}$: airgap flux density of I_{pk}, which links to coil r,

$N_c l_a u B_{ik,r}$: speed *emf* induced in one coil side of short-circuited coil r,

$N_c=5$: number of turns of armature coil,

$l_a=90mm$: axial length of armature core,

u: peripheral velocity of armature surface,

$L_{r,r}$: self-inductance of coil r,

$L_{r,p}$: mutual-inductance between coils r and p,

R_b: resistance of brush,

R_c: resistance of armature coil,

V_{sq}: contact voltage between segment q and brush, which is affected by current density crossing contact surface, vibration of brushes, evenness of brushes of commutator segments, etc.,

$k=1, 2, 3, 4$: interpole number,

$q=1, 2, \ldots, 15$: commutator segment number,

r and $p=1, 2, \ldots, 13$: coil number.

From Fig. 4 we can derive the following additional equations for the brush currents I_{b1} to I_{b4}

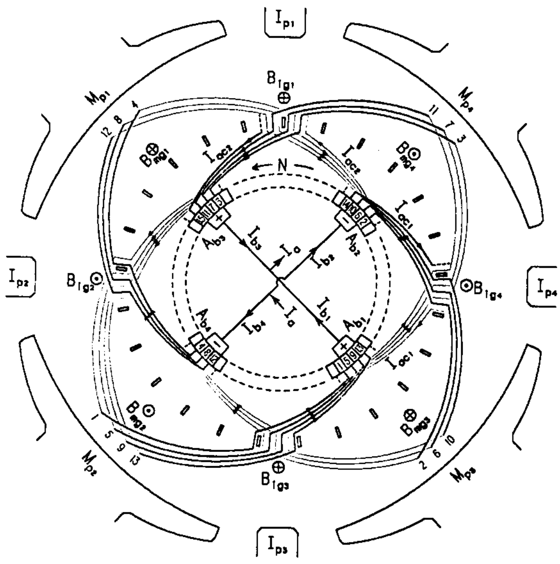

Fig. 4 Armature coils short-circuited by brushes and commutator segment.

$$\left.\begin{aligned} I_{b1}&=i_1+I_{ac1}+i_5-i_3+i_9-i_7+i_{13}-i_{11}\\ I_{b2}&=i_2+I_{ac2}+i_6-i_4+i_{10}-i_8+I_{ac1}-i_{12},\\ I_{b3}&=i_3-i_1+i_7-i_5+i_{11}-i_9+I_{ac2}-i_{13},\\ I_{b4}&=i_4-i_2+i_8-i_6+i_{12}-i_{10}, \end{aligned}\right\} \qquad (2)$$

where

$$I_{ac1} \fallingdotseq I_{ac2} \fallingdotseq I_a/2.$$

Equations (1) and (2) are often called commutation equations. Also, the left-side and the first term on the right side of Eq. (1) are called the commutating and the reactance voltage matrices, respectively.[4),8),9),10)]

As is well known, when the commutating voltages are too small to overcome the reactance voltages in Eq. (1), the reversions of the current directions in the short-circuited coils are decelerated. This kind of commutation is called the under-commutation. On the other hand, when the commutating voltages are too large and the reversions are over-accelerated, it is called the over-commutation. Especially, when the commutating voltages are suitable to overcome not only the reactance voltages but also the ohmic drops and the contact voltages in Eq. (1), the reversions may be done in a constant time rate. This commutation is called the straight-line one, and the r-th coil current i_r is given by the following equation

$$i_r = \frac{I_a}{2}\,\frac{15-2r}{13}\,\left(1-\frac{2t}{T_c}\right),\quad r=1,\ 2,\ 3,\ \ldots,\ 13 \tag{3}$$

where

$-I_a/2 \leqq i_r \leqq I_a/2,$

T_c: commutating period.

Also, it is well known that commutation sparks may occur in the cases of the under- and over-commutation. To prevent the occurrence of the spark, it is very important to obtain smooth reversions of the currents, such as those in the straight-line commutation.

For obtaining smoothed reversions, it is necessary to analyse the commutation characteristics by solving Eqs. (1) and (2). However, it is too difficult to solve the equations exactly, because the parameters $L_{r,p}$, $B_{ik,r}$, V_{sq}, etc. vary in both time and space, even when the motor is driven in the steady state. Nowadays, approximate analyses are carried out by giving some practical assumptions to the above variational parameters. In this connection, a number of methods to get the values of $L_{r,p}$ are introduced, in which the method of separation of variables and the Neumann formula are mostly used.[4),11),12)] Also, with respect to V_{sq}, the experimental relation as shown in Fig. 5 is obtained, where V_s is the contact voltage and J_s is the current density crossing the contact surface.[13)] Moreover, for simplifying the estimation of the commutating voltage,

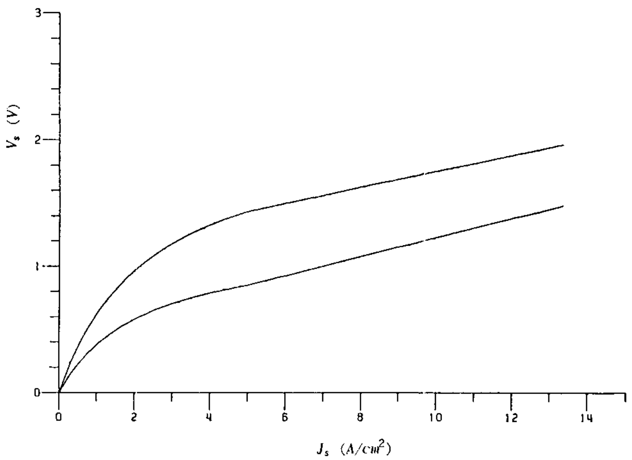

Fig. 5 Relation between contact voltage drop and current density.

the speed *emf* $N_c l_a u B_{ik,r}$ in Eq. (1) is often replaced by the following approximate expression

$$N_c l_a u B_{ik,r} \fallingdotseq N_c l_a u \overline{B_{ig}} = \frac{N_c \pi D_a}{W_c} \frac{N}{60} \overline{\Phi_{ig}} \qquad (4)$$

where

$\overline{B_{ig}} = \frac{1}{52} \sum_{K=1}^{4} \sum_{r=1}^{13} B_{ik,r}$: average magnetic flux density in interpole airgap,

$\overline{\Phi_{ig}} = l_a W_c \overline{B_{ig}}$: average magnetic flux through interpole airgap,
$N = 60u/(\pi D_a)$: revolutions of dc motor per minute,
D_a: outside diameter of armature core,
W_c: width of commutating zone,

under the assumption that every coil in Fig. 4 crosses equally $\overline{B_{ig}}$ or $\overline{\Phi_{ig}}$.

By the above discussions, we show that the magnetic flux density $B_{ik,r}$ or the magnetic flux $\overline{\Phi_{ig}}$ in the interpole airgap, which is controllable only by changing the interpole exciting magnetomotive force (*mmf*), has a great influence on the commutation characteristics of the dc motor which is driven in the steady state. Furthermore, with respect to the dc motor driven in the transient state, such as in the case where the armature current I_a changes abruptlly, the theoretical analysis of the transient commutation characteristics is an important subject for future study, although the variations of $L_{r,p}$, $B_{ik,n}$, V_{sq}, etc. are much more complicated than those in the steady state. In order to bring light on the subject, it seems to be suggested that the transient responses of the magnetic flux density distribution or the average magnetic flux in the interpole airgap to the sudden change of I_a must be sufficiently analysed.[14]

4. Transient Commutation Characteristics

4.1 Experimental circuit

Figure 6 shows the schematic circuit diagram for the experimental investigation of the transient commutation characteristics of the motor supplied in Section 2, where the motor is driven as the generator for simplifying the investigation. In the figure,

G_e: dc motor driven as generator,
M: dc motor for driving G_e,
$E_f = 100\ V$, R_f and $I_f = 1.3A$: supply voltage, resistance and field current of exciting field circuit of G_e,

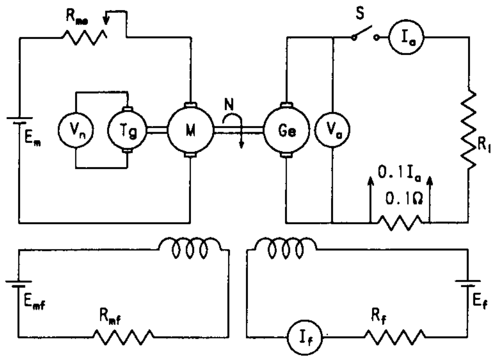

Fig. 6 Scheme of experimental circuit for studying on transient commutation characteristics.

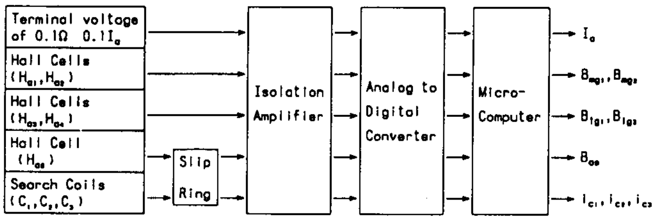

Fig. 7 Measurement system for circuit in Fig. 6.

E_m and R_{ms}: variable supply voltage and starter of armature circuit of M,
$E_{mf}=220\ V$ and R_{mf}: supply voltage and resistance of field circuit of M,
$0.1I_a$: terminal voltage of shunt resistance 0.1Ω,
N: revolutions of G_e and M per minute,
R_l, V_a and I_a: load resistance, output voltage and armature current of G_e,
S: switch,
T_g: tachometer generator,
V_n: output voltage of T_g.

When the abrupt change of I_a is brought on by closing S in Fig. 6, the transient commutation characteristics of G_e can be investigated by measuring the changes of the armature coil currents i_{c1}, i_{c2} and i_{c3} and the magnetic flux densities B_{mg1}, B_{mg2}, B_{ig1}, B_{ig2} and B_{as} in Fig. 1. Here, the electromotive forces induced in search coils S_{c1}, S_{c2}, S_{c3} and S_{c4} are fluctuated by the influence of the armature slots and the commutating currents. Hence, the fluxes Φ_{y1}, Φ_{y2}, Φ_{i1} and Φ_{i2} can't be measured accurately. Figure 7 shows the measurement system, in which the quantities measured by the search coils, *GaAs Hall* cells, etc. are processed by a personal micro-computer.

4. 2 Experimental results and discussion

Figure 8 (a) and (b) show the response waveforms of i_{c1}, i_{c2}, i_{c3}, B_{mg1}, B_{mg2}, B_{ig1}, B_{ig2} and B_{as} to the abrupt change of I_a when S is closed under the initial conditions of $I_f=1.3A$, $N=2100\ rpm$, $V_a=162V$ and $I_a=0$ in Fig. 6, where $R_l=8.96\Omega$, which gives $I_a=16A$, $N=2000\ rpm$ and $V_a=145V$ in the steady state for $I_f=1.3A$, and $T_m=1.15ms$ that is the time constant of I_a.

We can see in Fig. 8 (a) that i_{c1}, i_{c2} and i_{c3} are under-commutated for the initial duration $0<t<5T_m$. At about $t=5T_m$ those currents turn to good commutating states. The under-commutation for $0<t<5T_m$ may be brought forth by the initial lack of the commutating voltage, which occurred because of the delays of the responses of B_{ig1} and B_{ig2} to the rapid increase of I_a as shown in Fig, 8 (b). It is thought that the delays are caused by the eddy current induced in the yoke Y_o. On the other hand, as is well known, B_{mg1} and B_{mg2} are not influenced by I_a as is shown in Fig. 8 (b). Also, from B_{as} plotted in Fig. 8 (b), we can see that the flux density distribution in the peripheral airgap of the armature is fairly disturbed by I_a. This is well known as an armature reaction by I_a. In Fig. 8 (b), some visible differences between B_{mg1} and B_{mg2} and between B_{ig1} and B_{ig2} may be due to errors of measurement by the *GaAs Hall* cells and the residual magnetism.

Furthermore, from Fig. 8 (a) and (b), it is suggested that the transient commutation for the abrupt increase of I_a may be improved by intensifying B_{ig1} and B_{ig2} during the initial duration $0<t<5T_m$. For this purpose, we usually strengthen the interpole *mmf* by using an auxiliary interpole exciting winding, as given in Table 1.

Figure 9 (a) and (b) shows the experimental results when the 10-turn auxiliary winding is added to the 70-turn usual interpole winding, where $T_m=1.58ms$. In the experiment, the initial conditions are the same as those for Fig. 8. However, $T_m=1.58ms$ and $R_l=9.46\Omega$, $N=2000\ rpm$, $V_a=153V$, $I_f=1.3A$ and $I_a=16A$ in the steady state differ a little from those of Fig. 8. This is caused by intensifying the interpole *mmf*. Now, we can see that B_{ig1} and B_{ig2} in Fig. 9 (b) are about 1.2 times stronger than those in Fig. 8 (b). Hence, the commutations of i_{c1}, i_{c2} and $i_{c3}$for the initial duration $0<t<5T_m$ are much more improved than those of Fig. 8 (a). However, with the lapse of time, over-commutation arises as observed in Fig. 9 (a).

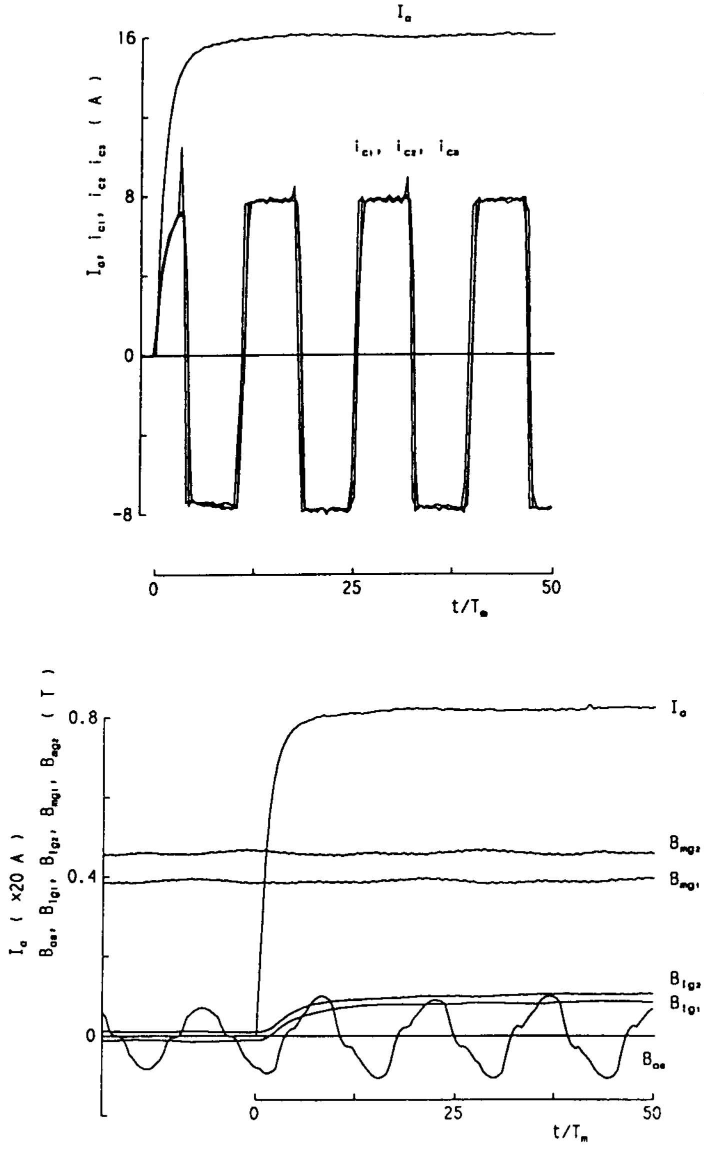

Fig. 8 Experimental results of transient commutation characteristics for $T_m = 1.15$ *ms* and $I_f = 1.3A$

(a) Transient commutation waveforms of armature coil currents.

(b) Transient responses of magnetic flux densities.

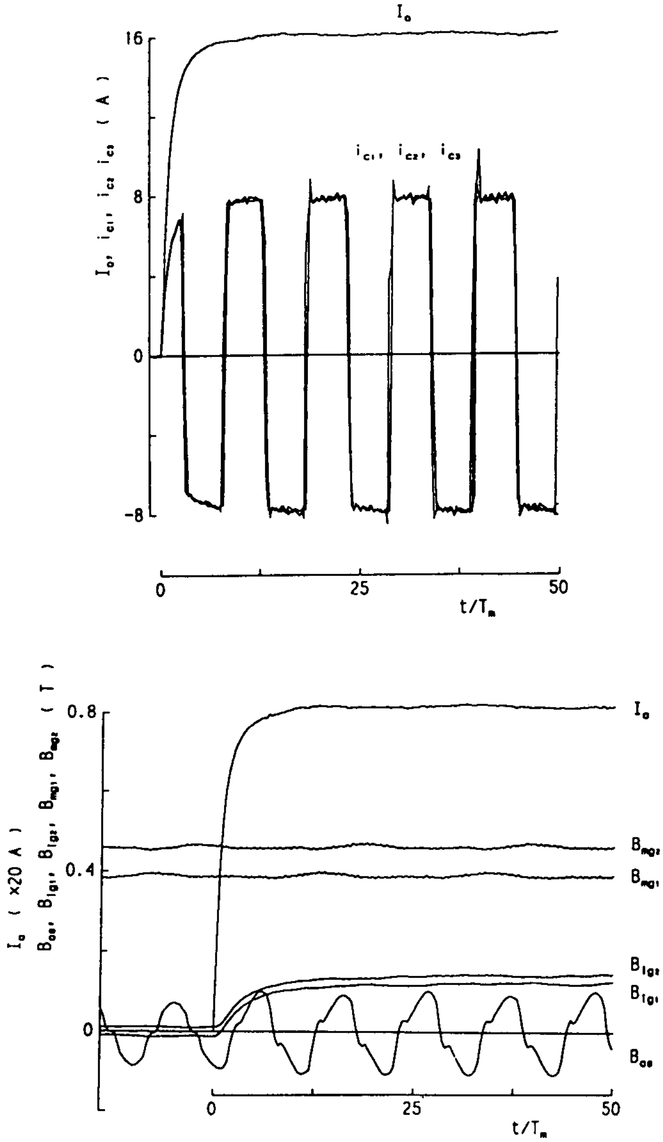

Fig. 9 Improvement of initial transient commutation by intensifying interpole exciting mmf for $T_m=1.58ms$ and $I_f=1.3A$

(a) Transient commutation waveforms of armature coil currents.

(b) Transient responses of magnetic flux densities.

From the experimental results shown in Figs. 8 and 9, we can affirm that the transient responses of the flux densities, such as B_{ig1} and B_{ig2} in the interpole airgaps to the abrupt change of I_a have a great influence on the transient commutation characteristics of the dc motor. Therefore, it is very important to analyse the transient response of the magnetic flux in the interpole airgap. Also, in the analysis, we must take account of the eddy current induced in the solid iron yoke and the interpole liner. This is because the eddy current delays not only the responses of the fluxes in the yoke and the interpole core, but also those in the interpole airgaps.

In some of the latest dc motors, the responsibility of the flux in the interpole airgap is improved by the automatic control of the interpole exciting *mmf*. Also, the partial inner surface region of the yoke is often laminated so as to reduce the initial large eddy current induced in its region.

5. Conclusion

In this paper, we first showed the specification of a small-sized dc motor to be used for an experiment, in which the search coils and the *GaAs Hall* cells are set to measure the transient commutation characteristics of the armature coil current. Also to be measured are the transient responses of the magnetic flux and the flux density in important regions of the moter when the armature current changes abruptly. Next, we introduced the theoretical commutation equations for the specified dc motor for the experiment. Also, we examined the transient commutation characteristics by using a small-sized dc motor, in the case where the armature current changes abruptly.

The main results, which were obtained by the theoretical commutation equations and the experiments of the transient commutation characteristics, are as follows:

(1) From the theoretical commutation equations, it was suggested that the transient responses of the magnetic flux density distribution and the average magnetic flux in the interpole airgap are closely concerned to the transient commutation characteristics of the dc motor whose armature current I_a changes abruptly.

(2) From the experimental results of the transient commutation characteristics, it was affirmed that the under-commutation arises for the initial duration $0 < t < 5T_m$ after an abrupt change of I_a because of the initial delay of the transient response of the magnetic flux density in the interpole airgap. The initial delay may be caused by the eddy current induced in the solid iron yoke and the

interpole liner. Consequently, it is very important to analyse the transient behavior of the magnetic flux in consideration of the eddy current.

(3) The under-commutation for the initial duration was improved by intensifying the interpole *mmf*. This shows that the initial bad commutation can be improved by the control of the interpole exciting *mmf* for the initial duration after the occurrence of the abrupt change of armature current.

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