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A STUDY ON TEMPERATURE RISE OF DC-MACHINE ARMATURE

—— HEAT TRANSMISSION BETWEEN COILS AND CORE ——

T. YAMAMURA, Y. SAITO, and H. NAKAMURA

College of Engineering, Hosei University, JAPAN

INTRODUCTION

The calculation of the temperature rise in the armature has long been considered one of the most important problems in the design of the DC motor. Despite many methods of calculation proposed, very few have been used in the actual design. In most cases, an approximated estimation of the temperature rise in the armature is made according to experimental data, in which the temperature in the armature was measured by the resistance method or by a thermometer. However, because of the complicated structure of the motor, these methods are found inadequate for measuring a wide range of temperature distributions.

For several years, one of the authors has been engaged in temperature measurement of JNR traction motors. In these measurements, the thermocouples were buried in each portion of the armature in the motor and the temperature was analyzed by simulating the heat flow in the armature by a thermal equivalent circuit. In this analysis, the armature was divided into three or five portions. The result shows a good agreement with the experimental values.[1,2] Dan'ko calculated the temperature distribution of a large-capacity DC motor.[3]

The above-mentioned thermal equivalent circuit method has a special merit, in that the estimation of the temperature distribution especially in transient states becomes very easy. The investigations of temperature distribution in the DC-machine armature are becoming increasingly important, as the designing condition of the motor becomes more severe. The thermal equivalent circuit simulating DC armature is composed of lumped constant elements. Among the elements, only the heat transmission between coils and core can not be determined by calculation based on the experimental data, because it depends on the fabricating techniques treating insulating materials. A new method and results are presented here to have this constant determined.

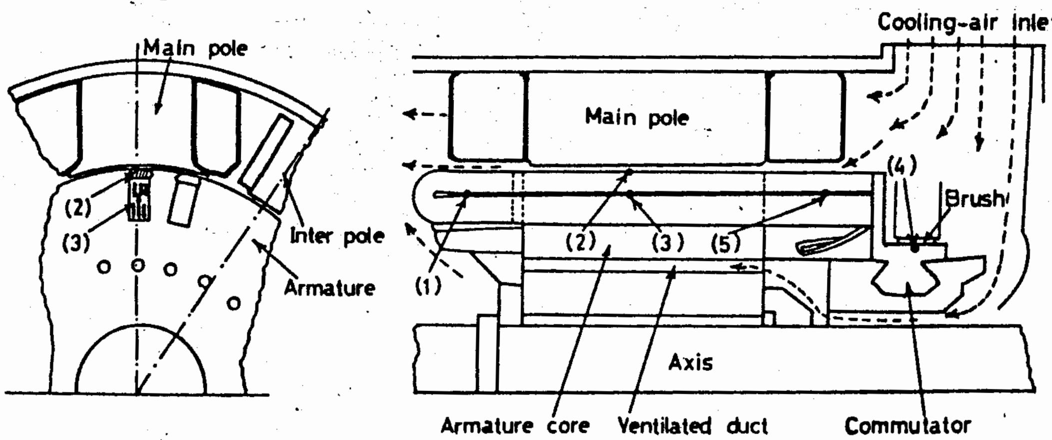

Fig. 1. Representative points for temperature of the armature in a traction motor

Prof. T. Yamamura : Dept. of Elect. Eng. College of Eng., Hosei University
3-7-2 Kajino, Koganei, Tokyo 184, JAPAN

THERMAL EQUIVALENT CIRCUIT OF ARMATURE

The heat flow in the armature can be simulated by a thermal equivalent circuit consisting of lumped constant elements. Table 1 shows the equivalency between thermal and electrical constants. Here C represents heat capacity or electrostatic capacitance, and t is time.

Table 1. Equivalency between thermal and electrical constants

Thermal constant	Electrical constant
Q : heat per unit time	I : current
θ : temperature rise	E : voltage
U : quantity representing heat conduction	1/R : R is resistance

Figure 1 shows a cross-section of the armature. The temperature at the point indicated by the arrow represents the temperature of each portion described in the following.

(1) The space between two layers at the coil ends located opposite the commutator.

(2) The center on the core surface in the armature.

(3) The space between two layers in the middle of the coils inside the core slot of the armature.

(4) The commutator.

(5) The space between two layers at the coil ends in the commutator side.

The armature shown in Fig. 1 can be simulated by a thermal equivalent circuit shown in Fig. 2. Here the suffixes in the notations represent each portion of the armature described above. $\theta_1 \sim \theta_4$ and θ_5 are the temperature rises at respective portions. Here the temperature at the cooling-air inlet is chosen as a reference. $U_1 \sim U_4$ and U_5 denote the heat conductance from the surface of each portion to the air. U_0 represents the heat conductance from the coil inside the core slot (3) to core (2). U_c is the heat conductance in the coil between (1) and (3) which is equal to the heat conductance in the coil between (3) and (5). Here the coil length between (1) and (3) is assumed to be equal to that between (3) and (5). The point (4) represents a location where the heat conductance from (5) is equal to U_c. $C_1 \sim C_4$ and C_5 are the heat capacities at respective portions.

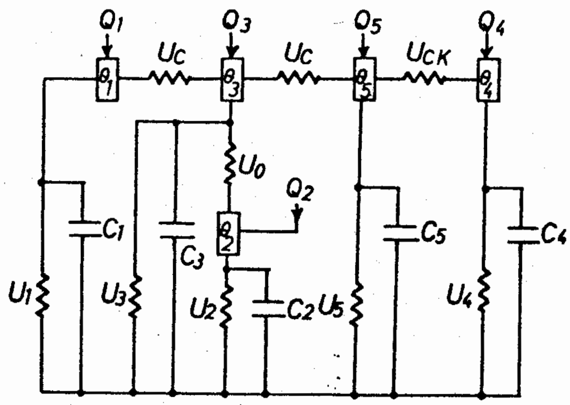

Fig. 2. Thermal equivalent circuit of an armature

From the thermal equivalent circuit shown in Fig. 2, the temperature rise at each point of the armature can be expressed by the following equations:

$$U_1\theta_1 + C_1\, d\theta_1/dt + U_c(\theta_1-\theta_3) = Q_1 \tag{1}$$

$$-U_0(\theta_3-\theta_2) + U_2\theta_2 + C_2\, d\theta_2/dt = Q_2 \tag{2}$$

$$-U_c(\theta_1-\theta_3) + U_3\theta_3 + C_3\, d\theta_3/dt + U_0(\theta_3-\theta_2) + U_c(\theta_3-\theta_5) = Q_3 \tag{3}$$

$$-U_c(\theta_5-\theta_4) + U_4\theta_4 + C_4\, d\theta_4/dt = Q_4 \tag{4}$$

$$-U_c(\theta_3-\theta_5) + U_5\theta_5 + C_5\, d\theta_5/dt + U_c(\theta_5-\theta_4) = Q_5 \tag{5}$$

Here the armature losses expressed in watts comprise the following losses:

Q_1 : copper loss at the portion (1) with temperature correction

Q_2 : no load iron loss

Q_3 : $Q_{3b} + Q_s$

Q_{3b}: copper loss at the portion (3) with temperature correction

Q_s : stray-load loss = input × 1/100

Q_4 : $Q_{4b} + Q_M$

Q_{4b}: brush electrical loss = 2 V × main current

Q_M : brush friction loss

Q_5 : copper loss at the portion (5) with temperature correction

The quantities representing the heat transfer, in other words heat conductance from the surface of each portion in the armature under the steady-state condition $t = \infty$, can be obtained from Eqs. (1) ∿ (4) and (5), and they have been analyzed in many cases. One of the examples is illustrated in Fig. 3.[1]

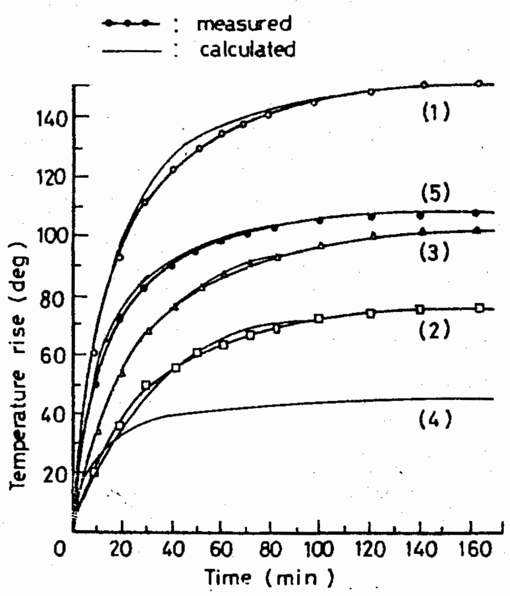

Fig. 3. Comparison between the calculated temperature curves for the armature parts and the measured results

HEAT CONDUCTANCE BETWEEN COILS AND CORE

Among the values of heat conductance in Fig. 2, almost all can be obtained through calculation based on the experimental data on the designing stage, but the heat conductance between coils and core is one exception which can not be determined through calculation, because it depends on the technique of treating insulating materials. For example, solventless epoxy resin is used for avoiding an air pocket having high heat conductance between coils and core.

(1) In Eq. (2), when the time is infinite, $d\theta/dt$ becomes zero, then we have

$$U_0 = (U_2\theta_2 - Q_2) / (\theta_3 - \theta_2) \quad . \qquad (2')$$

For convenience of comparison, the heat conductance per unit area and thickness λ_0 is introduced by dividing it by contact area and multiplying it by thickness of insulator. That is

$$\lambda_0 = U_0\, d_0/S_0 \quad .$$

(2) In the above-mentioned method, it takes several hours to have the saturated temperature rise values, then for simplicity the following method has been developed. The motor under test is not excited, but driven very slightly by another motor and supplied with direct current to the armature. In this transient condition, temperature at each point is recorded, with the results shown in Fig. 4.

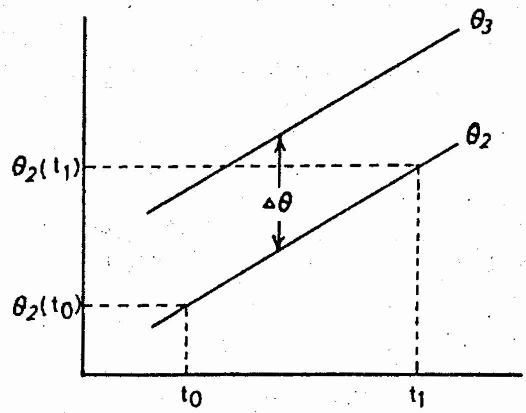

Fig. 4. Temperature of the armature coils and core

It is seen that in Eq. (2) the iron loss equals to zero, then,

$$-U_0(\theta_3-\theta_2) + U_2\theta_2 + C_2\, d\theta_2/dt = 0 \quad . \qquad (2'')$$

In Fig. 4 putting

$$\Delta\theta = \theta_3 - \theta_2 \quad .$$

$\Delta\theta$ is almost constant as given in the figure, and the following can be approximately given

$$\theta_2(t) = [\theta_2(t_1) - \theta_2(t_0)] / (t_1 - t_0) \quad . \qquad (6)$$

From Eq. (2") we have

$$C_2\, d\theta_2/dt + U_2\theta_2 = U_0\Delta\theta \qquad (7)$$

About Eq. (7) a solution can be obtained in terms of time t_0.

Table 2. Heat conductivities of the coil insulator in armature slots for the JNR traction motors and the Trial motors

Types of the motor	Rating (KW)	d_b (x10^{-3}m)	S_{ci} (m^2)	U_0 (W/deg)	λ_0 (W/mdeg)	Resin	Application
MT 200	185	1.5	0.50	80	0.24	Solvent epoxy	SHINKANSEN
MT 916	250	0.95	0.62	175	0.27	Solventless epoxy	SHINKANSEN
MT 52	375	1.3	1.17	170	0.19	Solvent epoxy	Locomotive
MT 52	375	1.3	1.17	260	0.29	Solventless epoxy	Locomotive
A	4.2	1.1	0.17	41.5	0.27	Solventless epoxy	Trial motor
B	1.5	≒0.8	≒0.01	11.0	≒0.16	Solvent epoxy	Trial motor

$$\theta_2(t) = U_0\Delta\theta/U_2\,(1-\varepsilon^{-U_2t/C_2}) \ . \qquad (8)$$

As seen in Fig. 4, $\theta_2(t)$ is linear with respect to time t near t_0, namely we have

$$\varepsilon^{-U_2t/C_2} \fallingdotseq 1 - U_2t/C_2 \ . \qquad (9)$$

Thus a fairly good approximation can be made by Taylor's series up to the second term. Then Eq. (8) becomes

$$\theta_2(t) = U_0\Delta\theta t / C_2 \ . \qquad (10)$$

Using Eq. (7) U_0 can be calculated as follows,

$$U_0 = C_2[\theta_2(t_1) - \theta_2(t_0)] / (t_1 - t_0)\Delta\theta \ . \qquad (11)$$

EXPERIMENTAL RESULTS

Table 2 summarizes the experimental results and the data published already.[2]

CONCLUSION

New method and its experimental results for determining the heat conduction between DC-machine armature coils and core in transient state have been introduced. These would be useful for designing DC-machine armature to work in severe operation.

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