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Thermal Analysis using Equivalent Thermal Network in IPMSM

# Thermal Analysis using Equivalent Thermal Network in IPMSM

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***Abstract*– This paper deals with temperature calculation using equivalent thermal network in interior permanent magnet synchronous motor (IPMSM) under the steady-state condition. The equivalent thermal network consists of heat sources, which are generated from copper loss and iron loss, and thermal resistances considering conduction and convection. The heat transfer coefficient in conduction is decided by material property but it has some disagreement between the value using numerical formula and experimental results. Therefore, temperature of each part in IPMSM is calculated by the equivalent thermal network using calculated thermal resistance based on experimental results. Finally, validation and reliability for proposed equivalent thermal network are verified by experimental results.**

## I. Introduction

Temperature of motor is increased because performance of motor requires compact size and high power density per unit volume. As a result of increase in temperature of motor, coercive force of PM is decreased and the possibility of irreversible demagnetization by armature reaction is boosted. Therefore, the performance of motor is decreased and lifetime of the motor is shortened. Accordingly, design of motor in order to satisfy performance of motor should be performed considering temperature of coil, core, permanent magnet, housing etc.

Using finite element analysis (FEA) is invariably too time-consuming to be acceptable, even with modern computing equipment. Consequently, using the equivalent thermal network which configures lumped parameter thermal model calculates thermal resistance and reconfigures it. Then according to the losses which are joule heating due to the flow of electric current and heating due to the hysteresis in the magnetic material temperature of each part of motor calculates rapidly.

Heat transfer coefficient of materials and geometry information are needed to calculate the thermal resistance. Generally, the heat transfer coefficient of conduction resistance is calculated using the material property. However, the heat transfer coefficient of convection resistance using the numerical formula has some tolerance compared with actual value. Therefore, thermal resistance of convection is calculated again based on experimental results of the motor. And then, the calculated temperature using modified the equivalent thermal network is compared with the temperature for another load condition.

## II. Analogy between Electrical and Thermal Equivlent Circuit

The electrical and thermal equivalent circuit have common point is shown as Table I. Therefore, unknown convection resistances are calculated using Kirchhoff's law and energy balance which is shown as Fig. 1.

TABLE I
ANALOGY OF BETWEEN ELECTRICAL AND THERMAL EQUIVALENT CIRCUIT

| Electrical equivalent circuit | | Thermal equivalent circuit | |
|---|---|---|---|
| Electrical Current | $i$ | Thermal power flow | $q$ |
| Electrical potential difference | $E\text{-}E_{\infty}$ | Temperature difference | $T\text{-}T_{\infty}$ |
| Electrical resistance | $R$ | Thermal resistance | $R$ |
| Electrical Capacitance | $C$ | Thermal Capacitance | $C$ |
| Ohm's law | $\Delta E=R\cdot i$ | Fourier's law | $\Delta T=R\,q$ |

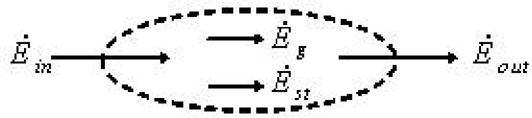

Fig. 1. Energy balance

$$\dot{E}_{in} + \dot{E}_{g} = \dot{E}_{out} + \dot{E}_{st} \tag{1}$$

where, $\dot{E}_{in}$ is energy transported by the fluid into the control volume, $\dot{E}_{out}$ is energy transported by the fluid out of the control volume, $\dot{E}_{g}$ is energy generation and $\dot{E}_{st}$ is energy storage.

## III. Thermal Equivalent Circuit

The process of calculation of thermal resistance is shown as Fig. 2. In order to use the equivalent thermal network, there are some assumptions which are below.

### *A. Assumptions*

1. Heat transfer considers conduction and convection.
2. Materials which have thermal conductivity have isotropy and uniform characteristics.
3. Losses consist of copper loss and iron loss
   Other losses are neglected.
4. Heat transfer considers laminar flow in the air gap.

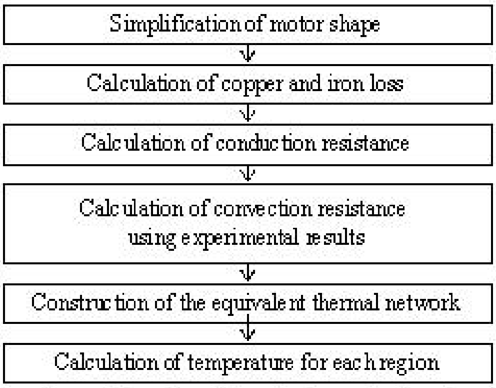

Fig. 2. Procedure of thermal analysis using the equivalent thermal network

## B. *Simplification*

In order to present the thermal equivalent network of the lumped parameter thermal model, the complex shape of motor is simplified. The configuration of simplification of rotor and stator is shown as Fig. 3 and Fig. 4. For this process, the cross section area of permanent magnet and barrier is same before simplification and after simplification.

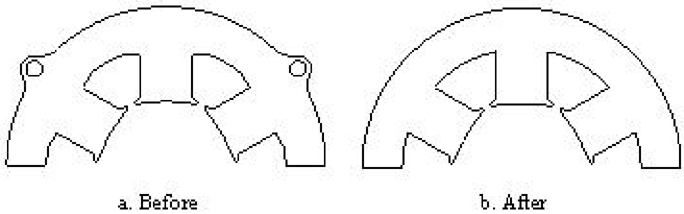

Fig. 3. Simplification of stator.

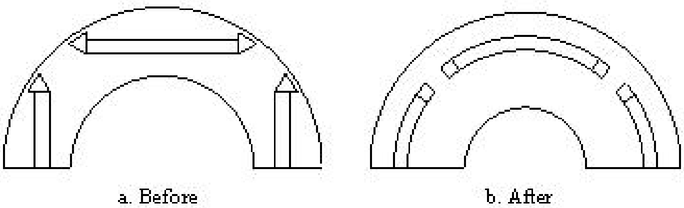

Fig. 4. Simplification of rotor.

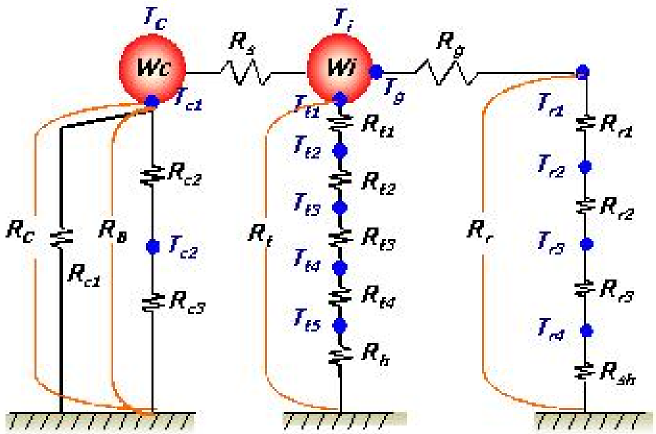

Fig. 5. Equivalent thermal network

TABLE II
MEANING OF SYMBOLS IN THE EQUIVALENT THERMAL NETWORK.

| | | |
|---|---|---|
| $W_c$ | | Copper loss |
| $W_i$ | | Iron loss |
| Conduction Resistance | $R_{s1}$ | at the stator tooth |
| | $R_{s2}$ | at the stator yoke |
| | $R_{s3}$ | between stator yoke and housing |
| | $R_{s4}$ | at the housing |
| | $R_{r1}$ | between PM and outer radius of rotor |
| | $R_{r2}$ | PM, barrier and rotor core |
| | $R_{r3}$ | between PM and inner radius of rotor |
| | $R_s$ | between insulating paper and stator core |
| | $R_{sh}$ | at the shaft |
| Convection Resistance | $R_h$ | between housing and ambient |
| | $R_g$ | at the air gap |
| | $R_{e1}$ | between end coil and ambient |
| | $R_{e2}$ | between end coil and housing |
| | $R_{e3}$ | between housing and ambient |

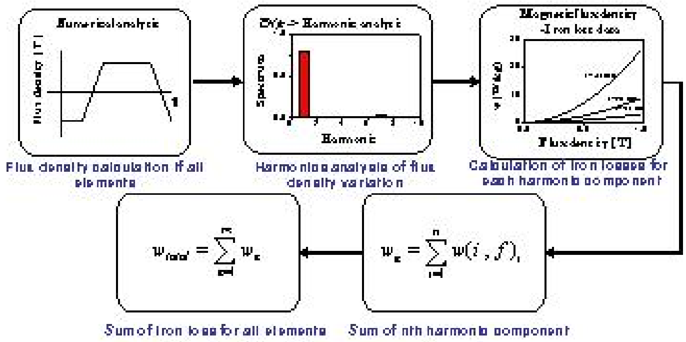

Fig. 6. Calculating process of iron loss

The equivalent thermal network is shown as Fig. 5 and Table I is explanation of each resistance.

## C. *Copper and iron loss*

Copper loss and iron loss which are generated by copper and silicon steel respectively act on heat source. Firstly, copper loss equation is

$$W_c = 3 \times I_p^2 \times R_p \quad (2)$$

Where, $I_p$ is phase current and $R_p$ is phase resistance.

The calculating process of iron loss is shown as Fig. 6.

## D. *Conduction resistance in the stator*

The conduction resistance in the stator is calculated using the heat transfer coefficient of material.

(a) Insulating paper of stator

$R_{s2}$ is thermal resistance of insulating paper. The heat which is generated by coil transfers to stator through insulating paper. So, conduction resistance of insulating paper is calculated using material property.

(b) Stator teeth

$R_{t1}$ is the thermal resistance of stator teeth. The heat which is generated by copper loss is translated from coil to teeth and generated by stator due to hysteresis in the teeth. The heat flows to ambient through yoke, housing and rotor from the teeth.

(c) Stator yoke

$R_{t2}$ is the thermal resistance of stator yoke and its equivalent shape is modeled as hollow cylinder. The equation of hollow cylinder is

$$R_{t2} = \frac{1}{(2\pi \times \lambda_{t1} \times L_{st})} \cdot \ln\left(\frac{D_{y0}}{D_y}\right) \qquad (3)$$

where, $L_{st}$ is stack length of stator, $\lambda_{t1}$ is the heat transfer coefficient of silicon steel, $D_{y0}$ is outer diameter of stator and $D_y$ is outer diameter of slot.

(d) Between yoke and housing

$R_{t3}$ is the thermal resistance of between yoke and housing and the shape of $R_{t3}$ is the same as hollow cylinder shape. The resistance is modeled as done for $R_{t2}$.

(e) Housing

$R_{t4}$ is the thermal resistance in the housing. The housing is modeled as done for hollow cylinder. The area of surface of housing is important to cool the motor.

*E. Conduction resistance in the rotor*

The conduction resistance in the rotor is calculated using the heat transfer coefficient of material.

(a) Between PM and outer radius of rotor

$R_{r1}$ which is silicon steel of upper permanent magnet can be calculated as done for hollow cylinder.

(b) PM, barrier and rotor core

$R_{r2}$ is consists of a parallel combination of three resistances such as $R_{pm}$, $R_{barrier}$, $R_{mp}$ and can be calculated as follows:

$$R_{r2} = \left(\frac{1}{R_{pm}} + \frac{1}{R_{barrier}} + \frac{1}{R_{mp}}\right)^{-1} \qquad (4)$$

(c) Between PM and inner radius of rotor

$R_{r3}$ which is silicon steel of lower PM can be calculated as done for hollow cylinder.

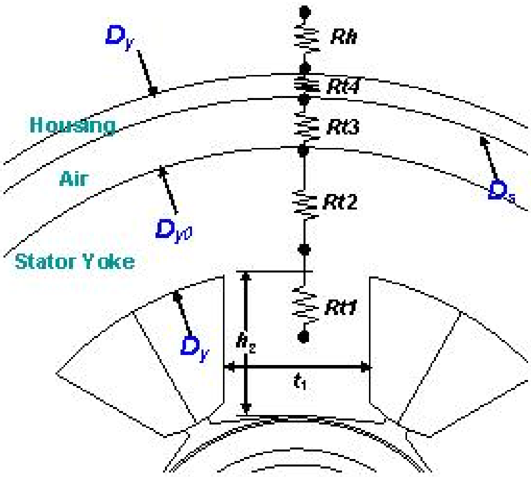


Fig. 7. Conduction thermal resistance from stator to ambient.

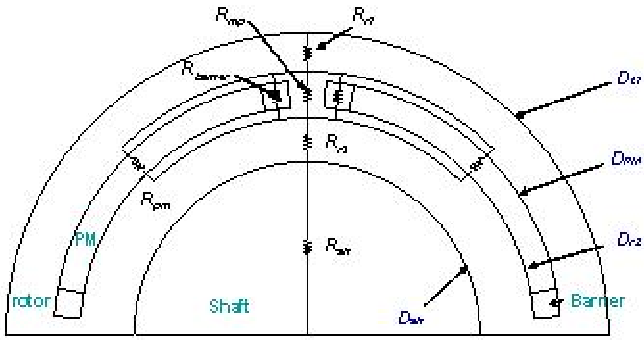


Fig. 8. Conduction thermal resistance from rotor to shaft.

(d) Shaft

$R_{sh}$ which is shaft can be calculated as done for teeth of stator.

*F. Convection resistance*

Experiment is needed to find the coefficient of convection resistance and unknown temperature of motor. Experimental conditions and losses are shown in Table III. The equivalent thermal network including measured temperature and calculated conduction resistance is shown in Fig. 9. In addition, unknown convection resistance and temperature are calculated and it is expressed by Fig. 10.

## IV. Experiment

In order to verify the validation of thermal resistance, other experimental conditions and losses are shown as Table IV. The predicted temperature is compared with the experimental result in order to verify reliability of thermal resistances.

Using calculated thermal resistance, experimental result compared with calculated temperature at operation with another condition and shown as Table V.

## V. Conclusions

In this paper, the temperature of motor is calculated by the proposed equivalent thermal network and the validity of proposed the equivalent thermal network in comparison with the experimental results is verified.

In order to satisfy the performance of motor, temperature of motor is important factor. However, it is difficult to measure the temperature in each part of motor during operating condition. The cooling method and current density is decided by predicted temperature. Therefore, the motor can be designed by considering characteristics of motor.

## References


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TABLE III
Experimental Conditions and Losses @ 1800 RPM

| | |
|---|---|
| Current [ $A_{rms}$ ] | 0.9 |
| Output power [ W ] | 850 |
| Phase resistance [ Ω ] | 3.9 |
| Copper loss [ W ] | 3.2 |
| Iron loss [ W ] | 1.4 |

TABLE IV
Experimental Conditions and Losses @ 3600 RPM

| | |
|---|---|
| Current [ $A_{rms}$ ] | 0.91 |
| Output power [ W ] | 1700 |
| Phase resistance [ Ω ] | 3.9 |
| Copper loss [ W ] | 3.2 |
| Iron loss [ W ] | 2.94 |

TABLE V
Comparison between Calculated and Measured Temperature

| | Calculation[ °C ] | Measurement [°C ] | error [ % ] |
|---|---|---|---|
| $T_1$ | 36.6 | 36.7 | 0.3 |
| $T_2$ | 36.9 | 37.4 | 1.3 |
| $T_{c1}$ | 31.9 | 34.5 | 7.5 |
| $T_{t1}$ | 32.9 | 33.9 | 2.9 |
| $T_{t3}$ | 35.2 | 36.2 | 2.8 |
| $T_{ro}$ | 33.1 | 33.6 | 1.5 |

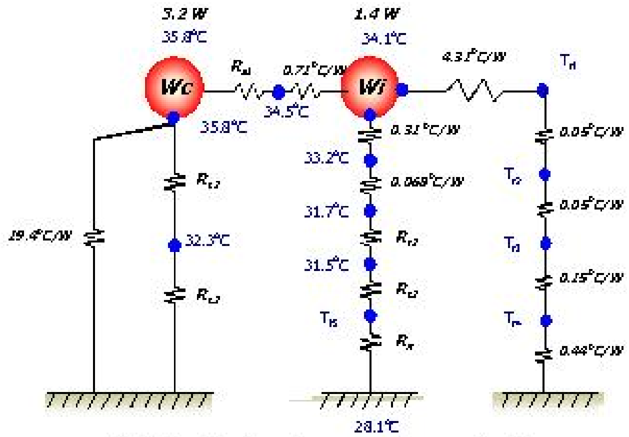


Fig. 9. Conduction resistances and copper, iron loss

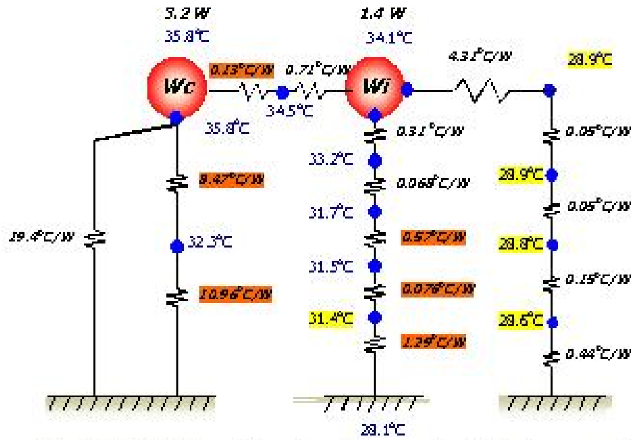


Fig. 10. Distribution of thermal resistances, calculated and measured temperature