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The Coupled Electro-Thermal Field Analysis for Predicting Over-Current Protector Behavior

Jae-Nam Bae* · Sung-Gu Lee · Jung-Ho Han · Hae-Yang Chung · Ju Lee**

Abstract

The characteristics of heat transfer of the bimetal disc for over-current protection device is specified. Bimetal consists of two metals which have a different thermal expansion coefficient. To analyze the thermal characteristics, temperature distribution when bimetal acts as a switch is calculated. As usual, heat source is applied to the bimetal and electric current is heat source in the over-current protection switch. In this paper, thermal distribution are obtained by solving a coupled electro-thermal field with 3D finite element method.

Key Words : Coupled field, Finite element method, Electric heating, Bimetal disc

1. Introduction

Because of its thermal control ability, a bimetal which operated by a difference of thermal expansion ratio between two metals is widely used for home appliances such as an electric iron or an electric kettle and industrial applications such as a current limiter or circuit breaker. Of course the source for the bimetal is heat and there are several kinds of heat sources. Electric current can be the source because most of ohmic losses by the current are converted to heat. In this case bimetal could be applied to an over-current protection device shown in figure 1 which is used for a compressor of a refrigerator or an air-conditioner.

The bimetal disc contacts with two terminals when it operates in normal conditions and the current flows through the disk. However the disk is toggled and the contact is broken when over-current flows through the disk. Therefore it can serve as a switch.

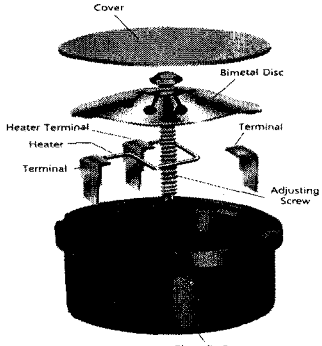

Fig. 1. Over-current protection device

* Main author : Ph.D Student of Department of Electrical Engineering at Hanyang University
** Corresponding author : Professor of Department of Electrical Engineering at Hanyang University
Tel : +82-2-2220-0349, Fax : +82-2-2295-7111
E-mail : baejn81@hanyang.ac.kr
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The most important thing for the over-current protection device is operating at a given current. As mentioned above, the bimetal disk operates as a switch and switching signal is the heat generated by the current flowing through the disk. Therefore it is very important to know the relationship between the current and heat. It can be obtained by measuring input current and temperature on the disk but it cost too much. Therefore it is better to know it by computer simulation.

In this paper, thermal characteristics of the disc as changing input current and disc shapes are obtained by calculating an electric field and thermal field simultaneously using 3-D finite element analysis (3-D FEA). The results are compared with the experimental results and the effect of disc shape on the heat distribution is investigated.

2. Bimetal Disc and Field Equations

2.1 Bimetal Resistivity and Adequate Current

When a layer of low or high resistance material is bonded between the high and low expansion materials such like in figure 2, the resistivity of the bimetal system can be changed to meet the products current carrying capacity needs. By varying the thickness of this intermediate layer the resistivity of the system can be adjusted.

Ohms per circular mil feet (Ohm/cmf) is normally used for the unit of measure and the bimetal disc has a resistivity with range of 35~850 Ohms/cmf.

A resistivity of some principal materials is shown in table 1.

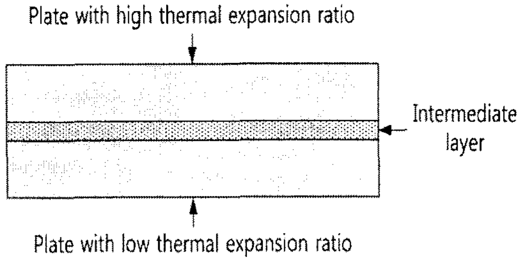


Fig. 2. Bimetal resistivity

Table 1. Resistivity of principal materials

Material	Resistivity [Ohms/cmf]
Copper	35~100
Nickle	100~400
Manganese	300~850

The disc needs adequate current to operate at particular temperature when the material for the disc is determined or material can be changed when current is fixed. Here the material is fixed and the effect of the current on disc temperature is investigated.

2.2 Current and Ohmic Loss Distribution on the Bimetal Disc

The current distribution can be changed by the disc shapes and the original shape is shown in figure 3.

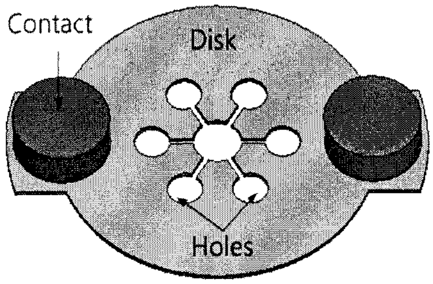


Fig. 3. Original disc shape

There are several holes near the center. An original aim for the holes is helping to operate the disc more pliable, however it can also change the current distribution on the disc.

The current distribution can be obtained by solving the Ampere's circuital law (1).

$$\nabla \cdot \mathrm{J} = 0 \tag{1}$$

where, J is current density and there is a relationship between electric field and current density as

$$\mathrm{J} = \sigma \mathrm{E} \tag{2}$$

Electric field is gradient of electric potential

$$\mathrm{E} = \nabla \Phi \tag{3}$$

Finally, equation (1) is rewritten as

$$\nabla \cdot (\sigma \nabla \Phi) = 0 \tag{4}$$

Equation (4) is Laplace equation which is second order differential equation in the domain of a position.

Boundary conditions are always necessary from a mathematical perspective in order to ensure the uniqueness of the solution. In our case, input current on the terminals and a Neumann homogenous condition on outer boundary are used. There are two current terminals for a excitation and sum of the current must be zero because of equation (1). So, one of the terminals is called current source and the other is called sink [1].

Finally, the solution is obtained by solving equation (4) with the boundary conditions and ohmic loss is calculated by the following equation

$$P = \int_{vol} (\mathrm{E} \cdot \mathrm{J}) dv \tag{5}$$

2.3 Thermal Field Calculation and Temperature of the Disc

In the governing equation for the temperature solution, the heat generation term is due to electromagnetic losses (i.e., copper and core losses). Theoretically, the heat is produced periodically at the frequency of excitation. However, because of the high frequency and the thermal capacitance of the core and windings, this generation can be assumed time independent and equal to the average power generated over a cycle (Smith, [3]). And here, it is assumed that the current is DC which is the same as the RMS value. Furthermore, the quasi-steady solution to the coupled thermal-magnetic problem is sought since this solution produces the maximum temperatures and thus the most extreme conditions. Correspondingly, the temperature solution is governed by the quasi-steady form of the heat conduction equation [2, 4-6].

$$-\nabla([k] \nabla T) = Q \tag{6}$$

where Q represents volumetric or surface thermal loads that can be defined as intrinsic thermal sources and [k] is the nonlinear anisotropic thermal conductivity tensor and can be spatially varying.

The heat generation is due to ohmic-loss in the bimetal disc and is calculated in locally as

$$Q = \frac{J^2}{\sigma} \quad \because J^2 = \mathrm{J} \cdot \mathrm{J} \tag{7}$$

with J as the electric current density and σ is the electric conductivity. Practically σ is nonlinear with temperature but here it assumed constant value.

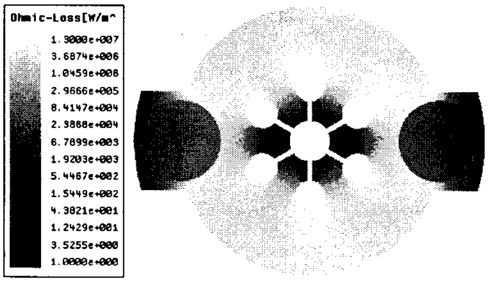
Only heat transfer by conduction is considered and it is assumed that the disc is surrounded by a solid material with the thermal conductivity of air.

3. Field calculation results

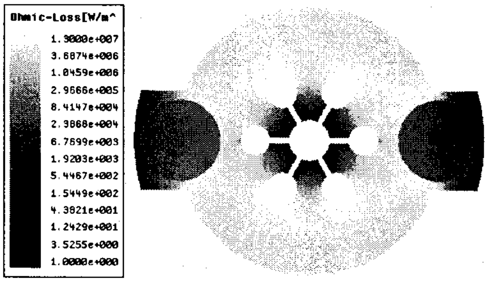
3.1 Effects of disc shapes on current distributions

A current path can be changed by the holes and it makes different ohmic-loss distribution on the disc. So, here the effect of position of 6 holes around center hole is investigated.

Figure 4 shows the distributions of two different cases when the resistivity is 35 [ohms/cmf] and current is 10 [A]. The size of the holes is the same but the position is different. Two holes facing each other in the six are unaligned to the contacts in figure 4 (a) and rotated by 30 degree, aligned, in figure 4 (b). On the whole, the distributions are similar each other except near the center and the magnitude is also very similar in two cases.



(a) unaligned to the contacts



(b) aligned to the contacts

Fig. 4. Ohmic-loss distributions at 10[A]

Figure 5 shows the ohmic loss as varying the hole position. As it can be seen in the picture, only small portion of the loss is varying as the position. Total power losses as varying current in both cases are nearly the same as shown in figure 6. Therefore the position of the holes has a little effect on thermal characteristics.

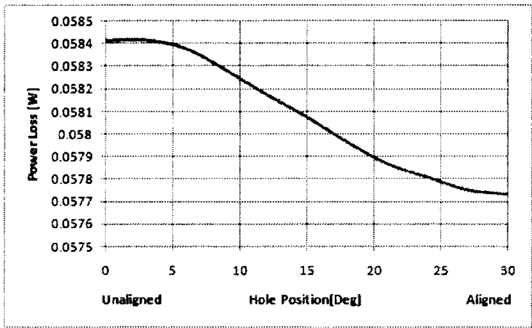


Fig. 5. Ohmic loss as hole position at 10[A]

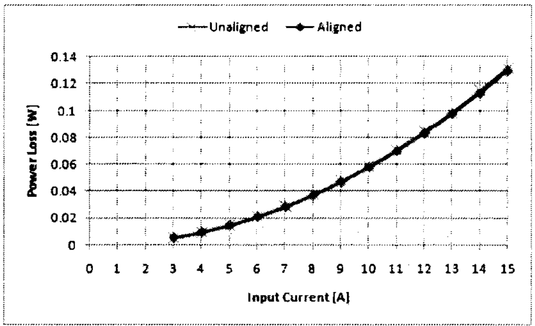


Fig. 6. Ohmic loss as varying current

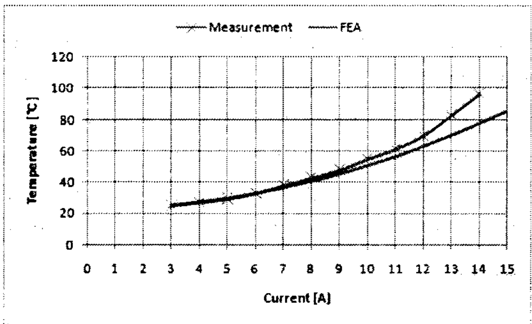


Fig. 7. Disc temperature as varying current

3.2 Current and disc temperature

The temperature of the disc can be predicted by solving the equation (7) on the disc. The heat source is obtained from calculating electric field and it can be changed by varying current.

Figure 7 shows the disc temperature as varying the current and figure 8 shows temperature measurement set. Thermal properties of the bimetal disc is presented in table 2 and ambient temperature is 21.5[°C].

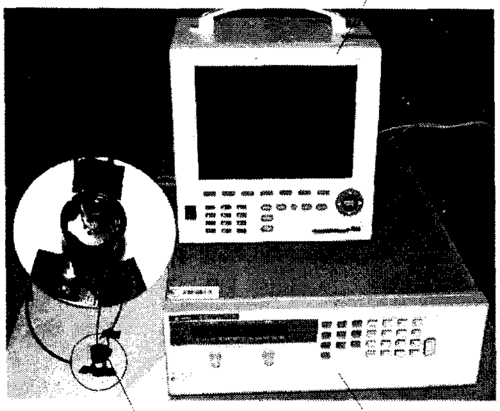


Fig. 8. Experimental set for temperature measurement

Table 2. Properties for the bimetal disc

Property	Value
Thermal conductivity(k)	400[$W/m\,K$]
Specific heat(C_p)	385[$J/kg\,K$]
density(ρ)	8,933[kg/m^3]

Simulation result and measurement result is well matched when the current is below 10[A] but the difference is increased as increasing current. The reason is that the resistivity is non-linear and increases as increasing temperature. Therefore, temperature feedback for the electric field analysis is needed for more exact prediction.

4. Conclusion

The coupled electric and thermal field has been investigated for over-current protect device. The 3D finite element method has been applied for the solution of the relevant differential equations. Thermal load for thermal field is mapped from electric field solution to take the coupling into account.

The effect of positions of the holes on the disc on thermal characteristics is investigated and it has only a few effect. And it is necessary to consider the effect of temperature on disc resistivity for more accurate prediction especially when the current is higher than 10[A].

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Biography

Jae-Nam Bae

He received the B.S and M.S degrees in electrical engineering from Hanyang University, Seoul, South Korea, in 2004 and 2006 respectively. He is in the Ph.D course in the department of Electrical Engineering, Hanyang University. His research is focused on the numerical analysis and the optimal design with small electrical machines.

Sung-Gu Lee

He received the B.S and M.S degrees in electrical engineering from Hanyang University, Seoul, South Korea, in 2003 and 2005 respectively. He is in the Ph.D course in the department of Electrical Engineering, Hanyang University. His research is focused on the analysis and the optimal design with Linear Induction Motor (LIM).

Jung-Ho Han

He received the B.S degrees in physics physical science from Soonchunhyang University, Chungnam, South Korea, in 2006. He works for 'Hanbecthistem'. His research is focused on the design of over-current protector.

Hae-Yang Chung

He received the B.S. degrees in electrical engineering from Sungkyunkwan University, Seoul, South Korea, in 1981. He found 'Hanbecthistem' in 1996 and is currently a managing director.

Ju Lee

He received the B.S. and M.S. degrees in electrical engineering from Hanyang University, Seoul, South Korea, in 1986 and 1988 respectively, and the Ph.D. degree in electrical engineering from Kyusyu University, Japan in 1997. He joined Hanyang University in September, 1997 and is currently an Assistant Professor of the Division of Electrical Engineering. He is a consultant member of EM, KT, NT, standardization of rotary machines and research committee for new technology movements. He is also a general manager of Human Resource Development Center for Electric Machine and Devices (HCEM), Seoul, Korea.