Electromagnetic and Thermal Design Technology for Reactor Development

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Sumitomo Electric Industries, Ltd. is working to develop low-cost and compact reactors, which contribute to the improvement of the converter. We have developed an original tool for reactor electromagnetic/thermal design based on logic equations and Computer Aided Engineering (CAE). In our study, the predicted values calculated using the tool were found to be highly consistent with observed values and the development time of the reactor was successfully shortened. This paper reports the details of our development.

Keywords: reactor, electromagnetic design, thermal design, eco-friendly vehicle

1. Introduction

Recently, global warming has become a serious social issue. To tackle this issue, the automobile companies are concentrating on the development of environmentally-friendly automobiles, such as the hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), electric vehicle (EV) and fuel cell vehicle (FCV). To promote the dissemination of these eco-friendly vehicles, it is vital to improve their driving performance and power acceleration as well as energy efficiency to the level of the gasoline vehicle performance.

In this regard, the converter plays an important role, specifically to increase the battery voltage for the high power motor and recharge the EV and PHEV batteries from household outlets. In response to these varied demands of the converter, automakers are trying to develop small and cost-efficient converters.

Sumitomo Electric Industries, Ltd. is working to develop low-cost and compact reactors, one of the core components for the converter. In our study, we developed an original tool for reactor electromagnetic/thermal design based on logic equations and Computer Aided Engineering (CAE). The evaluation result showed that the predicted values calculated using our tool were highly consistent with observed values and the development time of reactors was successfully shortened. This paper reports the details of the development.

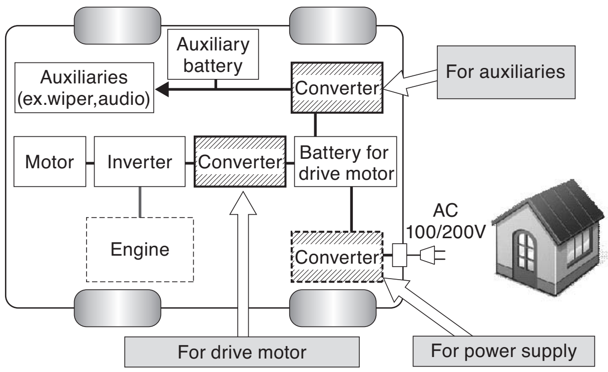

Fig. 1. HEV, PHEV, EV Systems

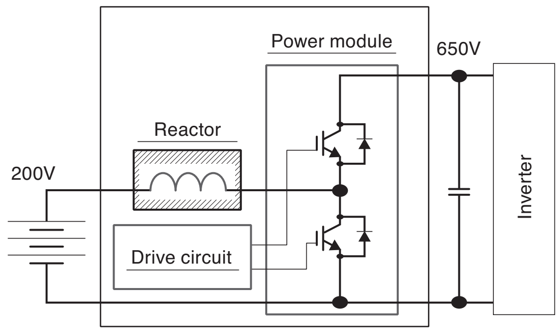

Fig. 2. Example of the boost converter

2. Reactor Structure

Figure 1 shows the possible locations where the boost converter is applicable in a battery converter for the HEV, PHEV, EV systems, etc. An example of the inner structure of the boost converter is shown in **Fig. 2**. The structure consists of a reactor, power semiconductor, condenser and the circuits which drive these components. As shown in **Photo 1**, a reactor is an iron core with a copper wire coil wound around it. The reactor is the core component of voltage conversion, which stores and emits energy in alternation by running a current through the coil.

The specifications for the reactor developed at our company are shown in **Table 1**.

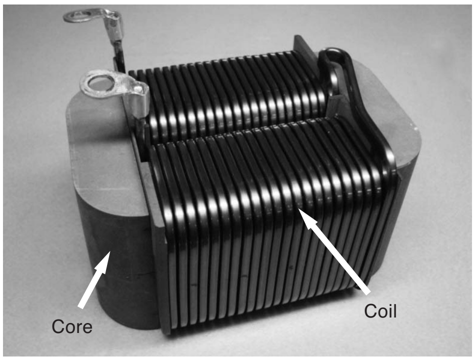

Photo 1. Developed reactor

Table 1. Specifications of the developed reactor

Inductance	~500μH
Current	~200A
Drive frequency	~100kHz

3. Design

When designing a reactor, the most important factors to consider are inductance, which is a necessary parameter for voltage conversion, and loss that affects fuel consumption. There are methods to measure inductance accurately; however, loss cannot be measured accurately because of the large phase error between current and voltage caused by the low phase factor of the reactor. Since loss is converted to heat when a current is applied to the reactor, we examined the consistency between the designed values and measured values of the reactor temperature to assess the validity of the loss design value as an alternate method to measure loss.

Figure 3 displays the process of designing a reactor. It can be largely divided into electromagnetic design and thermal design.

In electromagnetic design, inductance and size is found in 2 steps: basic design and detailed design. By using our original development tool to obtain the rough size during the basic design step, this design method enables us to shorten the design period.

The main feature of thermal design is the ability to predict the reactor temperature within ±10% accuracy by creating a model that is almost identical to the original structure. Heat resistant parts are selected based on the predicted temperatures, then the finalized structure and size is determined.

Ultimately, these analysis results should be compared with observed values to confirm the validity of the design.

By using the above process to design the reactor, we were able to perform high precision electromagnetic design and thermal design in a short time, and also develop a reactor that satisfies all the specifications on our first attempt. The details are discussed in the following.

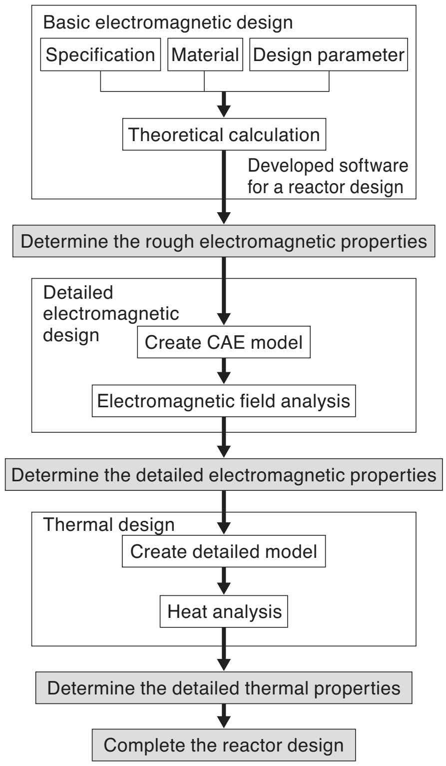

Fig. 3. Process of designing a reactor

3-1 Basic electromagnetic design

For basic electromagnetic design, our objective was to develop a tool that could efficiently determine the rough reactor structure satisfying the requested specifications (inductance, loss, size). Thus, there would be no need to repeatedly perform detailed design and the overall design period would be shortened.

The representative equations (1), (2) based on magnetic theory were used to calculate inductance during tool development.

$$B_{\max} = \frac{L I_{\max}}{NS} \quad \cdots\cdots\cdots\cdots (1)$$

$$L = N^2 \left(\frac{l_c}{\mu_r \mu_0 S} + \frac{l_g}{\mu_0 S} \right)^{-1} \quad \cdots\cdots\cdots\cdots (2)$$

$B_{\max}$: Maximum flux density
L : Inductance
$I_{\max}$: Maximum Current
N : Coil turns
S : Core cross-section area
l_c : Flux path length
l_g : Gap length
μ_0 : Space permeability
μ_r : Relative permeability of core

Loss can be classified as shown in **Fig. 4**. Alternating current (AC) resistance loss cannot be calculated using simple equations, so detailed design (magnetic flux analysis) was used. Coil loss was calculated using the general logic equations (3), (4).

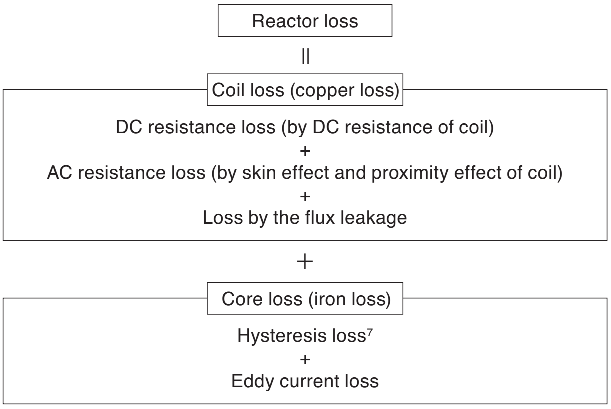

Fig. 4. Classification of the loss

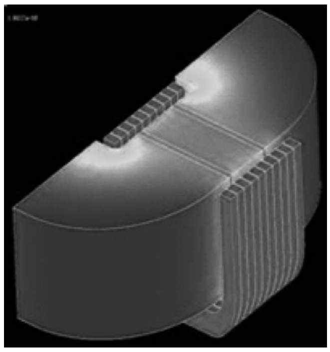

Fig. 5. Contour figure of electromagnetic field analysis

$$R_{dc} = \rho_0 \frac{l}{S}\{1+\alpha_0(T-20)\} \quad \cdots\cdots\cdots\cdots (3)$$

R_{dc} : Direct Resistance　T : Temperature
ρ_0 : Resistivity (at 20C)　S : Coil cross-section area
l : Coil length　α_0 : Temperature coefficient of resistivity

$$P_{coil} = I^2 R_{dc} \quad \cdots\cdots\cdots\cdots (4)$$

P_{coil} : Coil loss　I : Current

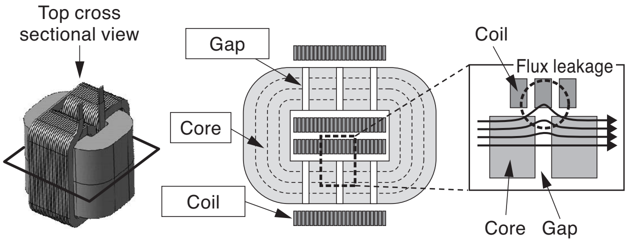

Fig. 6. Flux leakage from the gap

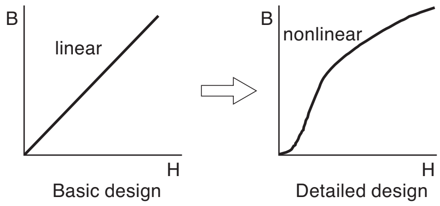

Fig. 7. Nonlinear magnetic properties

Core loss was calculated using the Steinmetz equation (5).

$$P_{core} = K_h B_m^{1.6\sim2} f + K_e B_m^2 f^2 \quad \cdots\cdots\cdots\cdots (5)$$

P_{core} : Core loss　B_m : Amplitude of magnetic flux density
K_h : Hysteresis loss coefficient　f : Frequency
K_e : Eddy-current loss coefficient

The core physical values (hysteresis loss coefficient, eddy-current loss coefficient, and amplitude of magnetic flux density) required for equation (5) differs depending on the material. Generally, the reactor core materials are magnetic steel plate, ferrite, and amorphous, but in this report we will discuss the results based on our study which utilized our original powder core (pure iron or Fe-Si based powder coated with insulation then press formed) and coil wire material. We were able to enhance the design accuracy by using the known detailed physical values of these main materials

In past designs, the optimal design parameters were found by a trial and error process, repeatedly altering the parameters then testing them, which was a time consuming task. For that reason, we developed our original software to automatically compute all combinations of the design parameters in a given range and determine the optimal reactor structure. As a result, we were able to significantly reduce the design time compared to past design methods.

3-2 Detailed electromagnetic design

Following the basic electromagnetic design step to determine the reactor's rough size, detailed electromagnetic design was performed to calculate inductance and loss (AC resistance loss, iron loss).

The details of the flux expansion flowing inside the core were analyzed using CAE analysis (**Fig. 5**), the effects of the flux leakage from the gap are also analyzed (**Fig.6**) and pre-measured nonlinear magnetic properties of the powder core (**Fig. 7**) were reflected to increase the precision of the inductance direct current (DC) superposition property.

Figure 8 is a contour figure showing the flux density calculated using the above mentioned contents with the magnetic flux analysis software (CAE), and the leakage flux from the gap shown in **Fig. 6** can be predicted.

The detailed inductance superposition property can be calculated with equation (6) using magnetic energy obtained from the magnetic field analysis, and current value.

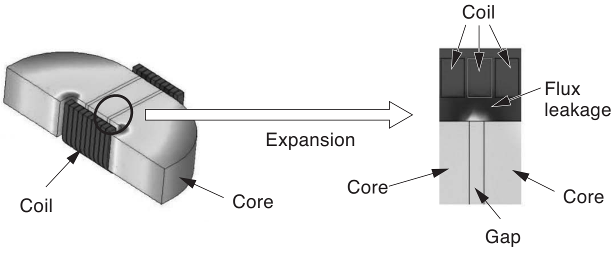

Fig. 8. Contour figure of electromagnetic field analysis

$$E = \frac{1}{2} L I^2 \qquad \cdots\cdots\cdots\cdots \ (6)$$

E : Magnetic field energy L : Inductance I : Current

Simultaneously, each loss is calculated from the magnetic field analysis. DC resistance loss was calculated from the current distribution flowing through the coil. AC resistance loss was calculated from the current distribution caused by skin effect, proximity effect, and leakage flux. Iron loss was calculated for every distribution of the core flux density using the Steinmetz equation (5).

The detailed loss value found from above was included as a heat generating condition for thermal design.

3-3 Thermal design

For thermal design, the validity of the loss value has to be verified and also, the design must allow for a sufficient temperature margin for each of the parts.

Based on the data calculated from detailed electromagnetic design, a heat analysis model (**Fig. 9**) including the peripheral parts (case, etc.) was created. Our company is proficient at producing a model that is structurally accurate. We are able to do this, for example, by creating separate models for the coil center wire and coating, and a detailed model for the places that effect heat dissipation, such as the core-case contact heat resistor and adhesive material between the gap and core, etc. As a result, the precision of the transient property was greatly improved.

The basic parameters of thermal conductivity and the physical values relating to the thermal properties for each part, as well as specific heat and density, used to identify temperature change over time, were entered as properties for the model. In order to increase the accuracy of these parameters, physical values were confirmed with actual measurements for each of the parts before configuring to the model.

In addition, we increased the accuracy of the thermal analysis results by giving the model specific values for the reactor heat release factors: DC resistance loss (**Fig. 10**: configure the entire coil with a function that considers the temperature dependency of the copper resistor), AC resistance loss (**Fig. 11**: configure the skin effects, proximity effects, leakage flux effects to the inner surface of the coil), and iron loss (**Fig. 12**: configure hysteresis and eddy current to the entire coil), calculated through detailed electromagnetic design.

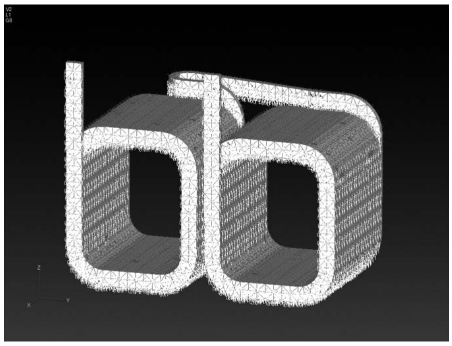

Fig. 10. Setting the DC resistance loss

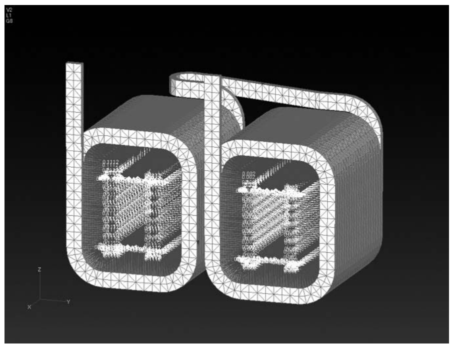

Fig. 11. Setting the AC resistance loss

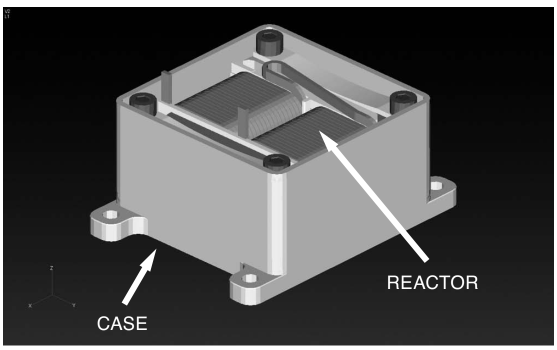

Fig. 9. CAE model for heat analysis

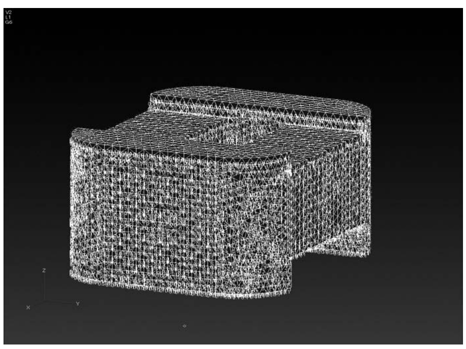

Fig. 12. Setting the iron loss

Figure 13 shows the results of the thermal analysis conducted with the above described conditions. The upper surface of the coil has very high temperatures. **Figure 14** is the cross sectional view represented by the white box in **Fig. 13**; the area where the white arrow points (the mid section of the coil's upper surface) has the highest temperature. From these results, we were able to compare the maximum temperature limit of each material and select the structure that has an adequate temperature margin.

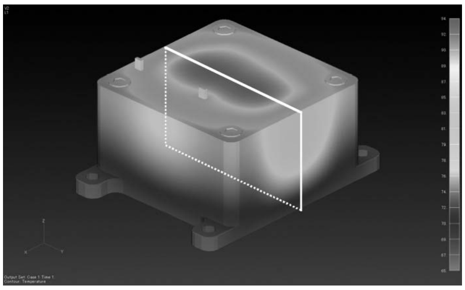

Fig. 13. Contour figure of heat analysis

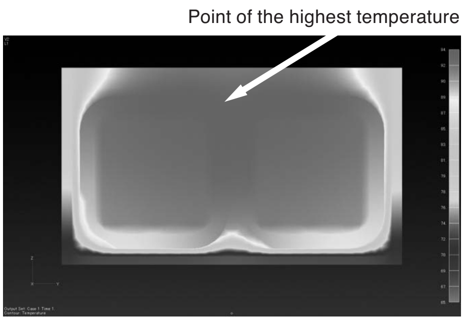

Fig. 14. Contour figure of heat analysis (cross-section view)

4. Evaluation

In order to verify the validity of the above design results, we manufactured the reactor, then compared the design values and observed values of inductance. The design values and observed values of 5 different current conditions set in between the minimum current and maximum current were compared. All results came within ±10% of each other.

In addition, 2 types of power distribution were used to test the thermal design results. In the transient temperature mode, the reactor was placed under high stress conditions and temperature was gradually increased from the start point as time elapsed, while in the other mode, the temperature remained constant. After evaluating the 6 measurement points shown in **Fig. 15**, we found that all values came out to be within ±10% accuracy when compared to the design values. In conclusion, both electromagnetic and thermal design was able to perform high precision design, and we were also able to confirm the capacity of the design tool.

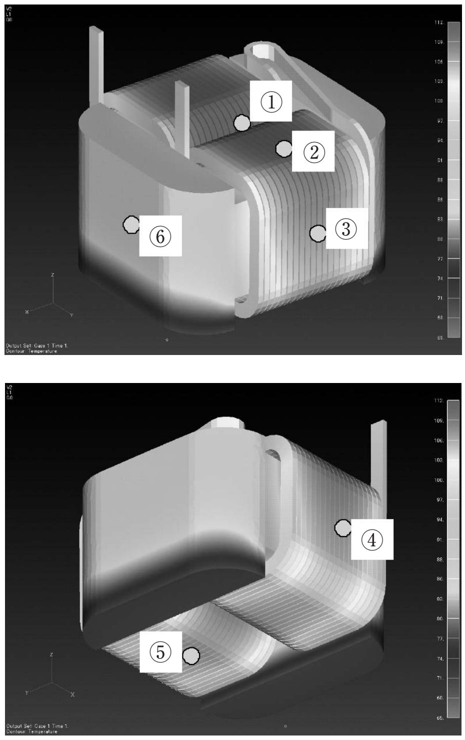

Fig. 15. Measurement point of the reactor temperature

5. Conclusion

We developed an original tool for reactor electromagnetic/thermal design, which performs basic design based on logic equations and detailed design based on CAE. The predicted values of inductance and transient phenomenon of elevated temperature calculated using our tool were found to be highly consistent with observed values. With these results, we hope that our design tool will be useful in reactor development and serve for product development in the future.

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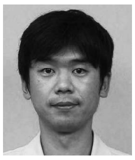

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