Simulation Technology Supporting Development of Sealed High-Voltage Contactors

SAKATA, Masayoshi*  TAKEMOTO, Takanori*

Abstract

Fuji Electric has developed a sealed high-voltage contactor for automotive applications that has a high overcurrent withstand capability to deal with high-output and large-capacity batteries. The high-voltage contactor achieves high-capacity switching and breaking performance despite its compactness because its contacts are arranged inside a sealed capsule container filled with a gas of good breaking performance. By conducting analysis-driven development that effectively utilizes simulation technology for various types of analysis, such as electromagnetic field, heat conduction and thermal analysis, we were able to determine feasibility in advance and implement a design that improves product performance and reliability.

1. Introduction

Fuji Electric has developed a sealed high-voltage contactor for automotive applications that has a high overcurrent withstand capability to deal with high-output and large-capacity batteries. The contactor achieves high-capacity switching and breaking performance despite its compactness because its contacts are arranged inside a sealed capsule filled with a gas of good breaking performance.

To develop the high-voltage contactor, it was essential to carry out development in a new technological domain in addition to using the technology and know-how accumulated through previous contactors. This was done while taking into account environmental performance such as contact switching inside a capsule and products for automotive use.

At present, for electric distribution, switching and control devices, much of the range of the performance evaluation is reproducible on computers by using simulation technology(1). The simulation technology here refers to use of the finite element method for structural strength analysis, heat conduction analysis, vibration analysis, electromagnetic field analysis and computational fluid dynamics analysis. Coupling these types of analysis can reproduce complicated phenomena. Therefore, to develop the high-voltage contactor, we use simulation technology effectively to improve performance and reliability.

2. Technological Issues and Simulation Technology

Developing the high-voltage contactor involves technological issues arising from the structure of the sealed capsule, as well as miniaturization and greater reliability as an extended development of contactors.

Figure 1 shows the technological issues behind achieving various performance requirements and the corresponding analysis methods using simulation. Technological issues relating to the high-voltage contactor are diverse and there are wide-ranging analysis methods including electromagnetic field, thermal and vibration analysis.

To develop the high-voltage contactor, we employed an analysis-driven method, in which feasibility is determined by carrying out simulation in advance and prototype experiments are conducted on effectual ideas, so as to resolve these technological issues.

We compared the results obtained from prototype
experiments with the simulation results and implemented modeling and revised boundary conditions for any divergence in order to improve the simulation accuracy.

3. Examples of Applying Simulation

3.1 Improvement of short-circuit withstand capability performance by electromagnetic field analysis

To improve short-circuit withstand capability performance, some measure must be taken to prevent the contact from lifting even when a short-circuit current flows. Lifting of a contact may cause the capsule to explode due to a high current arc.

In the initial phase of development, we used electromagnetic field analysis to examine the extent of the electromagnetic repulsion for various contact structures (see Fig. 2). As a result, we confirmed that a U-shaped flat plate structure could significantly reduce the electromagnetic repulsion, and decided to use this structure for the development.

In relation to the contact structure, we used an electricity-heat transfer calculation to predict how much time it would take for the contact to melt and become welded as a result of an overcurrent, as well as electromagnetic repulsion. By conducting these simulations, we achieved a very high overcurrent withstand capability on top of the ensured minimum required contact pressure of the contact.

3.2 Improvement of efficiency of polarized electromagnets by heat transfer and electromagnetic field analysis

In the automotive field, components are required to have shock resistance and vibration resistance in addition to being small, and at Fuji Electric, the high-voltage contactor employs polarized electromagnets that use permanent magnets. The characteristics of permanent magnets vary greatly according to the temperature, and the correlation between temperature and operating characteristics need to be verified. In the automotive field, ambient temperatures are significantly higher than those in the general industrial field, and contactor temperatures tend to be higher than those for industrial applications. Accordingly, to simulate the characteristics of electromagnets, it is important to take into account the temperature dependence of electric and magnetic characteristics so as to improve the prediction accuracy.

For this development, we made it possible to evaluate the electromagnet characteristics at high temperatures by feeding the temperature of the high-voltage contactor determined by electricity-heat transfer analysis back to electromagnetic field analysis (see Fig. 3).

For heat transfer analysis, we improved the prediction accuracy of the analysis model. Figure 4 shows the relationship between inter-terminal resistance and temperature rise as shown in the results of analysis and actual measurement. We evaluated these results considering the fluctuations of resistance between the main terminals, operating coil voltage and resistance that affect the temperature into account for evaluation.

In order to confirm that performance requirements are satisfied even in the worst conditions combined,
we predicted the worst-case temperature of the operating coil and permanent magnet, which may affect the electromagnet’s characteristics. Based on these temperature results, the electric resistance of the operating coil and magnetic characteristics of the permanent magnets can be set for electromagnetic field analysis to accurately evaluate electromagnet characteristics at high temperatures.

Figure 5 shows the magnetic flux density distribution and operating characteristics of electromagnet at room and high temperatures. With the initial plan, a simulation revealed that the electromagnet operated normally at room temperature, but insufficient attractive force caused two-stage operation at a high temperature, hindering normal operation. In order to find out improvement measures, we focused attention on the magnetic flux density and attempted to optimize the cross-section area of the magnetic path of the fixed plunger, which was magnetically saturated. As a result, we successfully established a high-efficiency electromagnet capable of operating normally at high temperatures.

3.3 Improvement of vibration resistance by vibration analysis

For industrial contactors, a resonance frequency of 100 Hz or higher is generally sufficient. For automotive applications, however, the resonance frequency must be designed to be at least 200 Hz. Resonance frequency can be calculated by eigenvalue analysis. However, due to its principle, eigenvalue analysis cannot handle nonlinear problems such as the viscoelasticity of materials. The resin material used for the housing is viscoelastic, which makes it difficult to predict the resonance frequency because the modulus of elasticity may vary depending on the resin orientation as it is molded, vibration velocity, amplitude and temperature dependence. For this development, we verified the resonance frequency from the vibration test with the initial plan and calculated back Young’s modulus so that the value agreed with the calculation, thereby improving the accuracy.

Figure 6 shows a comparison of vibration responses. Figure 6 (a) shows how vibration response is brought in line with the initial structure plan with the material properties and attenuation value identified. For structural change, we took measures based on the movement of the vibration mode.

Figure 6 (b) shows the result of the final structure plan. For the initial structure plan, measures taken such as addition of ribs to the case caused the natural frequency to increase to 240 Hz, showing that vibration resistance has increased. This result shows character-
istics at room temperature and, in view of environmental temperature change as shown in Fig. 7, the final structure is determined by confirming that the resonance frequency is avoided at 200 Hz or higher.

In this way, vibration response can be predicted with higher accuracy by reliably identifying the resin material properties according to the vibration amplitude and frequency.

3.4 Quality improvement of capsule structure by thermal stress analysis

For the high-voltage contactor, how to ensure the capsule is an airtight structure is an important technological issue.

Figure 8 shows a joint of the electrode in the capsule structure. This capsule structure is composed of different materials including ceramic, copper and iron, which are joined by brazing and laser welding. This makes it necessary to evaluate in advance strength degradation and damage due to residual stress generated at the time of joining and fatigue strength under thermal stress by temperature cycling.

To conduct a strength evaluation of the joint, we estimated fatigue life by using thermal stress analysis to calculate the residual stress generated in the joint and stress amplitude of temperature cycling.

In the thermal stress analysis, we divided the analysis model into two stages for calculation. In the first step, brazing is simulated for calculation from 780°C to 25°C, within which the brazing material is solidified. Subsequently, with the stress state maintained, the models of the yoke on the top face and flange cap in the lower part of the capsule are joined together, and pressure is applied to the inside of the capsule in that condition for thermal stress analysis, with the repetition of thermal cycles during temperature cycling taken into account. By continuously calculating this entire flow, it is possible to determine accurate stress amplitude with residual stress applied. Figure 9 shows the steps of calculation and an example of calculation of the stress generated in the brazed part during the process.

Predicting the lifespan requires a comparison of the residual stress and stress amplitude obtained by the analysis with an S-N curve. For the S-N curve of the brazing material, we made a specimen with the residual stress taken into account and obtained data in a fatigue test (see Fig. 10).

Based on this result, we examined whether the residual stress and stress amplitude obtained by the analysis could satisfy the requirement of number of cycles to fracture of the specification.

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**Fig. 8** Joint of electrode in capsule structure

**Fig. 9** Example of result of thermal stress analysis
3.5 Achievement of non-polarity breaking by arc analysis

To study the behavior of arcs generated during contact switching, Fuji Electric developed arc simulation technology coupling an electromagnetic field with a thermo-fluid\(^2\), and it has been applied to many products up to now.

The high-voltage contactor has a capsule structure, which makes it much more difficult to observe an arc inside compared with other switching devices. Information obtained by measurement is confined to information such as arc voltage and arc current, and this is not sufficient to judge how an arc behaves.

With arc analysis, it is possible to make a calculation including the external magnetic field of the permanent magnet. The contact material, characteristics of the internal gas and effect of the gas generated from the material of the inside wall can all be included in the study. In addition, arc behavior can be visually judged, and this has been applied in the initial stage of development and played an important role in determining the direction of the breaking mechanism.

The high-voltage contactor carries out breaking by stretching an arc using the magnetic field of a permanent magnet to increase the arc voltage.

Figure 11 shows magnet arrangements and the stretching directions of arcs. In Fig. 11(a), the permanent magnets have parallel magnetic flux and the current flowing in through the electrode on the left stretches to the left end of the capsule according to Fleming’s left-hand rule. However, running a current in the reverse direction causes the arc to stretch to the center and a sufficient arc length cannot be obtained.

In order to allow the contactor to be used in automotive quick-charging circuits, Fuji Electric devised a magnet arrangement as shown in Fig. 11(b) so that breaking can take place regardless of the direction of the current flow. In the initial stage of development, we checked to see if a simulation could reproduce the magnet arrangements and arc stretching. Figure 12 is an analysis of breaking with the magnet arrangement shown in Fig. 11(a). The results are in close agreement with the arc voltage and arc current measured in the experiment, and we have verified that a simulation can reproduce the arc behavior.

Figure 13 shows how the principle in Fig. 11(b) for

\[\text{Fig.10 S-N curve of brazing material}\]

\[\text{Fig.11 Magnet arrangements and arc stretching}\]

\[\text{Fig.12 Example of arc analysis result with parallel magnetic field and polarity}\]

\[\text{Fig.13 Arc analysis model of non-polarity model}\]
removing polarity can be modeled. For the magnet arrangement, we used electromagnetic field analysis to examine the optimum arrangement based on the magnetic flux distribution and vector.

Figure 14 shows the result of arc analysis of a non-polarity model. The results of calculation indicate that the targeted arc length and arc voltage can be expected and the prototype experiment results have shown equivalent characteristics.

Arc analysis makes it possible to grasp arc behavior and has revealed that, for example, a different electrode shape as shown in Fig. 15 makes a difference in arc stagnation. Other findings from observing the behavior of evaporative gas include that the cause of arc restriking is an effect of stagnation of metal vapor; expanding the space in the capsule allows the metal vapor in the vicinity of contacts to diffuse; and the initial arc speed may vary depending on the difference in the intensity of the external magnetic field and in the contact material. We have realized non-polarity breaking by determining the direction of the breaking mechanism based on these simulation results.

4. Postscript

This paper has described simulation technology that supports the development of the sealed high-voltage contactor. Some representative examples have been described and, for actual development, simulation has been conducted in advance for most of the technological items in an analysis-driven manner to determine a component’s feasibility. This method is not confined to design and development but has come to be applied to the field of manufacturing technology. Greater performance of computers and software has meant many technical fields can be analyzed, but reproducing an entire product by simulation is still not realistic. Accordingly, phenomena in a specific part are picked out for calculation, and this should be thoroughly understood before using simulation.

We intend to develop simulation technology that produces more practical results so as to improve product performance and reliability.

References

Fuji Electric
Innovating Energy Technology

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