Research Report

Modeling the Surge Voltage Generation Mechanism of an Electromagnetic Clutch and a Proposed Structure for Surge Voltage Suppression

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ABSTRACT In this paper, we clarify the surge voltage generation mechanism of an electromagnetic clutch and propose a new clutch structure for surge voltage suppression. We hypothesized that the non-linear magnetization characteristics and eddy currents in the coil housing affected the surge voltage. Based on this hypothesis, we constructed a 2D FEM model of the electromagnetic clutch and carried out electromagnetic simulations. The difference between the simulation results and the measurement results were less than 5%, confirming that our simulation model was correct. Next, we proposed a new electromagnetic clutch structure for surge voltage suppression based on the 2D FEM simulations. The structure contains a metal layer with low resistivity surrounding the clutch coil and located between the coil and the coil housing. Since a change in magnetic flux passing through the coil is relaxed by flowing an eddy current in the coil housing, the surge voltage generated by the change in the magnetic flux is suppressed. We demonstrate that the proposed structure can suppress the surge voltage by more than 50% compared with that of a conventional structure.

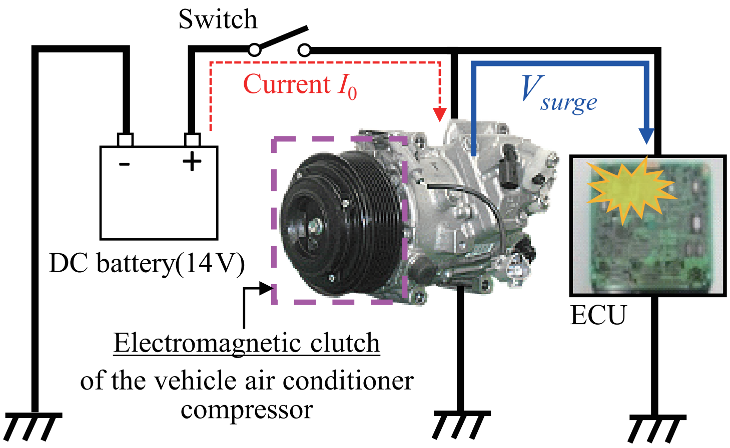
KEYWORDS Electromagnetic Clutch, Eddy Current, Electromagnetic Simulation, Non-linear Magnetic Material, Surge Voltage, 2D FEM

1. Introduction

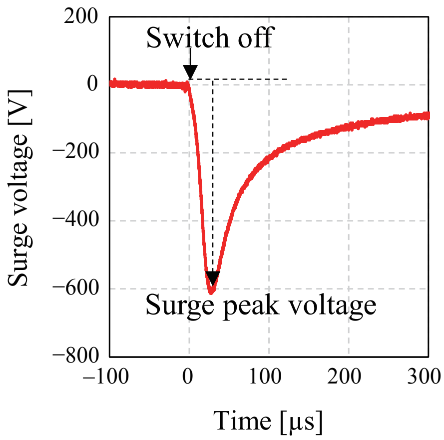
EM (electromagnetic) clutches are used as a mechanical interrupter between a vehicle's engine and air conditioner compressor. They have been used in vehicles for over 50 years, and more than 70 million are manufactured each year. The EM clutch is connected by wire to an electric control unit (ECU) and a DC battery, as shown in **Fig. 1**. The EM clutch functions as an electromagnet by passing a direct current through a coil. If the ignition switch is off when current flows into the clutch, a surge voltage of several hundred volts can be generated by the rapid change in current and magnetic flux passing through the coil. As a result, voltages exceeding the breakdown voltage can be applied to the connected ECU, potentially damaging it. Although countermeasures such as clamp diodes and snubbers have been used to prevent such damage,(1) the effectiveness of these countermeasures is insufficient for new devices. Since EM clutches have been analyzed and modeled only as mechanical components and electric circuits, the surge voltage phenomenon has not been examined to the required accuracy. A lumped model is usually used by designers of electrical equipment as an easy means of analyzing electrical behavior, resulting in circuit theory-like measures such as those described above. On the other hand, a new clutch structure based on analysis of the surge voltage generation mechanism from an electromagnetic viewpoint has not yet been proposed.

First, we hypothesized that the lumped model could not predict the surge voltage accurately because it did not consider the non-linear magnetization characteristics or the eddy currents flowing in the coil housing. To explore this possibility, we present a 2D axisymmetric finite element method (FEM) model that considers the magnetic bodies in the EM clutch. EM clutches have been modeled only as electro-mechanical actuators, with a focus on suction performance and mechanical movement.(2) However, the surge voltage, which is a multi-physics phenomenon involving electromagnetism and circuitry, has not been analyzed until now. The present model can calculate surge voltages accurately through a coupled analysis of electromagnetism and circuit theory. This approach produced results that are within 5% of the measured values.(3)

Next, we designed a new clutch structure using the above model to suppress the surge voltage. In



(a) The environment that surge phenomenon happens



(b) Actual surge voltage

Fig. 1 Electrostatic destruction of a circuit element of the ECU by a surge voltage from an electromagnetic clutch.

a parameter study based on the model, we discovered that the surge voltage can be suppressed by flowing a large eddy current around the coil. Then, a metal layer with low resistivity was placed between the coil and the coil housing in the EM clutch. By flowing a large eddy current positively in the metal layer, the time change of the magnetic flux passing through the coil is decreased, and the surge voltage is suppressed.

Finally, we fabricated the optimized structure, and experimentally verified that the proposed structure can reduce the surge voltage by more than 50% compared with that of the conventional structure.(4)

2. Modeling the Surge Phenomenon with an FEM Model Considering the Magnetic Bodies and Eddy Currents

2. 1 Limit of the Equivalent Circuit Model

Using circuit theory, the circuit shown in Fig. 1 was rewritten as the equivalent circuit shown in **Fig. 2**. The EM clutch and the ECU were modeled using linear lumped elements with L, R, and C components. These values were measured using an impedance analyzer. **Figure 3** shows the measured impedances of the EM clutch and the ECU. The surge voltage is generated in frequency bands from several kilohertz to tens of kilohertz. In this frequency band, the impedance of the EM clutch increases with increasing frequency and the phase is approximately 70 degrees, so the EM clutch can be considered as an inductor with internal resistance. Similarly, the ECU can be considered

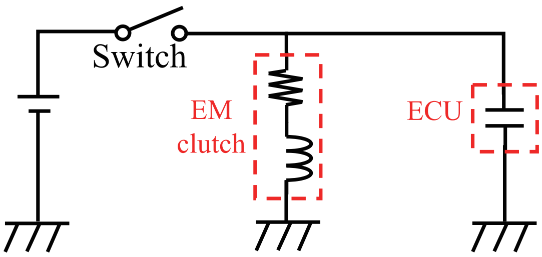


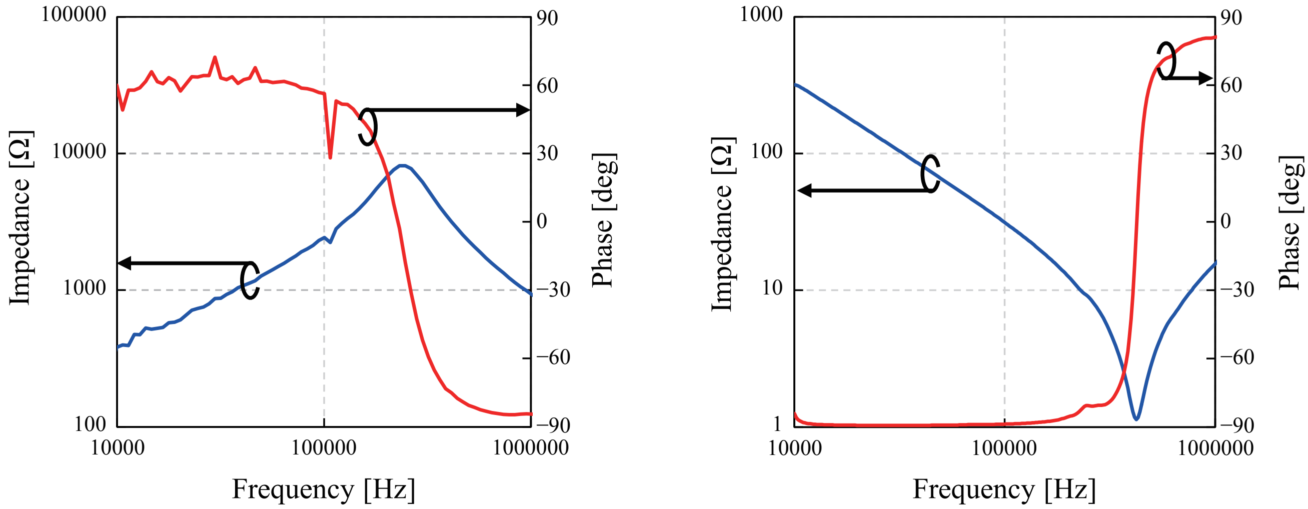
Fig. 2 Equivalent circuit for the surge phenomenon.

a capacitor in these frequency bands. The surge voltage can be calculated from this equivalent circuit. If the switch is turned off at time t_0, the subsequent surge voltage V_{surge} can be expressed as follows:

$$V_{surge} = L\frac{\mathrm{d}I(t)}{\mathrm{d}t} + RI(t) = -I_0\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}\cdot\exp^{\left(-\frac{R}{2L}t\right)}\cdot\sin\left(\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}\cdot t\right)+\frac{1}{2}RI(t) \quad (1)$$

where, $I(t) = I_0 \exp^{\left(-\frac{R}{2L}t\right)}\cdot\cos\left(\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}\cdot t\right)$.

R is the internal resistance of the inductor and I_0 is the current flowing in the circuit at time t_0. **Figure 4** shows a comparison of the surge voltage calculated using the equivalent circuit model and the measured values, revealing differences in the resonant frequency and amplitude of the surge. In this calculation, the values of L, R, and C were 5 mH, 170 Ω, and 0.1 μF,



(a) Impedance characteristics of the EM clutch (b) Impedance characteristics of the ECU

Fig. 3 Measured impedance of an EM clutch and an ECU.

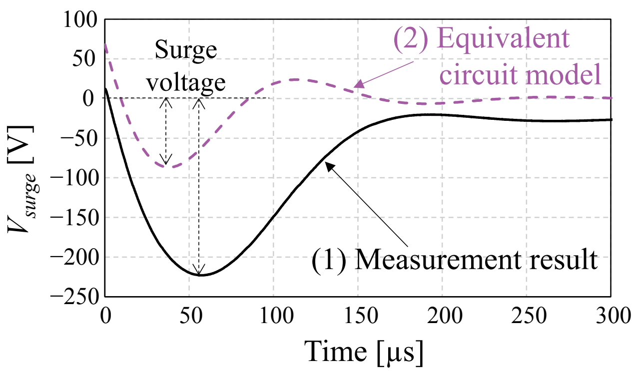


Fig. 4 Comparison of the surge voltage obtained using the equivalent circuit model and the measured values.

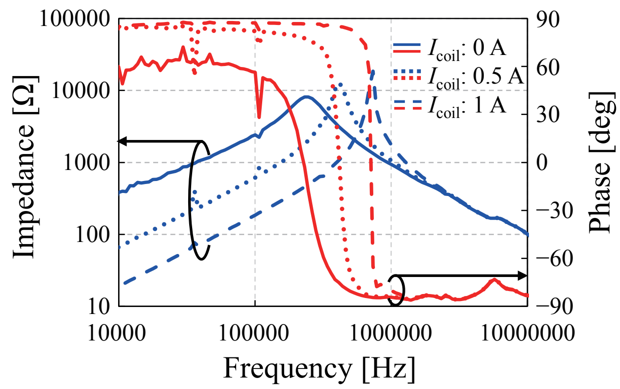


Fig. 5 Impedance characteristics of the EM clutch for various currents.

respectively. Various values of *L* and *R* were explored in an attempt to improve the agreement with measured results, but no satisfactory combination of lumped element values could be found. As a result, it was concluded that the surge behavior is not properly reproduced for any values of *L* and *R*.

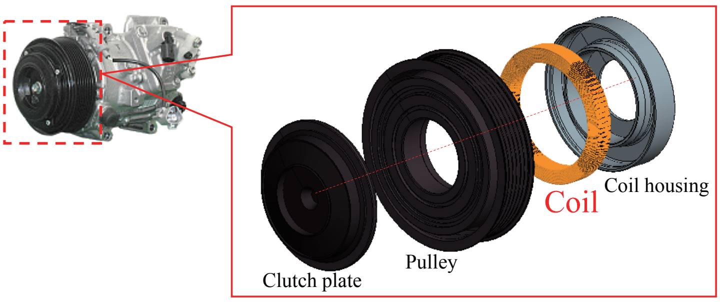
2. 2 Consideration of Eddy Currents and Non-linear Magnetization Characteristics of the Magnetic Body

We hypothesized that temporal variations in *L* and *R* are the reason why the equivalent circuit cannot reproduce the surge phenomenon. Therefore, the impedance characteristics were measured for various values of current, as shown in **Fig. 5**. It is clear that the impedance of the EM clutch decreases with increasing coil current. This phenomenon can be explained as follows. The actual EM clutch has magnetic bodies around the coil, as shown in **Fig. 6**, which include a clutch plate, a pulley, a coil, and a coil housing. These magnetic bodies are separate from the coil. When a current flows in the coil, the other magnetic bodies are magnetized by the magnetic field resulting from the coil current. The magnetization of the magnetic bodies causes the magnetic flux passing through the coil to become larger than that of an isolated coil. In addition, the magnetic flux passing through the coil is affected by the coil housing, even if the coil current supply is cut off. Since the magnetic bodies are also metal, if the magnetic flux passing through them changes, an eddy current will be generated in the magnetic bodies to prevent changes in the magnetic flux. This changes the amount of magnetic flux passing through the coil. As a result, the actual magnetic flux passing through the coil is different from that calculated from the measured inductance L and coil current I_0. For this reason, a coupled calculation considering the behavior of the electromagnetic field in the EM clutch and the circuitry of the ECU is required.

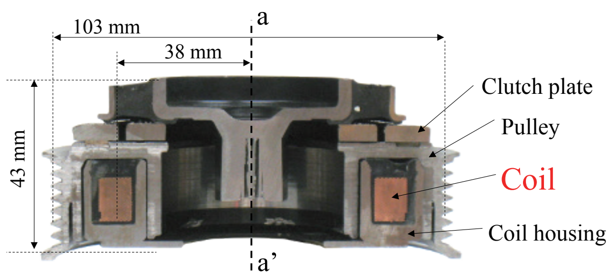
To this end, a model that can simulate the electromagnetic field in the EM clutch is proposed. As shown in **Fig. 7**(a), an FEM model in which magnetic bodies surround the coil was adopted. The model has axial symmetry along the line a-a' in Fig. 6(b). The coil consists of 260 turns of copper wire with a resistivity of 1.637×10^{-8} Ωm. The other magnetic bodies are steel, but their specific compositions were not known. Therefore, a general steel material with a resistivity of 1.34×10^{-7} Ωm was used. The eddy currents in the EM clutch and the temporal behavior of the magnetic flux can be calculated using this structural model.

First, the surge voltage was calculated under the assumption that the magnetic bodies have linear magnetization characteristics. Here, a relative permeability μ_r of 4000, which yields the linear characteristics shown in Fig. 7(b), was used. The surge voltage calculated using this model is shown as dotted line in **Fig. 8**. The figure reveals that the surge voltage obtained using the FEM model greatly exceeds the measured values when the assumption of linear magnetization characteristics is employed. The magnetic flux density distribution at the time when the surge voltage reaches its maximum value is shown in **Fig. 9**(a). It can be seen that the magnetic flux greatly exceeds 2 T, which is the general saturated magnetization of a magnetic body, and is not realistic.

Based on these results, the magnetization characteristics were changed to non-linear. The results are shown as dashed line in Fig. 8, and are clearly closer to the measured values than those obtained with the linear characteristics. The magnetic flux density distribution at the time when the surge voltage reaches its maximum value is shown in Fig. 9(b). The maximum magnetic flux density of the non-linear model is less than 2 T in the structure, which is a realistic value.

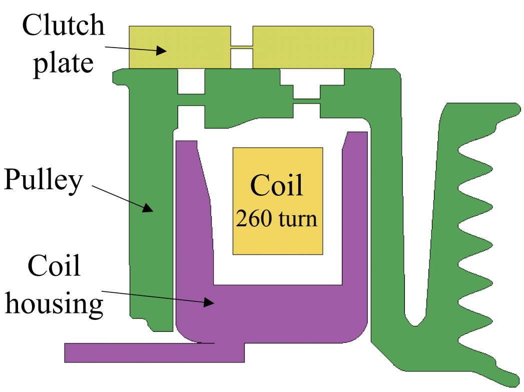


(a) Parts of the EM clutch

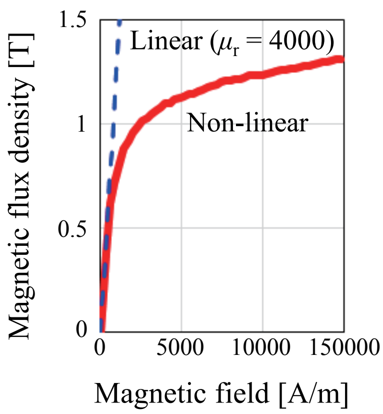


(b) Cross section of the EM clutch

Fig. 6 Constitution of the EM clutch.



(a) 2D FEM model of the EM clutch



(b) B-H curve which used in the calculation

Fig. 7 Proposed 2D FEM model of the EM clutch and B-H curve.

Therefore, it is possible to accurately reproduce the surge voltage using an axisymmetric FEM model with non-linear magnetization characteristics.

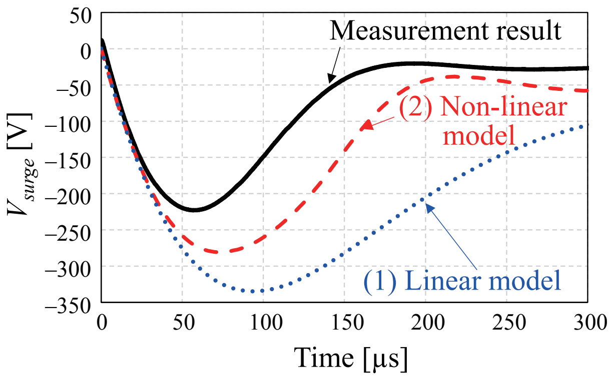
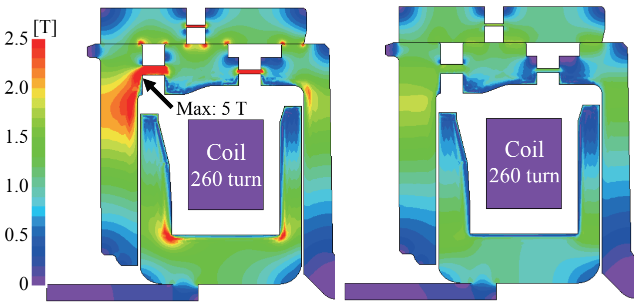


Fig. 8 Prediction of the surge voltage using the FEM model.



(a) Magnetic flux distribution: linear
(b) Magnetic flux distribution: non-linear

Fig. 9 Magnetic flux density in clutch at time of maximum surge voltage.

2. 3 Accurate Modeling of the Surge Phenomenon

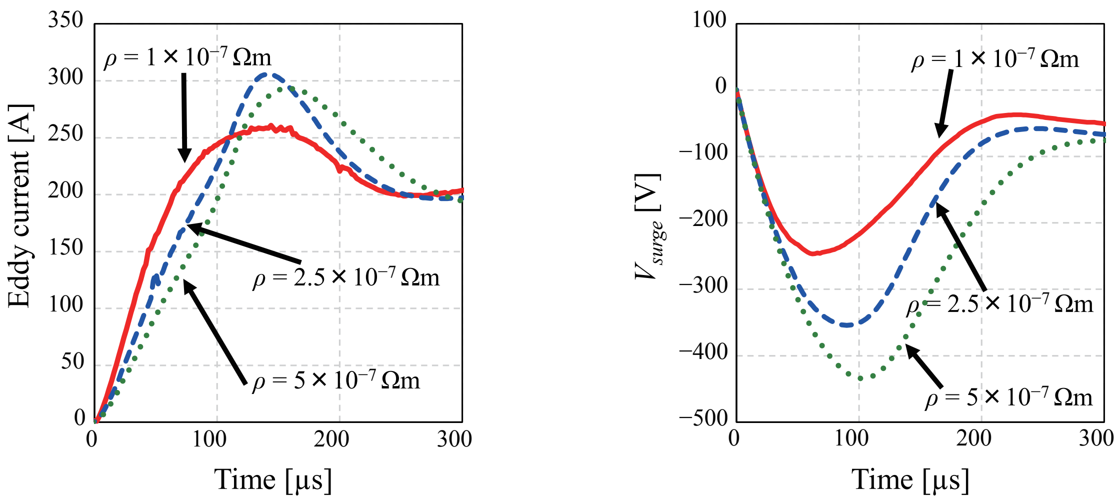
The magnetic bodies surrounding the coil are known to be steel, but the specific material properties of the steel in question are not known to a high degree of accuracy. Therefore, the surge voltage characteristics were investigated over the range of resistivity and non-linear magnetization characteristics possible for steel.

2. 3. 1 Influence of Resistivity

The resistivity of the magnetic bodies was expected to influence the eddy currents and the surge voltage. The resistivity of the magnetic bodies was varied from 1×10^{-7} Ωm to 5×10^{-7} Ωm, which is the generally accepted range for steel. In this investigation, the non-linear magnetization characteristics shown in Fig. 7(b) were used. **Figure 10** shows the resistivity dependence of the eddy current and surge voltage. It can be seen that when the resistivity is low, the eddy current increases and the surge voltage decreases. This confirms that the resistivity of the magnetic bodies influences both the eddy currents and the surge voltage.

2. 3. 2 Influence of the Magnetization Characteristics

Next, the effect of the magnetization characteristics on the surge voltage was investigated. An effect was expected because the magnetization characteristics



(a) Eddy current characteristics
(b) Surge voltage characteristics

Fig. 10 Surge voltage and eddy current characteristics for various electrical resistivities.

affect the initial magnetic flux, i.e., that before the circuit is opened. The surge voltage characteristics were investigated for three B-H curves, as shown in **Fig. 11**(a). The three materials corresponding to these B-H curves differ in their saturated magnetizations, but have similar resistivities. Figure 11(b) shows the surge voltages obtained. When the saturated magnetization is low, the surge voltage decreases and the resonance frequency increases. In turn, the initial magnetic flux passing through the coil is reduced. Therefore, the effective inductance of the EM clutch decreases based on $\Phi = LI$. This relationship is thought to be the cause of the influence on the surge voltage.

2. 3. 3 Accurate Prediction of the Surge Voltage

In conclusion, it was found that the resistivity and magnetization characteristics greatly influence the surge voltage. Based on the results obtained, the resistivity and B-H curve that yield the best fit to the measured values of the surge voltage were determined. A comparison of the measured values of surge voltage and those obtained using the proposed model is shown in **Fig. 12**. The resulting model reproduced the surge voltage data to within 5% when a resistivity of 1.1×10^{-7} Ωm and the B-H curve of steel C were adopted. It was found that the surge voltage can be quantitatively predicted by tuning the resistivity and magnetization characteristics within the realistic range for steel, even if the actual characteristics of the magnetic body material are not known to a high degree of accuracy.

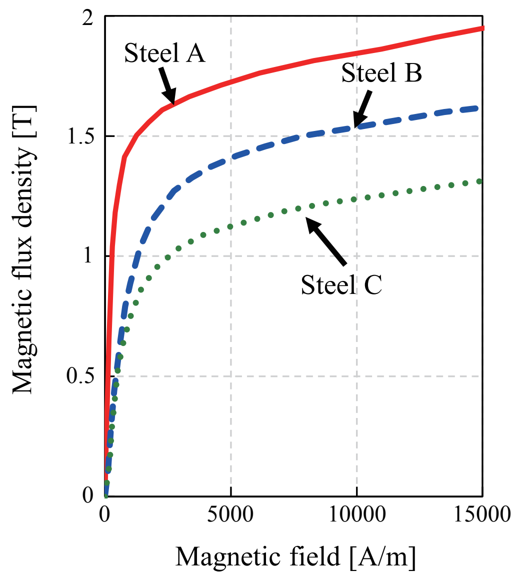
3. Proposal of a New EM Clutch Structure for Surge Voltage Suppression

3. 1 The Method of Surge Voltage Suppression

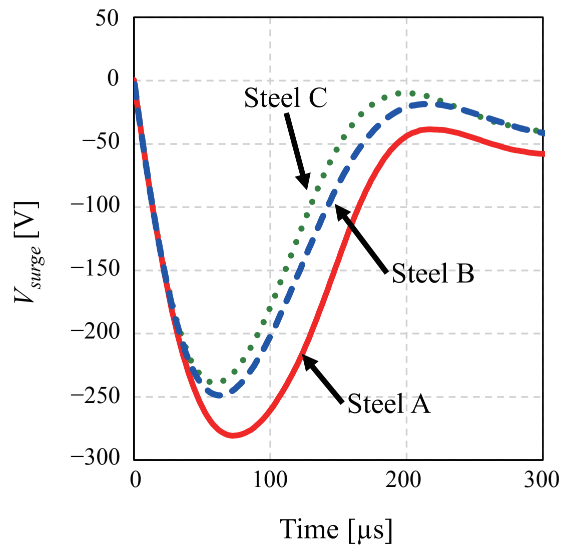
As demonstrated in the previous section, the measured surge voltage could be accurately expressed by electromagnetic FEM analysis of the EM clutch. Next, we examine the method of surge voltage suppression from an electromagnetic viewpoint, as follows:

1) First, the surge voltage V of the EM clutch is determined by the electromagnetic induction phenomenon as $V = -\mathrm{d}\Phi/\mathrm{d}t$, which is the time change of the magnetic flux passing through the coil. To suppress the surge voltage, it is necessary to make $\mathrm{d}\Phi/\mathrm{d}t$ small.

2) On the other hand, the current in the coil, which results in magnetic flux according to Ampere's law, decreases when the switch is turned off. A voltage corresponding to the electromagnetic induction is produced to disturb the change in magnetic flux, and an eddy current flows through the magnetic body around the coil. The eddy current decreases $\mathrm{d}\Phi/\mathrm{d}t$ in accordance with Lenz's law.



(a) B-H characteristics



(b) Surge voltage characteristics

Fig. 11 Surge voltage behavior for various B-H characteristics.

3) A large eddy current introduces a small dΦ/dt. In other words, the surge voltage can be reduced by increasing the eddy current because the surge voltage is equivalent to dΦ/dt.
4) Since the ease of eddy current flow is proportional to the electrical resistivity of the magnetic body, an additional metal structure that has a lower electrical resistivity than conventional magnetic bodies should be placed near the coil to suppress the surge voltage.

3. 2 New Clutch Structure for Surge Voltage Suppression

In this section, we propose an EM clutch based on the above discussion that has a structure included to suppress the surge voltage. The proposed design has a metal structure located around the coil that increases the eddy current. Hereinafter, the proposed EM clutch structure is optimized using the simulation described in Sec. 2.

3. 2. 1 Influence of the Metal Structure on the Surge Voltage

(I) Position of the metal structure

The effect of the location of the metal structure on the surge voltage was investigated by inserting a metal layer along one side of the coil, as shown in **Figs. 13**(b) through 13(e). The metal structure was 0.8 mm thick and 12 mm long, and the gap between the metal structure and the coil was 1 mm. The metal structure was made of copper with a resistivity of 1.637 × 10^{-8} Ωm. The simulated surge voltage dependence on the location of the metal structure is shown in **Fig. 14**. As shown in the figure, the surge voltages in four cases were suppressed by more than 70 V. Furthermore, it can be seen that the surge voltage with the metal structure in the “right” position was the lowest among four cases. The difference in surge voltage values among these four insertion locations was approximately 15 V. **Figures 15**(b) through 15(e) show the current density distribution for each structure at the peak surge voltage. Clearly, the eddy current is concentrated in the introduced metal structure instead of the coil housing and the pulley.

The reason for the dependence of surge voltage on the location of the metal structure was considered to be as follows. The magnetic flux Φ generated by the eddy current of the metal layer can be obtained as the surface integral of magnetic flux density B for the inside area of the metal structure:

$$\Phi = \int B \cdot \boldsymbol{n} \mathrm{d}s \,, \tag{2}$$

where B is proportional to the magnitude of the eddy current:

$$B = \frac{\mu_0}{4\pi} \cdot \oint \frac{I_{eddy} \mathrm{d}\boldsymbol{s} \times \boldsymbol{r}}{r^3} \,. \tag{3}$$

μ_0 is the permeability of vacuum, I_{eddy} is the eddy current, $\boldsymbol{s}$ is the unit vector of the eddy current, $\boldsymbol{r}$ is the distance, and $\boldsymbol{n}$ is the normal vector of the integral plane. The above equations indicate that, for the case in which the metal structure was positioned o
n the right, the magnetic flux generated by the metal layer was larger than in the other three locations. Thus, the surge voltage suppression effect of the “right” location is the strongest.

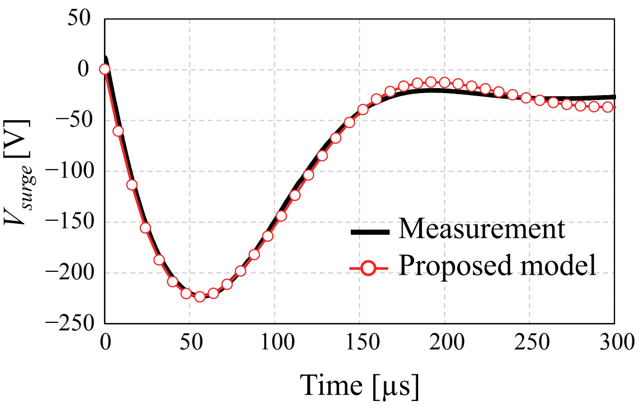


Fig. 12 Comparison of the measured values of surge voltage with those obtained using the proposed model.

(II) Case of the metal structure surrounding the coil

Based on the results described in the previous sub-section, it is natural to believe that the eddy current can be increased by placing the metal structure around the four sides of the coil, as shown in Fig. 13(f) instead of along only one side of the coil, and should therefore suppress the surge voltage even further. Figure 13(f) shows the resulting clutch design, which has copper structures on the left, right, top, and bottom of the coil. The same 1-mm gap between the copper structure and the coil was used in this case. For comparison, the surge voltage of this structure is also shown in Fig. 14(f). The structure shown in Fig. 14(f) can suppress the

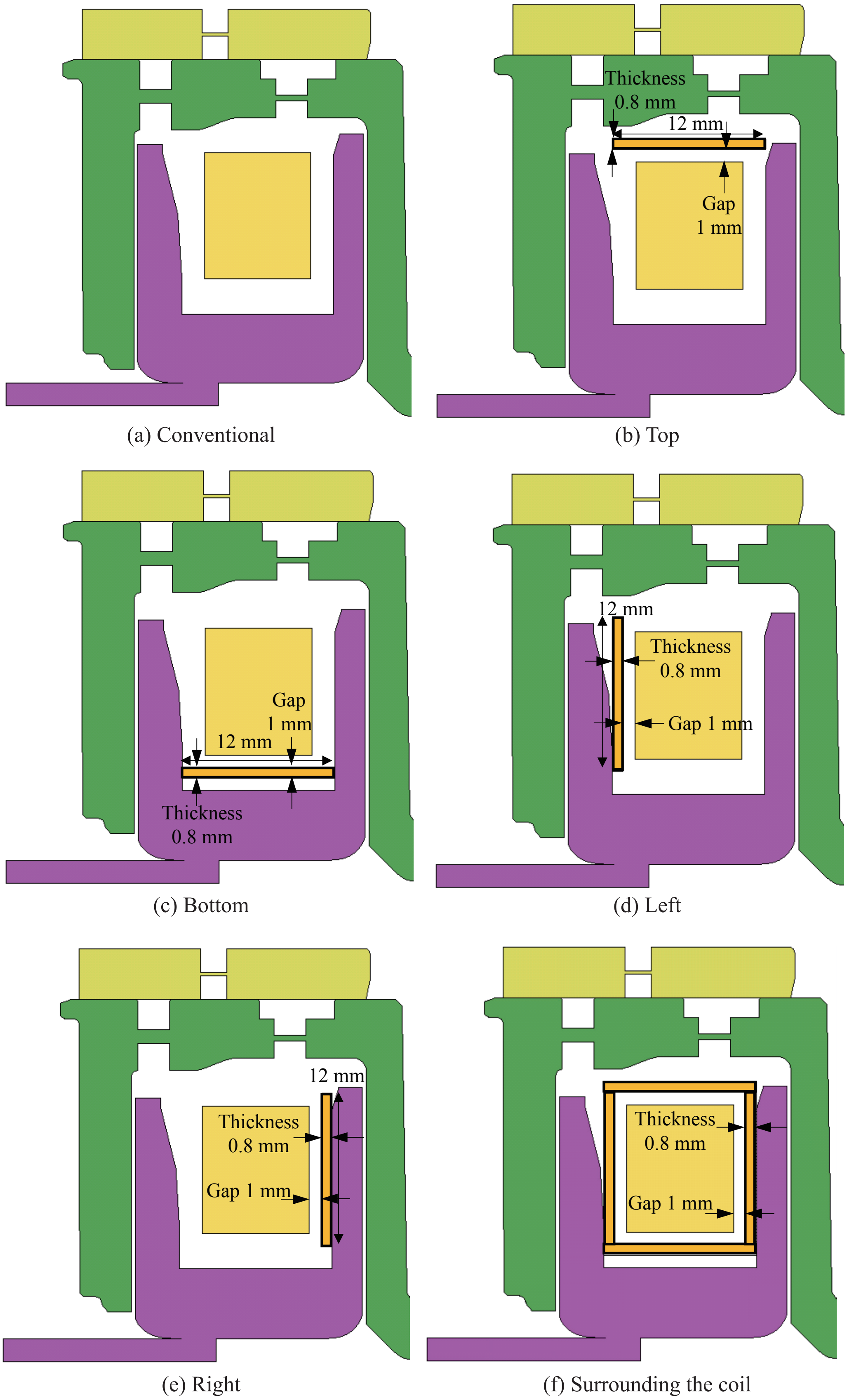


Fig. 13 Location of the inserted copper structure.

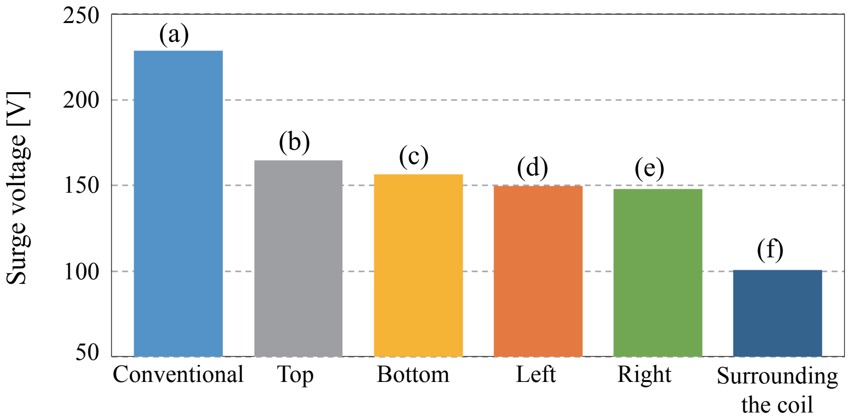


Fig. 14 Dependence of the surge voltage characteristics on the location of the copper structure.

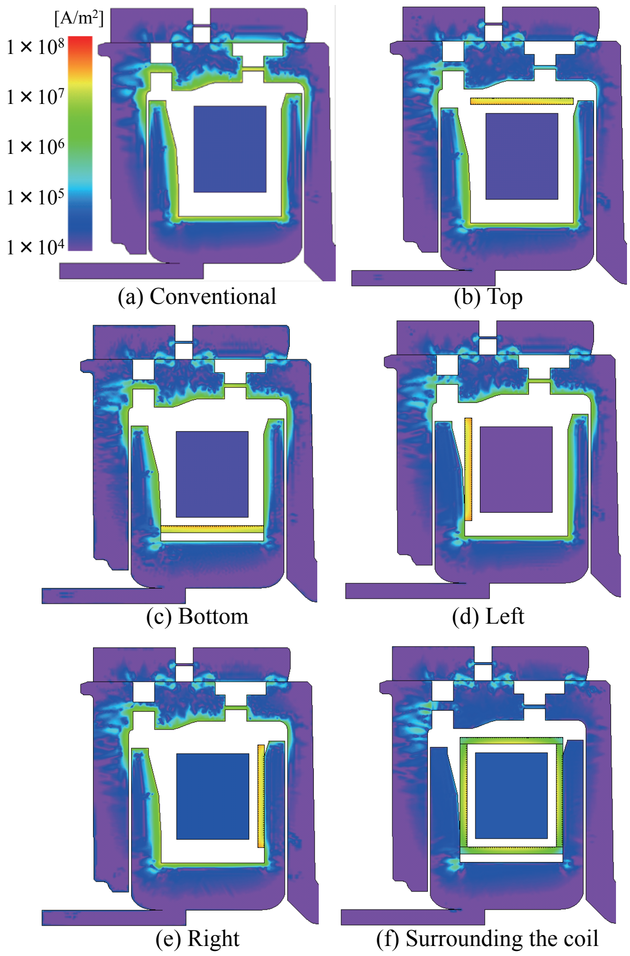


Fig. 15 Current density distribution dependence on the location of the copper structure.

surge voltage by approximately 50 V more than other the structures. The eddy current distribution is shown in Fig. 15(f). Although the eddy current density of this structure decreases in comparison with that of the structures containing a single copper structure on one side of the coil, the total eddy current increases. Moreover, in this structure, less eddy current flows in the magnetic bodies surrounding the coil.

As shown in this section, placing the metal structure on one side of the coil is effective for suppressing the surge voltage, but placing the metal structure on all four sides of the coil is even more effective.

3. 2. 2 Influences of the Thickness, Distance from the Coil, and Composition of the Metal Structure

Next, the structure shown in Fig. 13(f) was optimized. The parameters used in the optimization were (I) the thickness of the metal structure, (II) the gap between the metal structure and the coil, and (III) the composition of the metal structure.

(I) Thickness of the metal structure

The influence of the thickness of the metal structure on the surge voltage was investigated. Here, the gap between the metal structure and the coil was 1 mm, and the material was copper. The dependence of the surge voltage on the thickness of the copper structure is shown in **Fig. 16**. As the thickness of the copper increases, the surge voltage suppression effect increases. The surge voltage becomes almost constant when the thickness exceeds 0.65 mm, which is the skin depth of copper at 10 kHz.[5] Thus, the optimal thickness for suppressing the surge voltage is the same as the skin depth.

(II) Gap between the metal structure and the coil

The eddy current in the metal increases in proportion to the change in magnetic flux. Therefore, placing the metal structure closer to the coil should increase the eddy current and suppress the surge voltage because the coil is the magnetic field source. **Figure 17** shows the dependence of the surge voltage characteristics on the gap between the coil and the copper structure. The figure indicates that the surge voltage decreases as the gap becomes narrower. The results indicate that the metal layer should be placed as close as possible to the coil in order to suppress the surge voltage.

(III) Composition of the metal structure

Finally, the composition of the metal layer was investigated. The total eddy current in the metal layer is inversely proportional to the electrical resistivity of the metal. Here, copper ($\rho = 1.673 \times 10^{-8}$ Ωm), aluminum ($\rho = 2.65 \times 10^{-8}$ Ωm), and steel ($\rho = 1.1 \times 10^{-7}$ Ωm) were chosen as candidate materials for the metal structure. The dependence of the surge voltage characteristics on the resistivity of the material is shown in **Fig. 18**. As expected, the smallest surge voltage appears at the smallest resistivity. Thus, copper has the best surge voltage suppression effect among the three materials. Although the permeabilities of the magnetic body (steel) and the non-magnetic bodies (Cu and Al) differ, this has little influence on the surge voltage.

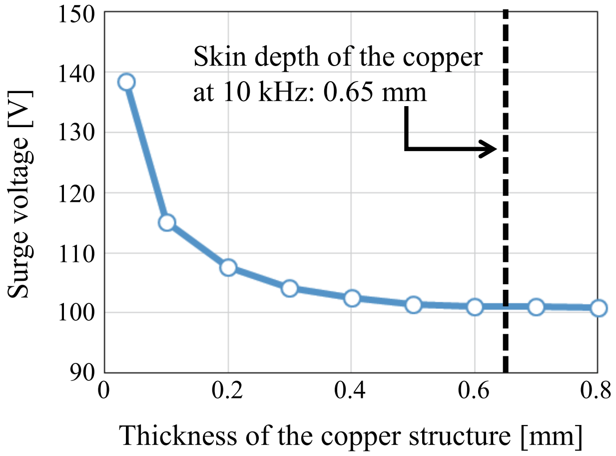


Fig. 16 Dependence of the surge voltage characteristics on the thickness of the copper structure.

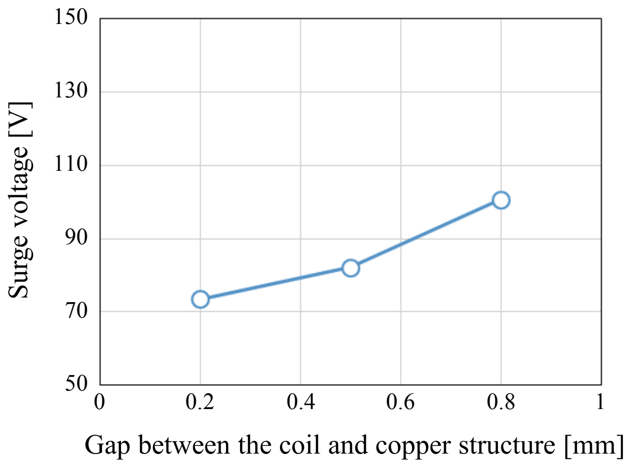


Fig. 17 Dependence of the surge voltage characteristics on the width of the gap between the coil and the copper structure.

The optimal structure for surge voltage suppression is as follows:

1) The metal layer should be placed around all four sides of the coil.
2) The metal layer should be placed as close as possible to the coil.
3) The thickness of the metal layer should be approximately equal to the skin depth at the surge frequency.
4) The resistivity of the metal layer should be as low as possible.

4. Experimental Verification of the Surge Voltage Suppression Effect

An EM clutch was fabricated with the proposed structure and the surge voltage suppression effect was experimentally verified. Cross sections of the fabricated structure are shown in **Fig. 19**. The optimized parameters obtained in Sec. 3 were used to fabricate the structure. A 0.8-mm-thick copper layer

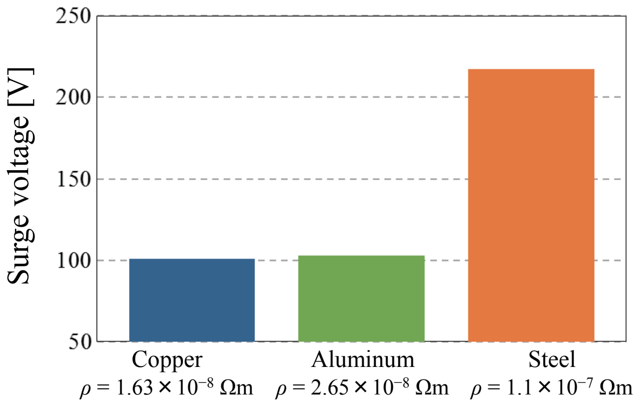


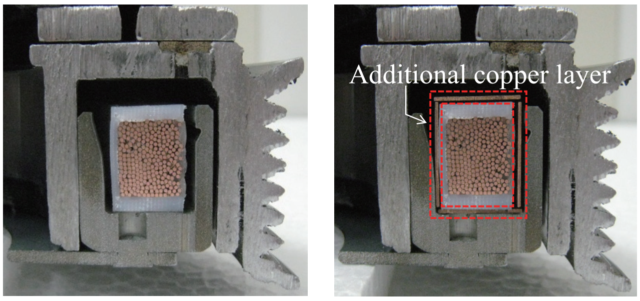
Fig. 18 Dependence of the surge voltage characteristics on the resistivity of the material.

was placed around all four sides of the coil. As a result of technical restrictions with respect to fabrication, the gap between the coil and the copper layer was 1 mm on the right and left sides and 2 mm on the top and bottom sides. The red lines in the figure indicate the copper layer. **Figure 20** compares the surge voltage characteristics of the proposed structure with those of a conventional structure. As shown in the figure, it was experimentally confirmed that the proposed structure can reduce the surge voltage by more than 50%, compared with that of the conventional structure. Furthermore, the measurement results are in good agreement with the simulation results. Therefore, the model used in the present study may be very useful for designing surge voltage suppression structures.

5. Conclusion

A model for the numerical prediction of the surge voltage generated in an EM clutch has been developed. The EM clutch was modeled as an axisymmetric FEM model that considers eddy currents and non-linear magnetization characteristics. The model can accurately predict surge voltages through a coupled analysis of electromagnetic field theory and circuit theory. An EM clutch structure with a copper layer surrounding the coil was proposed as a means of suppressing the surge voltage. Despite its simple structure, the proposed clutch was experimentally observed to reduce the surge voltage by more than 50%, compared to that of a conventional clutch.

As hybrid and electric vehicles become increasingly widespread, the proposed analytical technique and structures will likely be applied widely not only to clutches but also to other conventional mechanical devices. Therefore, this analytical technique will be useful in redesigning future vehicular devices from an electromagnetic viewpoint.



(a) Conventional structure (b) Proposed structure

Fig. 19 Cross sections of clutches fabricated for the experiment.

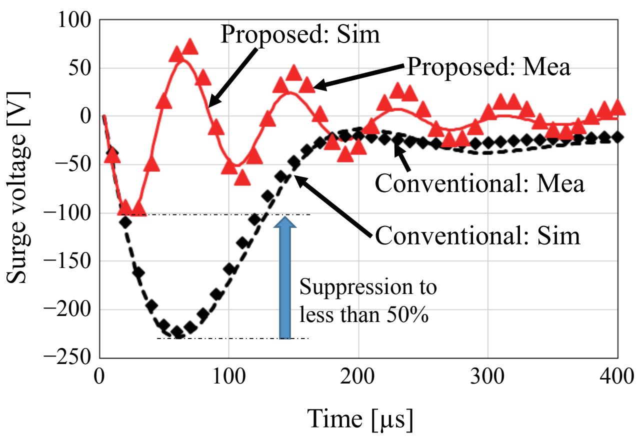


Fig. 20 Measured and simulated surge voltages of the proposed structure and a conventional structure.

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Fig. 7(a)
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