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Development of High Voltage Insulation of the Motor for BEVs, HEVs and PHEVs

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ABSTRACT: In automotive motors, high voltage driving has become the mainstream approach to achieve high output and compactness. Meanwhile, in terms of structure, motors that use rectangular coil wires are becoming more prevalent compared to those that use round wires. Given this background, capturing the differences in surge voltage due to changes in motor structure is crucial to enhancing insulation reliability. This paper examines the characteristics of surge voltage in motors with rectangular coil windings. Additionally, it presents the surge analysis results of high-voltage motors using rectangular coil wires obtained through surge voltage prediction technology developed in-house, and compares those results with actual measured values.

KEY WORDS: motor, surge, analysis method

1. INTRODUCTION

In recent years, the rapid development and spread of environmentally friendly vehicles has become necessary to address energy and environmental issues. In that context, automotive motors are required to achieve higher output and be more compact and lightweight to improve fuel efficiency[1-7].In response, motors using rectangular coil wires, as shown in Table 1, were developed and the driving voltage was increased to 650 V to achieve higher output and compactness. However, with the increase in high voltage, surge voltage also rises, making it important to estimate changes in surge voltage when considering insulation reliability[8]. Surge voltage prediction technology for motors using round wires had already been developed, and that technology is also applicable to motors using rectangular coil wires[9]. This paper examines the characteristics of surge voltage in a high voltage-driven motor with rectangular coil windings. Additionally, it presents the surge analysis results of high voltage motors using rectangular coil wires obtained through the surge voltage prediction technology developed in-house, and compares these results with actual measured values.

Table 1. Motor Specifications

		1st	2nd	3rd	4th
			P112	P410	P710
Wire type	-	Round	Round	Round	Rectangular
Output	kW	30	50	60	88
Size	L	5.1	4.7	2.7	2.5
Power density	kW/L	5.9	10.6	22.2	34.6
Voltage	V	288	500	650	650

2. CHARACTERISTICS OF SURGE VOLTAGE IN A MOTOR WITH RECTANGULAR COIL WINDINGS

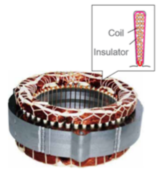
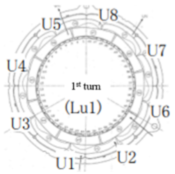
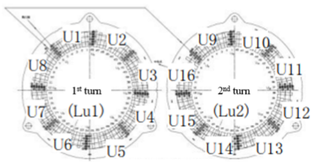
This section examines the characteristics of surge voltage in a motor with rectangular coil windings.

2.1 Overview of the Motor with Rectangular Coil Windings

Table 2 shows an overview of the motors for which surge voltage prediction was conducted, as well as their coil arrangements.

By employing rectangular coil windings, the motor achieves a reduction in overall size compared to a motor that uses round wires. Additionally, as shown in Table 2, the motor with round wires is configured with eight coils per turn, whereas the motor with rectangular coil windings is configured with sixteen coils over two turns.

Table 2. Compared Motor Coils and Sizes

	Motor with round windings	Motor with rectangular windings
Exterior		
Coil arrangement		

2.2 Comparison of Surge Voltage by Motor Structure

HEV and EV drive motors are driven by inverters and, as shown in Fig. 2, surge voltage occurs at the motor input terminals during this operation. Surge voltage is influenced by multiple factors, including overshoot during inverter switching, voltage reflections in the cable, current concentration within the motor, and resonance. Therefore, changes in motor structure also affect the surge voltage distribution. This section presents the verification and discussion of changes in surge voltage distribution due to different motor structures.

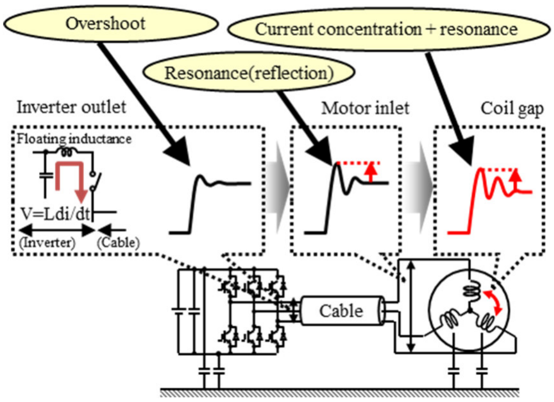


Fig. 2. Surge Voltage Mechanism

For verification, voltage waveforms at the switching instant were obtained at the measurement points shown in Fig. 3, and the results are presented in Fig. 4.

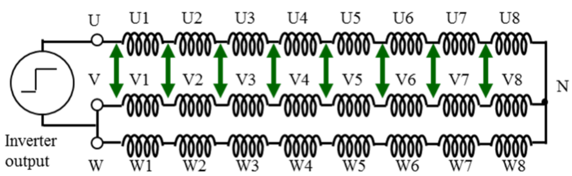


Fig. 3. Voltage Distribution Measurement Points

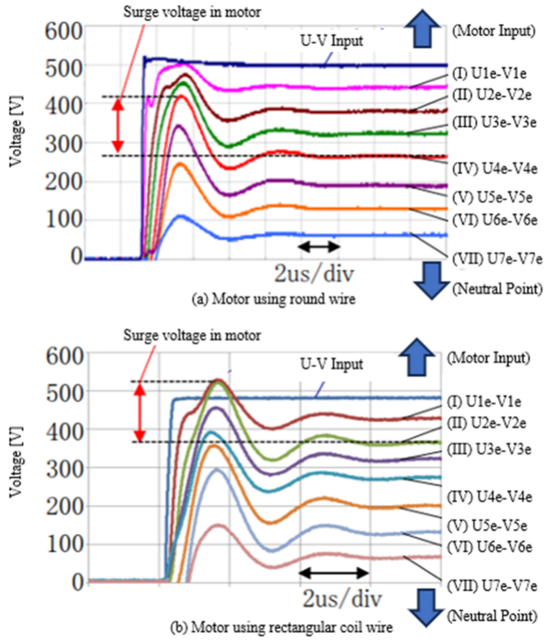


Fig. 4. Voltage Waveform Measurement Results

Additionally, Fig. 5 presents a graph displaying only the surge voltage increment extracted from the surge voltage waveform. These results make it evident that in the motor using round wires, the surge voltage increment is most significant between coils in the middle section between the motor input terminal and the neutral point. In contrast, in the motor using rectangular wires, the surge voltage between the coils in the middle section decreases, while the surge voltage increase is most prominent between coils in the surrounding areas.

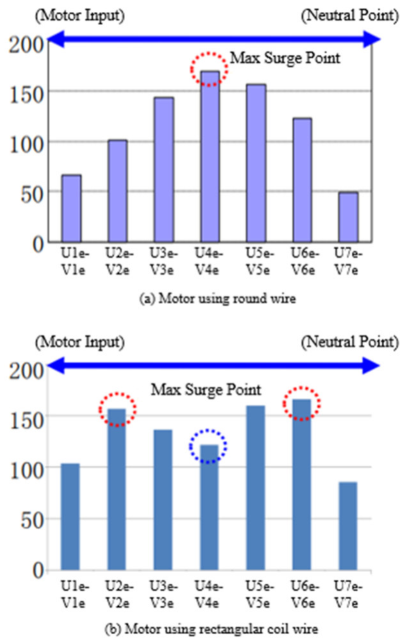


Fig. 5. Surge Voltage Distributions

Subsequently, the reasons for the changes in the surge voltage distribution were analyzed by focusing on variations in the winding structures of the two types of motors. In the motor with rectangular wires, the placement of the second-turn coils (U9–U16) creates a structure where magnetic coupling occurs between the first-turn coils (U1–U8) and the second-turn coils. As mentioned earlier, surge voltage is generated due to electrical resonance within the motor. Therefore, it is considered that the increase in magnetic coupling caused a change in the surge voltage distribution.

To investigate the relationship between magnetic coupling and resonance voltage, a voltage signal at the resonance frequency was applied to motors with different magnetic coupling conditions between the first- and second-turn coils. The resonance voltage was then calculated based on the measured voltage amplitude and phase at various locations. The measurement setup is shown in Fig. 6.

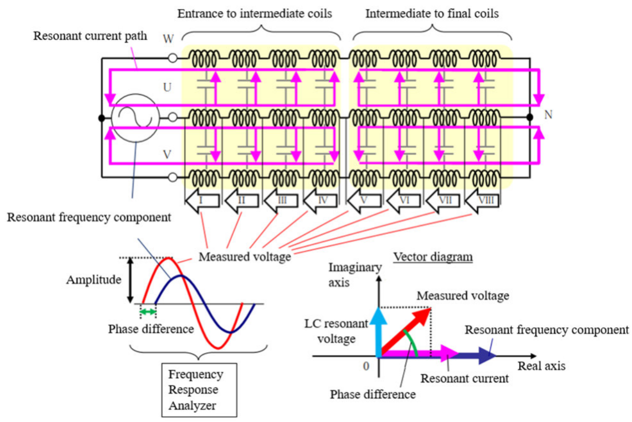


Fig. 6. Measurement Setup for Verifying Magnetic Coupling and Resonant Voltage

The measurement results are shown in Fig. 7. In the motor with round wires, where the magnetic coupling is zero, the resonant voltage monotonically decreased from the inverter side to the neutral point side, as shown in Fig. 7(a). In contrast, in the motor with rectangular wires, the increase of the coupling coefficient was accompanied by a decrease in the resonant voltage at (III)–(IV) decreased and an increase at (V)–(VI), as shown in Fig. 7(b).

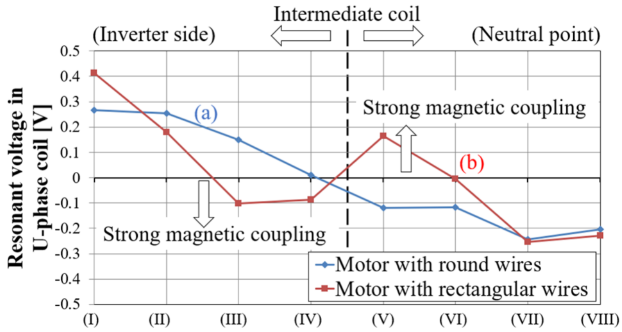


Fig. 7. Distribution of Resonant Voltage in U-phase Coil

Integrating these results from the neutral point side toward the inverter side yielded the results in Fig. 8. Note that the results in Fig. 8 correspond to the resonance voltage in reference to the neutral point.

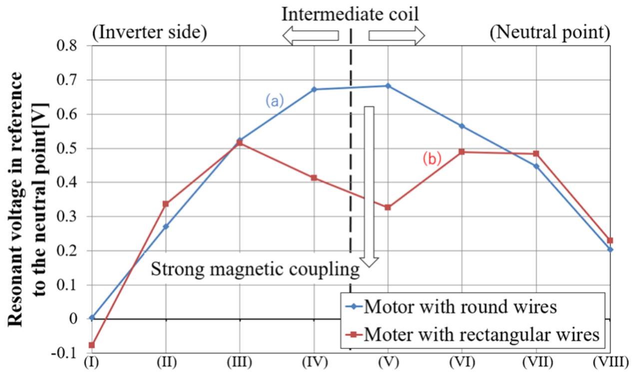


Fig. 8. Distribution of Resonant Voltage in Reference to the Neutral Point

Since the resonant voltage in reference to the neutral point is approximately two-thirds of the resonant voltage between the U-V phases, it closely aligns with the surge voltage trend observed in Fig. 5. Based on these results, the voltage distribution in the motor with round wires is considered to have changed due to LC resonance between the inlet and intermediate coils. In contrast hand, as shown in Fig. 9, the change in surge voltage in the motor with rectangular wires is attributed to the magnetic coupling between the first- and second-turn coils. This coupling causes the voltage of the first-turn coils (I)–(IV) to be transferred to the second-turn coils (V)–(VII) and vice versa, similar to a transformer. As a result, the voltage between the inlet and intermediate coils is superimposed, leading to a change in the resonant voltage distribution.

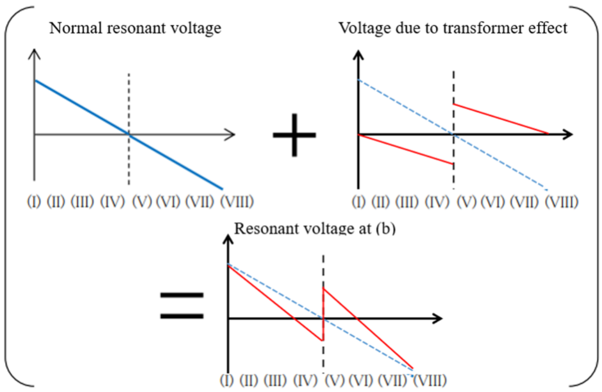


Fig. 9. Comparison of Motor Structure and Magnetic Coupling between Coils

3. SURGE VOLTAGE OF MOTORS WITH RECTANGULAR COIL WIRES

This section presents an overview of surge voltage prediction technology, along with the analysis and actual measurement results of surge voltage in motors with rectangular coil wires.

3.1 Overview of Surge Voltage Prediction Technology

As previously discussed, surge voltage between motor coils is influenced by several factors, including overshoot during inverter switching, voltage reflections in cables, and the current concentration or resonance within the motor. To predict surge voltage, we developed a computational method that relies on frequency response analysis[9,10]. This method involves the direct measurement of the frequency response function between two points of interest, as illustrated in Figs. 10 and 11, allowing the calculation of the output voltage waveform based on frequency computations.

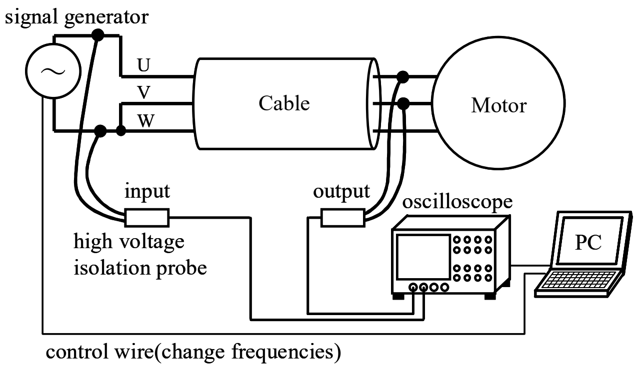


Fig. 10. Configuration for Measuring Transfer Characteristics

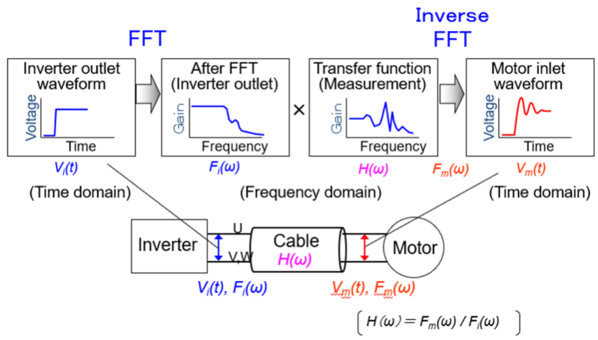


Fig.11 Mechanism for Surge Voltage Investigation Using Transfer Characteristics

Previous investigations have confirmed that this technology can predict changes in motor surge voltage caused by cables. This technology was applied to develop a predictive technique for estimating the transfer function and performing surge analysis within a theoretical framework. This technique enables the prediction of surge voltage by estimating the transfer function based on an equivalent circuit model that accounts for inductance, capacitance, and reactance between motor coils.

3.2 Comparison of Analysis Results and Measured Results

One factor contributing to the inaccuracies observed may be that the floating capacitance generated through the ground was not taken into account. The motor is connected to ground during actual operation and testing, which can result in floating capacitance. Given that a common mode path through the body may also serve as a route for high-frequency currents, it is essential to reflect floating capacitance for further improvements in accuracy.

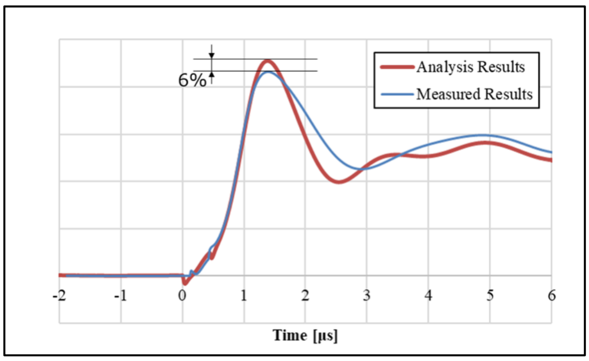


Fig. 12 Comparison between Analysis and Measurement Results

4. COUNTERMEASURES AGAINST SURGE VOLTAGE INCREASE

In recent years, the demand for higher voltages in automobiles has been increasing, leading to a predicted rise in surge voltage.

This s discusses countermeasures to mitigate the increase in surge voltage.

4.1 Methods for Improving Dielectric Strength

The dielectric strength of motor coils can be expressed by Equation (1), which is derived from Dakin's empirical formula.

$$V_p = \sqrt{2} \times 163 \times \left({}^{t}/_{\varepsilon_r}\right)^{0.46} \quad (1)$$

t: Coating thickness, εr: Lowering dielectric constant

As shown in Equation (1), two effective methods for improving coil dielectric strength are increasing the coating thickness and reducing the dielectric constant of the coating material.

In P710, polyimide (PI) was selected to achieve both improved insulation and high-temperature durability. Compared to the conventional aramid-imide (AI) material, used in P410, PI exhibits superior relative permittivity and glass transition temperature, as shown in Fig. 13. Additionally, Fig. 14 illustrates the relationship between coating thickness and dielectric strength, calculated using Equation (1). At the same coating thickness, PI improves dielectric strength by 20%. Nevertheless, the development of materials that allow for even greater coating thickness and a lower dielectric constant is becoming increasingly necessary to achieve further insulation enhancement.

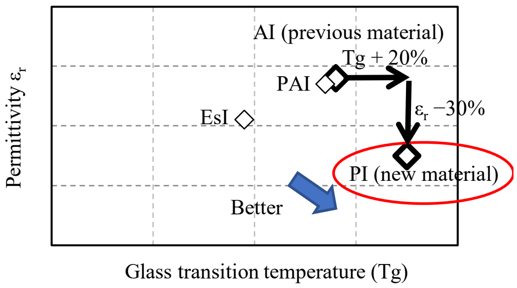


Fig. 13. Coil Coating Material

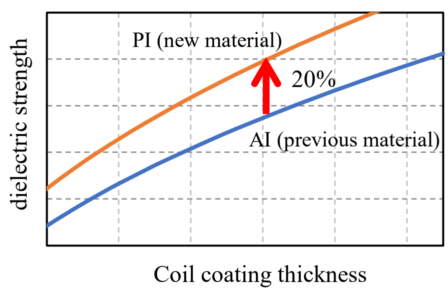


Fig. 14. Effect on Coating Permittivity Reduction

5.CONCLUSION

This paper discussed the surge voltage characteristics of a motor using rectangular coil windings. It was clearly shown that in a motor with rectangular windings, the magnetic coupling between the first-turn and second-turn coils alters the surge voltage distribution. The insulation technologies developed through HEV and PHEV research can also be effectively applied to future motor development for multi-pathway electrification.

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