Insulation Diagnosis with a Focus on Partial Discharge of the Propulsion Coils of the Superconducting Maglev

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Maglev train systems require a high number of ground coils which are installed in the open over extended periods of time. Efficiency is therefore crucial for the maintenance of these ground coils in operation. When Maglev vehicles are running, a high voltage is applied to propulsion coils. Insulation diagnosis methods have been designed to detect partial discharge, which is a predictor of insulation failure in the propulsion coils [1], [2]. This paper describes the development of a partial discharge generation test specimen to evaluate insulation performance, and examination of electromagnetic wave propagation involved in partial discharges.

Keywords: superconducting Maglev, propulsion coils, insulation diagnosis, partial discharge

1. Introduction

Superconducting Maglev systems require a large number of ground coils which are installed along tracks. The ground coils are employed in specific conditions, such as outdoors and vibration and high-voltage environments. Accordingly, the ground coils need to have excellent environmental resistance, vibration resistance, and good insulation performance. In addition, when developing the ground coils, it is necessary to reduce manufacturing cost and achieve high performance.

The ground coils comprise a levitation-and-guidance coil and a propulsion coil. The levitation-and-guidance coil gives Maglev vehicle a vertical force and crosswise-direction force, while the propulsion coil produces the force which propels the vehicle forward. Proper voltage is applied to the propulsion coil when a vehicle runs because of its electric current and the counter electromotive force produced by passing the superconducting magnets.

Insulation diagnosis methods focusing on partial discharge were verified. Discharge can be used as physical indicator to predict insulation failure in the propulsion coils. A partial discharge generation test specimen was therefore developed to evaluate insulation performance, and examine electromagnetic wave propagation involved in partial discharges from the propulsion coil.

2. Ground coil insulation failure

2.1 Ground coil structure

The ground coil is an air core coil that has no iron core. The coil winding is integrally molded with resin to increase rigidity. Ground coils comprise a levitation-and-guidance coil and a propulsion coil. Epoxy resin is used for molding in the propulsion coils used in high-voltage environments. Glass reinforced fiber resin is used for molding the levitation-and-guidance coil, which requires mechanical strength and durability.

2.2 Role of propulsion coils

A number of propulsion coils are connected in series along a guideway to form a feeding section. If propulsion coils within a specific span are unable to energize, the vehicle cannot obtain sufficient propulsion. On the other hand, the levitation-and-guidance coil forms a dependent electrical closed circuit with two coils on both sides of the guideway. Therefore, obviously, the effect of one propulsion coil failure is much greater than that of one levitation-and-guidance coil. The faster a Maglev vehicle runs, the higher the propulsion coil voltage because of its electric current and counter electromotive force generated when passing the superconducting magnets. Therefore, the propulsion coil needs to be considered in the same way as general high-voltage equipment.

2.3 Propulsion coil insulation abnormality

Partial discharge is a small dielectric breakdown phenomenon that occurs in the void inside the mold resin insulation of the propulsion coil. Even if the partial discharge is slight at the initial stage, the occurrence of repeated partial discharges leads to expansion of breakdown points, and finally leads to dielectric breakdown of the molding resin of the propulsion coil. We therefore use partial discharges measurement as a method for evaluating the insulation performance of propulsion coils. The insulation abnormalities assumed for a propulsion coil are as follows:

(1) Void in mold resin

When integrally molding coil winding with resin, voids may remain in the mold resin mixed with various compounding materials. The relative dielectric constant of the inherent void in the mold resin is different from that of the
mold resin. Therefore, when a voltage is applied to mold resin containing voids, the electric field concentrates on the void which may cause partial discharges.

(2) Peeling between the resin and the conductor coil
In the propulsion coil, the interface between the winding coil and the mold resin is bonded. However, as propulsion coils are used outdoors and exposed to temperature changes and repeated electromagnetic vibration surface exfoliation between mold resin and coil conductor may occur forming gaps. Spaces between the resin and the conductor coil may generate partial discharges.

(3) Incorrect installation of propulsion coils
Incorrect connection of the propulsion coil and the coil-to-coil cable may cause abnormalities in the insulation.

3. Development of partial discharge test specimen

In the proposed diagnostic method, the evaluation index is the maximum partial discharge charge amount generated at a specific occurrence frequency (number of occurrences per second). However, the relationship between this index and the long-term insulation performance of the propulsion coil has not been fully confirmed. One of the purposes of this study was to apply the maximum partial discharge charge as a quantitative evaluation index of propulsion coil insulation degradation. We examined the necessary parameters for this quantitative evaluation, and manufactured a partial discharge generation specimen. The results are shown below.

3.1 Examination of parameters

There are a number of issues relating to the production of a partial discharge generation test specimen, which are described here:

(1) Control of partial discharge
Research on how to embed insulation defects into the propulsion coil has been conducted but so far there has been little success in manufacturing them whilst also controlling the partial discharge charge amount.

(2) Visualization of defects
The molding resin of the propulsion coil is mixed with a filler. For this reason, the internal state in the molding resin cannot be confirmed after molding.

(3) Partial discharge generation voltage
The partial discharge generation voltage of the specimen manufactured so far was as high as the voltage used for the actual propulsion coil. If the partial discharge voltage can be lowered, the required capacity of the test equipment can be reduced, and the test can be performed in a narrower space.

(4) Securing test specimen
In order to obtain the correlation between the partial discharge charge amount and the evaluation index of the insulation performance, it is necessary to secure a certain number of models.

3.2 Control of partial discharge

The partial discharge charge $Q$ is given by Equation (1), assuming a capacitance $C_s$, voltage drop $V_s$, discharge start voltage $V_s$, and the discharge extinction voltage $V_e$ (where $V_s > V_e$).

$$Q = C_s (V_s - V_e) = C_s V_s \Delta V_s$$ (1)

In Equation (1), $V_s$ is generally higher than the breakdown voltage $V_e$ of the discharge, and $V_e$ is considered to be lower than $V_s$. There are some problems when calculating $Q$. First, partial discharge does not occur immediately when the voltage applied to the void exceeds $V_e$. Conversely, partial discharges can occur even at an applied voltage not exceeding $V_e$. All the charge stored in the void is not completely discharged. This is because the partial discharges phenomenon occurs probabilistically and the breakdown voltage varies depending on the minute shape of the void. Next, when manufacturing a propulsion coil, the size of the internal defect in the void cannot be estimated. In addition to $\Delta V_e$ in Equation (1), $C_s$ is also an unknown, and the partial discharge charge measurement result is the product of the two unknowns. Therefore, if the shape of the void is not known, it is difficult to evaluate the insulation performance by the partial discharge amount. However, if a partial discharge specimen with a simplified defect can be produced, the shape of the defect becomes a known parameter. It is considered that the partial discharge amount can be controlled to some extent.

3.3 Shape of defect

In order to control the partial discharge, we developed a partial discharge generation test specimen with a simply shaped defect (hereafter, referred to as pd test specimen). The overall shape of the pd test specimen is shown in Fig. 1, and the specifications are described below. Two kinds of defects were embedded between the electrodes which were spaced at a distance of 5 mm in the pd test specimen. One of the defects was a pre-made void. The other was a perforated flat plate assuming a partial discharge charge of about 100 pC.

(1) Resin mold
Shape: Square prism shape
Dimensions: 60 mm x 60 mm x 110 mm
Material: Epoxy resin

(2) Electrode (voltage application side)
Shape: Cylindrical
Dimensions: φ25 mm x 70 mm
Material: Brass

(3) Electrode (ground side)
Shape: Cylindrical
Dimensions: φ25 mm x 52.5 mm
Material: Brass

(4) Shape of defect
(a) Pre-made void
Resin block containing pre-made void of about 2 mm in diameter buried between the electrodes.

(b) Flat air gap (processed hole)
Figure 2 shows the shape of the processed hole. A hole with a diameter $B$ of 2 mm was formed in a pre-made plate
with a thickness C of 2 mm was cut into a block shape and fixed between the two electrodes. After fixing this plate, the hole was covered with another plate of the same shape.

(c) Standard model (for comparison)

For comparison, a test specimen without defects was manufactured.

![Fig. 1 Overall shape of the pd test specimen](image)

**Fig. 1** Overall shape of the pd test specimen

**Table 1** Type of partial discharge model

| Specimen number | Type          | Number |
|-----------------|--------------|--------|
| 1, 2            | Pre-made void| 2      |
| 3, 4            | Flat air gap | 2      |
| 5, 6            | Standard model| 2     |

![Fig. 2 Shape of processed hole](image)

**Fig. 2** Shape of processed hole

3.4 Results of experiments

Table 1 shows the type and number of the manufactured partial discharge specimens. Figures 3 and 4 show the appearance of the defect. Until now, it has been difficult to confirm the state of the defect in the mold due to the influence of the filler. In the developed pd test specimen, since no filler was mixed, it was possible to visualize the defect.

![Fig. 3 Appearance of pre-made void model](image)  
Fig. 3 Appearance of pre-made void model

![Fig. 4 Appearance of perforated flat air gap (processed hole) model](image)  
Fig. 4 Appearance of perforated flat air gap (processed hole) model

3.5 Summary of pd test specimen

A pd test specimen was developed to evaluate the insulation performance of ground coils. Although the discharge charge amount could not be controlled, sufficient results were obtained while lowering the generated voltage and it was possible to visualize the defect.

4. Propagation of electromagnetic wave generated by partial discharge of propulsion coils

In order to gain greater quantitative insights, the intensity of the electromagnetic wave generated by the partial discharge inside the mold resin was examined.

4.1 Discharge current

Assuming that there was a flat gap inside the mold resin of the propulsion coils, the discharge current generated in this gap was calculated [3]. The capacitance C of the flat air gap is given by (2).

\[
C = \epsilon_0 \epsilon_r \frac{S_j}{D_j} \frac{S_j}{D_j} 
\]

(2)

\( \epsilon_0 \): Dielectric constant of vacuum \((= 8.854 \times 10^{-12} \text{ [F/m]}) \),  
\( \epsilon_r \): Relative permittivity of air gap \((= 1.001) \),  
\( S_j \): Cavity area,  
\( D_j \): Cavity length
Next, each physical quantity such as charge amount was expressed quantitatively as follows:

\( t: \text{time}, \ i(t): \text{discharge current}, \ \nu(t): \text{voltage}, \ q(t): \text{charge amount}, \ Q_0: \text{initial discharge charge}, \ k: \text{spark constant}. \)

Hence, the relationship with capacitance \( C \) is given by Equations (3) to (6).

\[
\begin{align*}
\nu(t) &= k D_q q(t) \quad (3) \\
i(t) &= \nu(t) i(t) \quad (4) \\
\nu(t + \Delta t) &= \nu(t) - i(t) \times \Delta t / C \quad (5) \\
q(t + \Delta t) &= q(t) + i(t) \times \Delta t \quad (6)
\end{align*}
\]

For Equations (3) to (6), the initial values were \( \nu(0) = V, \ i(t) = 0, \ q(0) = Q_0 \) for the charge \( q(t) \) and the discharge current was calculated repeatedly until voltage \( \nu(t) \) reached the discharge extinction voltage \( V_E \). The calculated results of the discharge current under the conditions shown in Table 4 are shown in Fig 5. It can be seen that the discharge is generated up to about 3 ns, and the smaller the gap, the shorter the discharge time and larger the maximum discharge current. Results suggested that the smaller the gap, the lower the discharge resistance.

**Table 4 Discharge current calculation conditions**

| Item                        | Condition          |
|-----------------------------|--------------------|
| Cavity temperature [°C]     | 80                 |
| Cavity length \( D \) [mm]  | 0.6, 1.0, 1.5, 2.0, 2.5, 3.0 |
| Discharge start voltage \( V_s \) [kV] | 2.9, 4.2, 5.7, 7.2, 8.5, 9.8 |
| Discharge extinction voltage \( V_E \) [kV] | 0 |
| Discharge charge \( Q \) [pC] | 100               |
| Initial discharge charge \( Q_0 \) [pC] | 0.5               |
| Spark constant \( k \) [\( \Omega \cdot \text{C/m} \)] | \( 1 \times 10^{-7} \)  |
| \( \Delta t \) [s]          | \( 1 \times 10^{-12} \) |

### 4.2 Frequency characteristics of electric field strength

The discharge current waveform calculated in the previous section was subjected to a discrete Fourier transform at 10000 points between 0 and 10 ns. Using the Fourier amplitude of the current, the electric field strength \( E \) at a location 1 m away from the location where the partial discharge occurred was calculated using (7).

\[
E = \sqrt{\mu_0 / \varepsilon_0} I / l / 2 \lambda r = 60 \pi I / l / \lambda r \quad (7)
\]

\( \mu_0: \text{vacuum permeability}, \ I: \text{current}, \ l: \text{length}, \ \lambda: \text{wavelength (} = c / f, \ c: \text{speed of light,} \ f: \text{frequency}), \ r: \text{distance (} = 1 \text{ [m]}) \)

Figure 6 shows the frequency characteristics of the electric field strength obtained by Equation (7). Figure 6 shows that the frequency at which the electric field strength peaked was between 300 and 500 MHz. On the other hand, the larger the gap \( D_g \), the greater the maximum value of the electric field strength and the lower the generated frequency.

### 4.3 Relationship between distance and antenna reception induced voltage

First, the discharge current waveform calculated in Section 4.1 was subjected to a discrete Fourier transform at 2000 points between 1 ns before and after the maximum value. The detection frequency of the electromagnetic wave associated with the partial discharge was set to 500 MHz, and the intensity was calculated. In the calculation, \( f = 5 \times 108 \text{ [Hz]} \) was substituted into Equation (7). Next, the induced voltage \( V \) was calculated using Equation (8) for the case where the half-wavelength dipole antenna received electromagnetic waves with the calculated electric field strength.

\[
E = \sqrt{\mu_0 / \varepsilon_0} I / l / 2 \lambda r = 60 \pi I / l / \lambda r \quad (8)
\]

\( l_e: \text{effective length of antenna (} = \lambda / \pi) \)

Figure 7 shows the relationship between the distance from the partial discharge occurrence point to the antenna and the induced voltage. From the figure, it can be seen that the induced voltage increased as the gap \( D_g \) increased. This was because the induced voltage was proportional to the discharge current and the gap size.
4.4 Summary of electromagnetic wave propagation

The discharge current at the time of partial discharge generation inside the mold resin was calculated. Using the calculated result, the antenna reception induced voltage of the electromagnetic wave generated by the partial discharge was calculated. The results confirmed the antenna reception characteristics of the electromagnetic waves accompanying partial discharge. Note that in this chapter, propagation loss or directivity is not considered because we aim to qualitatively understand the electromagnetic wave intensity.

5. Electromagnetic wave detection test at high speed

The investigations to this point were to find an efficient diagnostic method that detected electromagnetic waves generated by partial discharges inside the propulsion coil generated when the propulsion coil of Maglev system deteriorated on a running vehicle. However, the performance of this method was tested and confirmed whilst the vehicle was stationary or running at low speed [1], [4], but not at high speed. Further tests are therefore planned employing the test bogie used for current collection at the test facility at RTRI and equipped with an electromagnetic wave receiver, in order to capture electromagnetic waves from the ground discharge power source while the test bogie is running at high speed. Prior to this test, electromagnetic waves were measured at the current collection test facility.

5.1 Ground measurement of electromagnetic waves of running test bogie and tow vehicle

A half-wave dipole antenna (for 500 MHz measurement) was installed about 1 m away from the end of the guideway of the current collection test facility, and at a height of about 1 m. Electromagnetic waves were measured when test bogie or towing vehicle passed in front of the half-wave dipole antenna. The results are shown in Fig. 8, and confirm that no electromagnetic waves other than those from the onboard data transmission radio telemeter (169 MHz) mounted on the test bogie were generated from the test bogie and the towing vehicle.

5.2 Onboard measurement of electromagnetic waves at low speed

A half-wave dipole antenna (for measurement at 500 MHz) was temporarily installed on the test bogie, and the environmental electromagnetic waves of a tow vehicle running at low speed and the electromagnetic waves of an air discharge power source beside the guideway generating sparks, were measured. Figure 9 shows the measurement results while Figure 10 shows the test set up. Figure 9 shows that the intensity of the electromagnetic wave from the ground discharge power source was significantly larger that the intensity of the environmental electromagnetic wave. Therefore, by setting the trigger level of the measuring instrument appropriately, it was found that it is possible to automatically measure the electromagnetic waves from the simulated discharge source on the ground.
6. Summary

Partial discharge test specimens were produced to quantitatively evaluate insulation abnormalities in Maglev propulsion coils. The propagation of electromagnetic waves generated by the partial discharge of the propulsion coils was also investigated. The results are summarized below:

(1) From the partial discharge charge measurement results of the manufactured pd test specimens, it was confirmed that using the models, the generated voltage can be lowered and defects can be visualized.

(2) The discharge current when partial discharge occurs in the mold resin was calculated, and the antenna reception induced voltage of the electromagnetic wave generated by the partial discharge was calculated based on the calculation result.

(3) Using the current collection test facility, the electromagnetic wave under the running environment of the facility was measured prior to the test to detect the electromagnetic wave from the ground discharge power source while a test bogie was run at high speed. As a result, it was found that it is possible to automatically measure the electromagnetic waves onboard from the simulated discharge source on the ground.

Future work aims to manufacture and test the partial discharge models for more accurate evaluation of insulation performance, analyze detailed electromagnetic wave propagation with reference to the calculation results of discharge current when partial discharge occurs, and conduct electromagnetic wave detection tests using the test bogie at high speed.

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