

Influence of Inverter Surge Voltage Waveform and Environmental Change on Partial Discharge Phenomena in Automobile Main Motor Magnet Wire

Makoto KUBOTA¹Yuta ITO¹Takeshi YANAGISAWA¹Yoshito TSUKAMOTO¹Riku INABA²

ABSTRACT

Evaluation was conducted of the partial discharge inception voltage resulting from inverter surge voltage in the magnet wire, also known as winding wire, of the main motor used in an electric-powered vehicle.

Having clarified the influence of the waveform on partial discharge, the voltage waveform used for evaluation was configured to include waveform conditions under which partial discharge is most likely to occur during operation of the inverter in an electric-powered vehicle. With use of the inverter surge voltage, it was found that the partial discharge inception voltage rose 22% higher than the usual sine wave voltage. Envisioning the environment in which the main motor would be used, the influence of the environmental factors of ambient temperature, atmospheric pressure, and relative humidity on the partial discharge phenomena was also clarified. The use of inverter surge voltage for evaluation based on the above results yields the expectation that a rise in the partial discharge inception voltage can be expected. It also indicated that insulation design that takes the influence of the environmental factors into consideration can contribute to a reduction in the thickness of the insulation film.

1. Introduction

In light of the heightened awareness of environmental issues in the world in recent years, the electrification of automobiles has advanced rapidly. In Japan, the hybrid electric vehicle (HEV) began to rise in popularity as an electric-powered vehicle from the late 1990s. Because of demand for further reduction of environmental impact, popularity is presently shifting to the battery electric vehicle (BEV), which can use renewable energy. The performance of the main motor in this kind of electric-powered vehicle has an influence on the vehicle's cruising range, so raising motor efficiency to a high level is particularly desirable.

For that reason, many studies are underway⁽¹⁾ into methods for suppressing the motor losses from iron loss and copper loss, which are factors that diminish motor efficiency. It is possible to suppress copper loss in the main motor magnet wire by increasing the cross-sectional area of

the conductor, thereby lowering the resistance of the magnet wire. Recently there have been instances of approaches that reduce the relative permittivity of the magnet wire by introducing minute air bubbles into the insulation film on the wire, thereby making the film as thin as possible so as to increase the copper filling factor of the magnet wire slot^{(2),(3)}. However, making the insulation film on the motor magnet wire thinner than necessary reduces the insulating properties of the magnet wire, and partial discharge ends up occurring. The occurrence of partial discharge causes erosive wear of the insulation film surface, which ultimately lowers its insulation performance⁽³⁾. It is necessary, therefore, to accurately grasp the partial discharge inception voltage (PDIV) in the magnet wire specifications for that motor and design it so that partial discharge does not occur. Also, given the characteristics of the main motor magnet wire in an electric-powered vehicle, the magnet wire is used under the environmental conditions of the circumstances in

¹ Honda Motor Co., Ltd.

E-mail: makoto_kubota@jp.honda

² Auto Technic Japan Co., Ltd.

which the vehicle is used. During high load operation, the temperature will rise, and in areas at high elevations, the atmospheric pressure will be lower. The influence that such environmental changes have on partial discharge also needs to be taken into consideration when studying ways to assure the insulation.

With the main motor of an electric-powered vehicle, the direct current voltage supplied from the batteries is converted into an intermittent pulse wave voltage by high-speed switching of the inverter devices, and that voltage is applied. As the voltage rise of that pulse wave voltage is steep, the surge voltage is superimposed on the pulse wave voltage from the inverter and is applied to the main motor input terminal as an inverter surge voltage. In PDIV evaluation of magnet wire, on the other hand, sine wave voltage in the commercial frequency range is most commonly used. It was reasoned for the present study that this is the case because methods of PDIV evaluation using inverter surge voltage have not become widespread and because sine wave voltage waveforms can easily be standardized and have general applicability, among other such reasons. In the phenomena of partial discharge due to inverter surge voltage, however, the course that arrives at discharge is complex by comparison with sine wave voltage, so that PDIV is known to be different⁽⁴⁾.

The insulation for main motor magnet wire is designed by first setting the PDIV for the magnet wire on its own and then taking into consideration the motor configuration, the environmental conditions, and other such PDIV variable factors. When PDIV evaluation of the magnet wire uses a sine wave voltage so that it diverges from the actual PDIV in the main motor, it becomes necessary to design a film thickness that is greater than needed in order to assure a safety factor. This had become an issue.

The aim of this research was to enable the design of an optimal thickness of insulation film by clarifying the PDIV characteristics of motor magnet wire resulting from inverter surge voltage, and enhancing main motor performance by reducing the thickness of the insulation film while assuring the necessary insulating performance.

2. Purpose

The purpose was defined as clarification of the following items (1) through (4), which have not previously been clarified sufficiently, for the study of insulation design for main motor magnet wire in electric-powered vehicles, and particularly the thick-film rectangular wire used for segment conductors⁽⁵⁾.

- (1) Influence of the shape of the inverter surge voltage waveform
- (2) Influence on PDIV due to the change of applied voltage from sine wave voltage to inverter surge voltage
- (3) Correlation between PDIV and the gas density estimated from temperature and atmospheric pressure
- (4) Correlation between relative humidity and PDIV

3. Evaluation Method

3.1. Sample Material

The material used as samples for PDIV evaluation was thick-film rectangular wire with insulation film of polyimide with relative permittivity ϵ_r of 3.0. A film thickness of 120 μm was chosen. It is a characteristic of polyimide that it absorbs and releases moisture according to the relative humidity of the atmosphere. This characteristic has an influence on partial discharge, so before measuring the PDIV, the sample material was placed in a constant-temperature, constant-humidity chamber adjusted to 25°C and 50% RH, which is close to the laboratory atmosphere environment, and given stabilization treatment to suppress change in the percentage of moisture content of the polyimide insulation film during testing. The atmosphere environment while discharge testing was being conducted was also set to the basic conditions of 25°C and 50% RH, except when verifying the influence of temperature and relative humidity.

3.2. PDIV Test Samples

For PDIV evaluation of magnet wire, a pair of magnet wires with film insulation that are connected together are held in place. One of the wires is grounded and the other wire has a gradually higher voltage applied to it. This causes a strong electric field to form in the space between the magnet wires. The test evaluates the value of the voltage applied when partial discharge occurs.

The partial discharge occurs according to Paschen's law⁽⁶⁾ in the small air gap between the insulation films of the two magnet wires. This is because, due to the difference between the relative permittivity of a solid body and a gas, the strength of the electric field is increased in the gaseous portion where the relative permittivity is lower. The space in which this partial discharge occurs is called the electric field air gap, and it is an important factor in studying the partial discharge phenomena.

For the research here, reproducibility of the shape of the electric field air gap was sought by adopting the new test sample shape shown on the right in Fig. 1. The new test sample shape is made up of a pair of magnet wires, one of which is in a straight line and the other of which has a fixed curvature. The magnet wires themselves are connected together in a slightly bent state and held in a holder so that they remain connected at a single point and a constant surface pressure. In the present research, these test samples are referred to as single R pair test samples, and these were used to evaluate partial discharge.

Figure 1 shows a conventional arrow pair test sample and a single R pair test sample to which voltage at or above the PDIV is applied to cause partial discharge. In the area where partial discharge occurs, a purple light is emitted in the space of the electric field due to the collision between electrons and gas molecules. The change in color therefore makes it possible to know the area where discharge occurs.

With the arrow pair test sample, partial discharge occurs across a wide range from the straight line portion where the two magnet wires are side by side to the fork portion where they branch away. When the area where partial discharge occurs extends across a wide range, the shape of the electric field air gap cannot readily be reproduced over multiple test samples. This causes variation in measurement. With the single R pair test samples, partial discharge occurs within the comparatively narrow range of the area between the straight line and the fixed curvature parts. This makes it possible to raise the reproducibility of the electric field air gap shape as well as to suppress measurement variations.

3.3. PDIV Evaluation Method

Figure 2 shows an overview of the PDIV evaluation device. The single R pair test sample is connected to the output of the inverter, and the partial discharge detector is connected in parallel with that. When partial discharge occurs in the single R pair test sample, the charge balance in condenser Ck breaks down so that charge transfer occurs and voltage is generated on both sides of detection impedance Z. The noise of the frequency component produced by the applied voltage is filtered out from that voltage to detect the partial discharge signal more clearly. For quantification of the discharge quantity, the detection voltage and discharge quantity calibration values that were acquired in advance are used to derive the quantity.

Figure 3 shows an example of measurement of the relationship between the applied voltage, discharge quantity, and time. The partial discharge signal appears at the time of $0.55\ \mu\text{s}$, immediately before the applied voltage reaches the set peak value of $1.5\ \text{kV}$. At the time

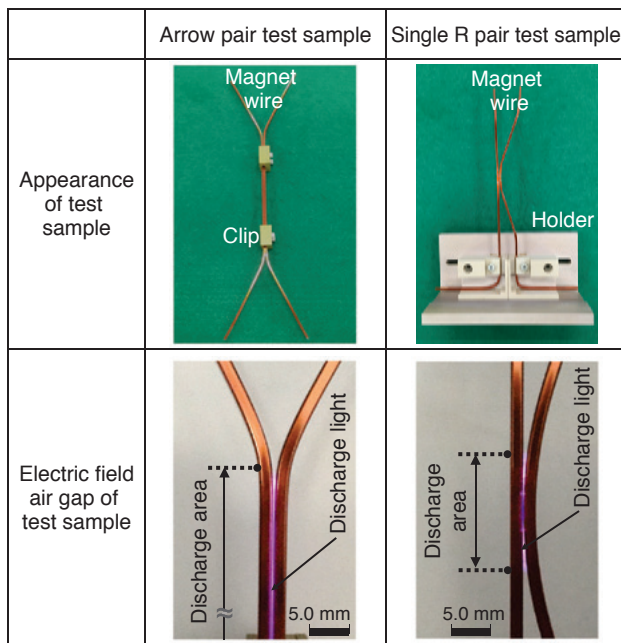


Fig. 1 Appearance of arrow pair test sample and single R pair test sample

of $0.1\ \mu\text{s}$, which is the rise time of the applied voltage, a switching noise signal from the inverter device appears that the filter was not able to remove. However, this does not interfere with measurement because it is in a different temporal phase from the partial discharge. The criterion used in this research to determine when PDIV has occurred is that partial discharge with a discharge quantity of $100\ \text{pC}$ or more per discharge has occurred at or above a certain probability. As there is no clear standard for setting the value of the discharge quantity⁽⁷⁾, it was decided to make it the same as the discharge quantity generally used for sine wave voltage PDIV measurement.

Figure 4 shows the process by which the initial

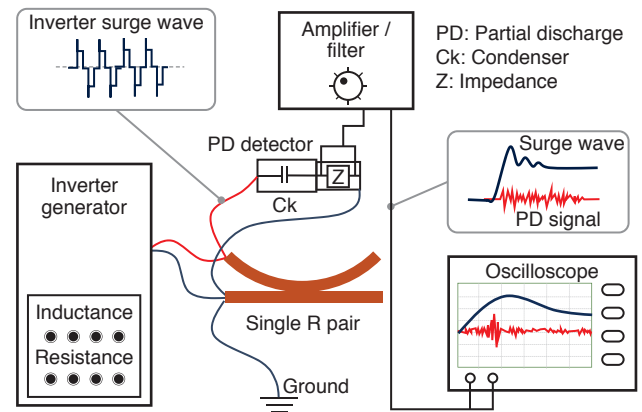


Fig. 2 Schematic diagram of PDIV measurement system

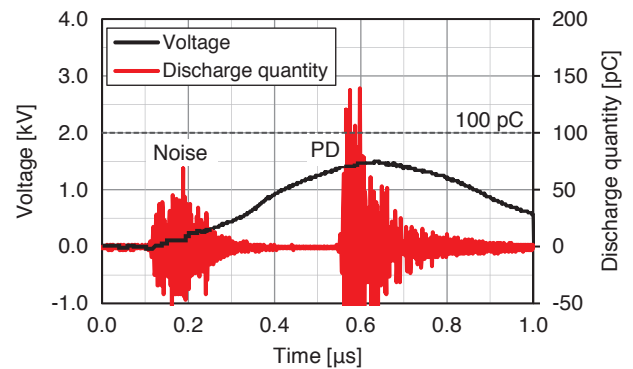


Fig. 3 Example of measurement of applied voltage and discharge quantity

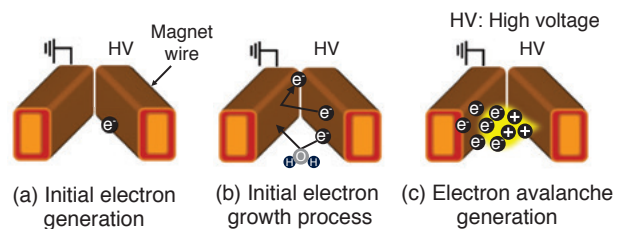


Fig. 4 Process of initial electron growth to electron avalanche

electrons generated in the electric field space between the magnet wires grow into the electron avalanche that is the initial stage of discharge.

- Initial electrons are generated from the electric field space and film.
- The initial electrons are accelerated by the electric field and collide with water molecules in the air and with the surface of the solid film, generating new electrons.
- The multiplied electrons grow into the electron avalanche formed from the electron swarm and positive ion cloud.

Although this is an extremely brief phenomenon, even in the partial discharge from the inverter surge voltage shown in Fig. 3, the same course is followed to arrive at discharge⁽⁴⁾. With the partial discharge phenomena caused by inverter surge voltage, the process of growth from the generation of initial electrons up to the electron avalanche is changed by the influencing factors of voltage waveform and environmental conditions. It is important, therefore, to clarify those influences.

4. Evaluation Results

4.1. PDIV Influence of Inverter Surge Voltage Waveform

As shown in the example in Fig. 5(a), the voltage waveform for driving the main motor appears as a square wave pulse waveform as a result of pulse width modulation (PWM) conversion. The inverter changes that

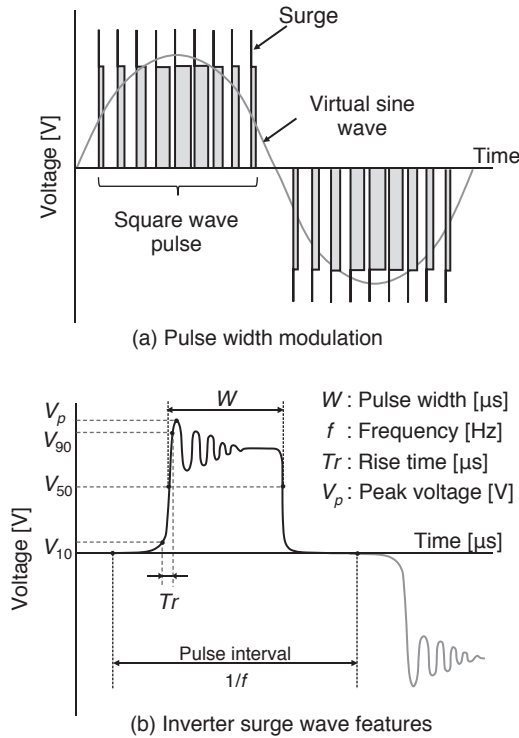


Fig. 5 Square wave pulse controlled by PWM and inverter surge wave features

Table 1 Test conditions for pulse width, frequency, and rise time

Test	Scope	Pulse width W [μ s]	Frequency f [kHz]	Rise time Tr [μ s]
Condition 1		1-500	1.0	0.06
Condition 2		10	0.1-50	0.06
Condition 3		10	1.0	0.06-0.35

form according to the requirements for output to the main motor. In addition, this square wave pulse is affected by the characteristics of the inverter devices, by impedance mismatching between the power cable and the main motor, and other such structural influences so that it takes on the shape of an inverter surge waveform specific to that main motor. That pulse waveform is expressed by the feature values of pulse width W , frequency f , and pulse rise time Tr (the time taken to rise from 10% to 90% of the peak voltage value). The definitions of the respective feature values are shown in Fig. 5(b).

In order to verify the influence that the feature values have on the PDIV, while taking into account the conditions of the waveform output by the actual electric vehicle inverter and the range supported by the evaluation device, the pulse widths, frequencies, and pulse rise times shown in Table 1 were set as the parameters and the sensitivity of PDIV to the influence of each parameter was evaluated.

4.1.1. Pulse width W

Figure 6 shows that the measurement results for the relationship with PDIV of pulse width W varied from 1 to 500 μ s. In the pulse width region of 100 μ s and below, a longer pulse width W has an influence that lowers the PDIV.

4.1.2. Frequency f

Figure 7 shows that the measurement results for the relationship with PDIV of frequency f varied from 0.1 to 50 kHz. Higher frequency f has an influence that lowers the PDIV.

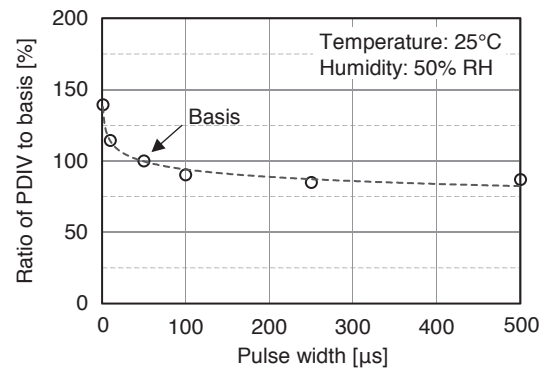


Fig. 6 Relationship between PDIV and pulse width as inverter surge voltage wave features

4.1.3. Pulse rise time T_r

Figure 8 shows that the measurement results for the relationship with PDIV of pulse rise time T_r varied from 0.06 to 0.35 μs . Longer pulse rise time T_r has an influence that lowers the PDIV.

4.2. PDIV Influence of Sine Wave Voltage and Inverter Surge Voltage Waveforms

In order to verify the influence of sine wave voltage and inverter surge voltage waveforms, the same magnet wires were used to conduct PDIV evaluation of the voltage waveform of both sine wave voltage and inverter surge voltage. When setting the waveform conditions for the inverter surge voltage, it was taken into consideration that the various feature values obtained in Section 4.1. have a tendency to lower the PDIV. Therefore, with a view to assuring the insulation, the voltage waveform that lowers the PDIV the most was set so as to include the voltage waveform output by the inverter in an actual electric-powered vehicle. The results are shown in Fig. 9, and this was taken as the basic condition for inverter surge voltage in this research.

Figure 10 shows the PDIV comparison results. This indicates that the PDIV with inverter surge voltage rises 22% higher than that with sine wave voltage. This indicates that, by including the inverter surge voltage in the design

of the insulation film, it will be possible to reduce the thickness of the insulation film by an amount corresponding to the amount by which the insulation film had to be thicker with the previous PDIV. A factor in this rise in the PDIV, as shown in Fig. 11, is that the sine wave voltage and inverter surge voltage differ in the duration that voltage is applied in the high-voltage region that can result in partial discharge. Focusing on the duration that voltage is applied in the high-voltage region, it is apparent that because the sine wave voltage time is given in millisecond units, the application of voltage is sustained until the initial electrons occurring in the electric field space grow into an electron avalanche. With the inverter surge voltage, on the other hand, as the time is given in nanosecond units, there are cases when the applied voltage ends up disappearing before the initial electrons have grown into an electron avalanche.

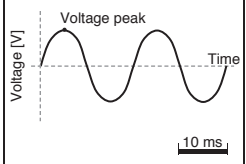
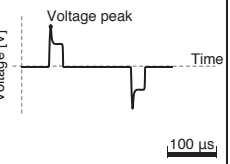
	Sine wave voltage	Inverter surge voltage
Waveform image		
Waveform specifications	Waveform: Sine Frequency: 60 [Hz]	Waveform: Bipolar pulse Pulse width: 50 [μs] Frequency: 10 [kHz]

Fig. 9 Basic conditions of sine wave voltage and inverter surge voltage

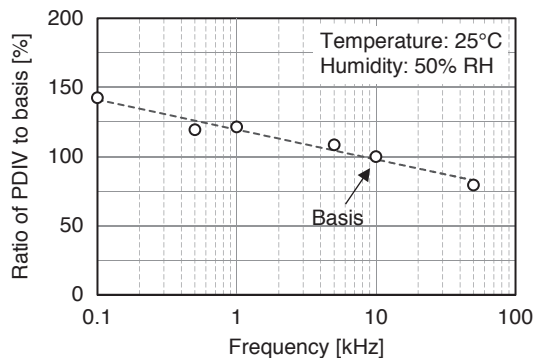


Fig. 7 Relationship between PDIV and frequency of pulse as inverter surge voltage features

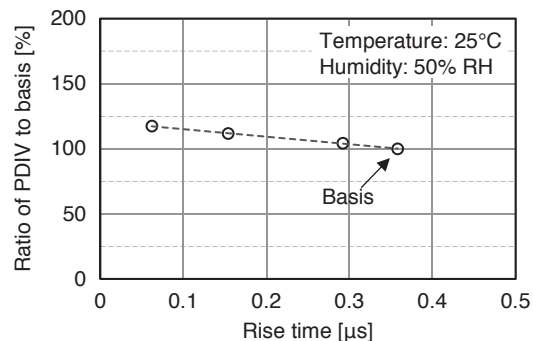


Fig. 8 Relationship between PDIV and rise time of pulse as inverter surge voltage features

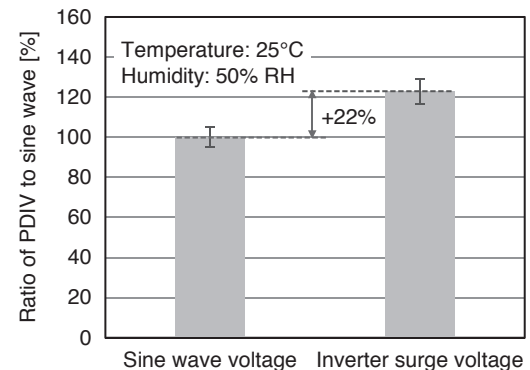


Fig. 10 Comparison of PDIV between sine wave voltage and inverter surge voltage

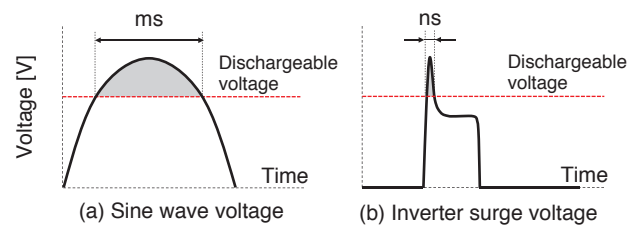


Fig. 11 Comparison between dischargeable times of sine wave voltage and inverter surge voltage

4.3. Influence of Environment on Inverter Surge Voltage

In the occurrence of partial discharge with inverter surge voltage, the probability of initial electrons occurring in the electric field space and the process of their growth into an electron avalanche are factors, and these factors are influenced by environmental conditions. It is important for the study of assuring the insulation, therefore, to ascertain the relationship between the PDIV and the environmental factors that have an influence on the partial discharge phenomena. For the present research, the ambient temperature, atmospheric pressure, and relative humidity were isolated as the environmental factors, and their relationship with the PDIV was verified.

4.3.1. PDIV influence of temperature and atmospheric pressure

In order to verify the influence of temperature and atmospheric pressure on the PDIV, the gas density was estimated from the temperature and atmospheric pressure and its relationship with the PDIV was sought.

The gas density was estimated using the state equation of Eq. (1) and converting it into Eq. (2). In an ideal gas, the temperature and atmospheric pressure are described by a state equation. The properties of a real gas also resemble those of the ideal gas, excluding high-density states at low temperatures and at high pressures. Here, therefore, the state equation was assumed to be valid and the study was pursued accordingly.

$$\text{State equation: } PV = nRT \quad (1)$$

$$\text{Gas density: } \frac{n}{V} = \frac{1}{R} \times \frac{P}{T} \quad (2)$$

P : Pressure

V : Volume

n : Number of moles

R : Gas constant

T : Temperature

For the measurement conditions, the operating environment of the actual motor and the range covered by the evaluation equipment were taken into consideration, the atmospheric pressure was taken as the ambient atmospheric pressure in a constant state with the temperature varied from 40°C to 170°C, the temperature was taken as a constant state at 25°C with the atmospheric pressure varied from 0.1 atm to 1.0 atm, and the relative humidity was kept in the range of 30% RH or lower. Figure 12 shows the measurement results for the relationship between gas density and PDIV.

It is apparent from these results that increases in gas density cause the PDIV to rise. Also, although some deviation in the PDIV value may be seen due to the difference in relative humidity conditions between the

measurements along the plotted line under atmospheric pressure control and the measurements along the plotted line under temperature control, it has become clear that the sensitivity of PDIV to the influence of changes in gas density remains the same.

The reason for this is that the main cause of the influence of changing gas density on the PDIV arises largely from changes in the number of gas particles that obstruct the activity of the initial electrons⁽⁸⁾. When the gas density decreases so that the free path for the electrons becomes longer, the electrons are accelerated sufficiently in the electric field space so that collisions between electrons and gas particles, and further collisions between the positive ions generated by collision and the solid film, begin to occur more frequently. This causes new electrons to be generated in the electric field space, making it more likely that discharge will occur and lowering the PDIV.

4.3.2. PDIV influence of relative humidity

In order to verify the influence of relative humidity on the PDIV, the relative humidity was varied from 10% to 95% RH and measurements were made to determine the relationship between it and the PDIV. Figure 13 shows the results. The measurement atmosphere had the temperature fixed at 40°C at ambient atmospheric pressure to enable control of the relative humidity over a wide range.

It is apparent from Fig. 13 that when the relative humidity is increased from the dry state of 10% RH, the PDIV tends to decrease. This is because as the relative

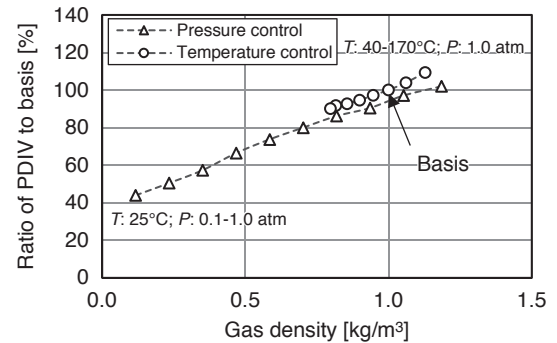


Fig. 12 Relationship between gas density and PDIV

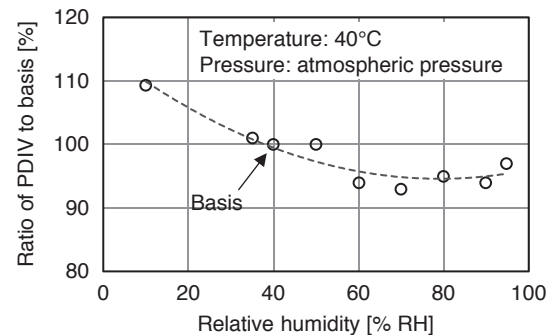


Fig. 13 Relationship between relative humidity and PDIV

humidity rises to a high level, the number of water molecules suspended in the electric field air gap increases, and those molecules ultimately become the source of oxygen negative ions and their hydrates that are sources of initial electrons⁽⁹⁾. However, where the PDIV tended to go lower as the relative humidity rose, in a high relative humidity environment at 60% RH or higher, such tendency to go lower was no longer seen.

Even though an environment is prepared in which discharge can occur more readily because of the rise in relative humidity, the phenomenon whereby the tendency for the PDIV to decrease disappears in a high relative humidity environment of 60% RH or higher suggests that some other influencing factor is at work.

5. Discussion of PDIV Behavior in a High Relative Humidity Environment

5.1. Differences from the General View of the Influence of Relative Humidity

There have been many reports regarding the relationship between relative humidity and PDIV in magnet wire with a film of polymeric insulating materials^{(5), (10)}, and the general view is that raising the relative humidity causes the PDIV to decrease. However, in the verification of inverter surge voltage conducted for this study, as shown in Fig. 13, the tendency for the PDIV to decrease was no longer visible in a high relative humidity environment of 60% RH or above. The cause of this is presumed to be that in a high relative humidity environment, a change of physical properties of some kind occurs in the surface of the insulation film that inhibits the generation of the initial electrons. Verification was therefore conducted of relative humidity, the discharge quantity, and the surface resistivity of the insulation film.

5.1.1. Relative humidity and discharge quantity

Figure 14 shows the relationship between relative humidity and the initial discharge quantity. In order to make it possible to evaluate even very small discharge quantities here, measurement included even discharges with very small discharge quantities that do not satisfy the

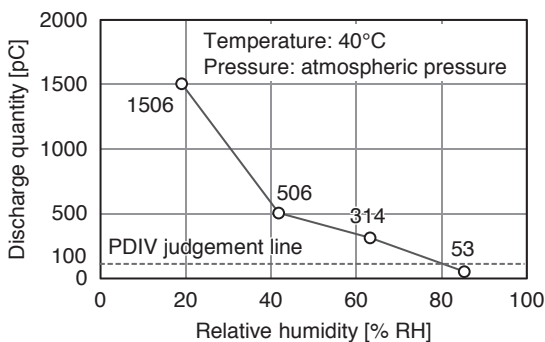


Fig. 14 Relationship between relative humidity and initial discharge quantity per one discharge signal

100-pC criterion for determining PDIV occurrence. The measurement atmosphere was 40°C at ambient atmospheric pressure, and the discharge quantity for the single initial discharge was derived from the mean value for initial discharge quantities in the first 10 sampling iterations. This showed that where the initial discharge quantity at the relative humidity of 19% RH was 1506 pC, the figure decreased to 53 pC at the relative humidity of 85% RH. It was apparent from this that even if partial discharge did occur in a high relative humidity environment, the discharge did not develop to the point of having an electron avalanche accompanied by a large discharge quantity as found when the relative humidity was low. It was found to develop only into a slight electron avalanche with a relatively small discharge quantity. It is presumed from this that when the discharge quantity for determining PDIV is set to 100 pC, there is a low possibility that partial discharge that satisfies the PDIV discharge quantity criterion will occur in a high relative humidity environment and that the tendency toward a lower PDIV is inhibited.

5.1.2. Surface resistivity and electric field strength simulation

The fact that when the relative humidity is increased, the initial discharge quantity decreases is clear, and the factors causing this were inferred.

In a high relative humidity environment, it is assumed that moisture adheres to the insulation film surface such that the surface resistivity is changed. The change in surface resistivity has an influence on the strength of the electric field in the electric field air gap. Simulation analysis was therefore conducted of the strength of the electric field formed in the electric field air gap when there was no film of moisture on the insulation film and when there was a moisture film 1.0 μm thick.

The analysis used the discharge area of the single R pair test sample as a model. The analysis conditions were set as insulation film with thickness of 120 μm , applied voltage of 1.5 kV, and two levels of conductivity of moisture of 5.0×10^{-6} S/m and 5.0 S/m on the assumption that the water would have different degrees of cleanliness. Figure 15 shows the simulation analysis results. It was found from the analysis results that the presence of a moisture film caused

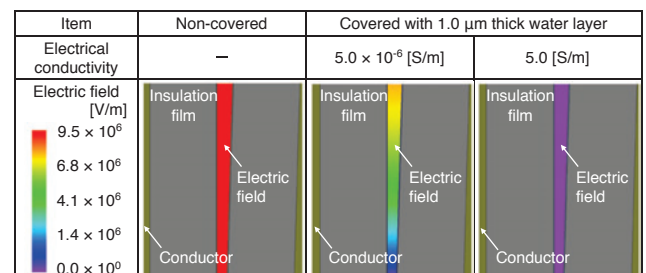


Fig. 15 Simulation of electric field strength at air gap with 1.0 μm thick water layer on insulation film

relaxation of the electric field that forms in the electric field air gap between magnet wires. It also became clear that this tendency was intensified when the conductivity of the moisture was higher. It can be inferred from this that when a moisture film forms on the insulation film so that electric field relaxation occurs in a high relative humidity environment, this is one of the factors in the decrease of the initial discharge quantity.

5.1.3. Relative humidity and surface resistivity measurement

As reduction in the surface resistivity of the insulation film was inferred by simulation to result in electric field relaxation in the electric field air gap, the relationship between relative humidity and surface resistivity was verified using actual polyimide film. Figure 16 shows the sample material and measurement method. A polyimide film 120 μm thick was used for evaluation and electrodes were fabricated by gold (Au) sputtering. The film was prepared using a drying furnace at 100°C so it would be in an absolute dry condition. The surface resistivity was then measured at a temperature of 40°C while varying the relative humidity from 30% to 95% RH.

Figure 17 shows the relationship between the relative humidity and the surface resistivity of the polyimide film. A tendency was observed for the surface resistivity of the polyimide film to decrease as the relative humidity

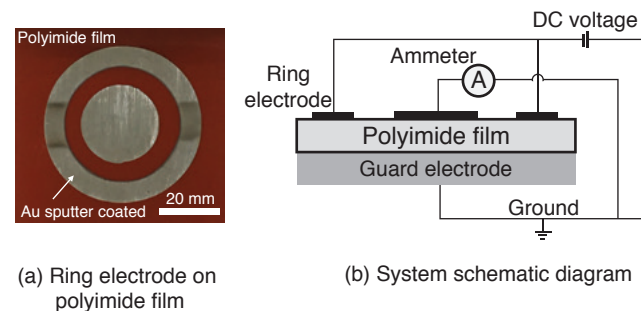


Fig. 16 Surface resistivity measurement method

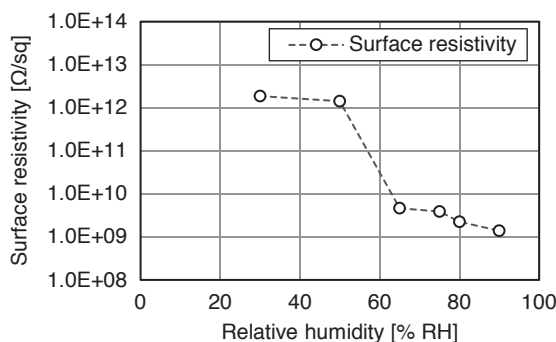


Fig. 17 Relationship between surface resistivity of polyimide film and relative humidity

increased. It also became clear that under these testing conditions, a sharp decrease occurred in the relative humidity range from 50% to 65% RH.

It can be inferred here that the rise in relative humidity results in water molecules that are in the atmosphere adhering to the surface of the polyimide film, ultimately forming multiple layers of moisture film. As the moisture film contains ions, it reduces the surface resistivity. It can be inferred from this that the decrease in surface resistivity in a high relative humidity environment due to adhesion of moisture causes electric field relaxation to occur so that the tendency of the PDIV to decrease is no longer visible.

6. Conclusion

This research successfully yielded the following findings regarding the PDIV characteristics of main motor magnet wire resulting from inverter surge voltage, a matter that had not previously been sufficiently clarified.

- (1) When the inverter surge voltage feature values of pulse width and pulse rise time increase, and frequency becomes higher, this has an influence that lowers the PDIV. The causal factor in this for each of the feature values is that when the time that such voltage is applied in the high-voltage range grows longer, this promotes development into an electron avalanche by the initial electrons that are generated in the electric field space.
- (2) In PDIV evaluation that assumes the inverter surge voltage applied to an actual main motor, there was a 22% increase over the PDIV using sine wave voltage. This indicated that a reduction in the thickness of the insulation film would be possible.
- (3) Converting temperature and atmospheric pressure into gas density allows it to be treated as a single influencing factor, and increased gas density raises the PDIV. Assuming the environment in which the main motor of an electric-powered vehicle is used, the influence on PDIV from atmospheric pressure is greater than that from temperature.
- (4) Raising the relative humidity from 10% to 60% RH resulted in the PDIV decreasing by 15%. At 60% RH or above, however, the tendency of the PDIV to decrease is no longer visible. One factor in this is that the increase in relative humidity results in a decrease in the surface resistivity of the insulation film so that electric field relaxation occurs in the electric field air gap.

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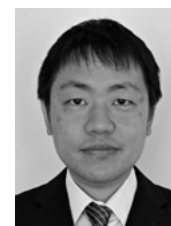
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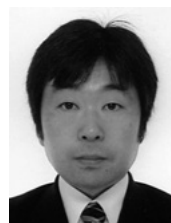
Makoto KUBOTA



Yuta ITO



Takeshi YANAGISAWA



Yoshito TSUKAMOTO



Riku INABA