A Study on Partial Discharge Phenomena of Winding Wires

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ABSTRACT   Partial discharge inception voltage (PDIV) in the 50 Hz AC sine wave voltage has been evaluated and the influence of the environmental condition and the shape of the winding wire give on its mechanism have been considered. Also showing the effect of the thicker insulation and the lower permittivity by using the twisted pair insulated with various materials, the validity of the PDIV estimated by the model computation has been explained. Also, it was confirmed that the PDIV of the twisted pair at the temperature of 25-230℃ reduces as the temperature increases and it has been shown that the dominant factor is the spark voltage of the air and the temperature dependence of the permittivity of the insulating material. Further, it has been verified that the PDIV of specimen combined with rectangular wires reduces significantly at a 95% relative humidity and that the ionic contaminant on the wire surface is one of the main factors.

1.   INTRODUCTION

In recent years, vehicles such as hybrid vehicles (HV) and electric vehicles (EV) powered by an electric motor have been rapidly growing within the framework of the environmental issues and the depletion of the energy sources. From the viewpoint of the power performance of the vehicles and the improvement of their fuel mileage, the driving motor mounted in the vehicles requires the improvement in their power density, i.e. high output and small size. Since the increase in voltage is an effective measure against these challenges, there are also vehicles that are operated at a high voltage exceeding 500 V. In general, these motors are driven by the inverter, thereby achieving a satisfactory control and power. However, the effect of the surge generated due to the fast switching of the inverter on the coil insulation of the motor is a concern and many studies on the partial discharge phenomenon and the insulation deterioration caused by the inverter surge, its evaluation technology and the insulating material having a partial discharge resistant have been carried out.

Furukawa Electric and Furukawa Magnet Wire worked quickly to strengthen the coil insulation for the high voltage of motor and the partial discharge and have developed the rectangular wires having an unprecedented insulator structure. The developed product of our company has been adopted as a motor stator coil of compact HV, thereby contributing to the downsizing/weight reduction of the motor and the improvement of the fuel mileage of the vehicle[1].

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In this paper, the research results of the authors about the partial discharge phenomenon of the winding wires and its mechanism are reported and further, our approach for the improvement of the partial discharge characteristics of the winding wires is introduced.

2.   PARTIAL DISCHARGE PHENOMENON OF THE WINDING WIRES

2.1   Estimation of The Partial Discharge Inception Voltage (PDIV)

Because the partial discharge has a strong effect to the insulation deterioration of the coil, it is important to clarify the mechanism. It is extremely important to capture, especially the mechanism for the partial discharge inception voltage (PDIV). In general, the PDIV of the winding wires is estimated by the electric field strength and the Paschen curve[2]. For example, the relationship between the electric field strength for the air gap of the twisted pair and the gap distance was evaluated by using the electric field analysis such as the finite element method and the estimated PDIV is defined as the applied voltage when the Paschen curve and the electric field strength coincide. Further, Dakin et al have shown that the PDIV of the insulator which is sandwiched by the cylindrical electrodes can be approximated by a function of the ratio of the insulation thickness and the relative permittivity[3]. Referencing these techniques, the authors have estimated the PDIV of the conventional round wires and rectangular wires which are applied to HV motor in recent years.

Two-dimensional computation models of the electric field strength are shown in Figure 1. The twisted pair model of 1 mm conductor diameter is used for the calculation of the electric field for the round wires. The shortest

distance of the air gap is set to 1 μm and the relationship between the wedge-shape gap distance which is formed between the wires and the electric field strength is evaluated. A parallel plate model consisting of combined planar section is used for the calculation of the electric field of the rectangular wires. A parallel plate gap of 10-250 μm is given and the relationship between the gap distance and the electric field strength is evaluated. In the case of the rectangular wires, the sufficient length of the flat portion was secured in order to avoid the effect of the distortion of the electric field at the corner and the electric field strength at its near center was calculated. A high speed surface charge method is used for the calculation of the electric field. As shown in Figure 2, the voltage which the electric field strength of the air gap coincides with the Paschen curve was defined as the estimated PDIV.
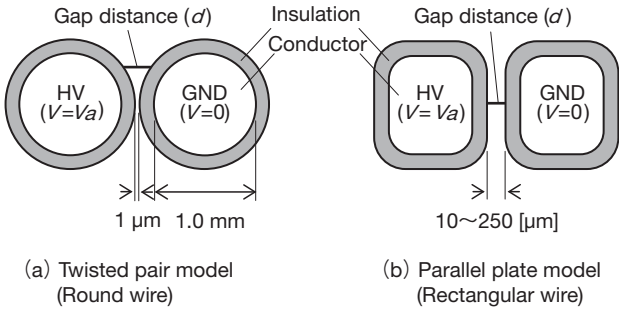

(a) Twisted pair model (Round wire)　　(b) Parallel plate model (Rectangular wire)

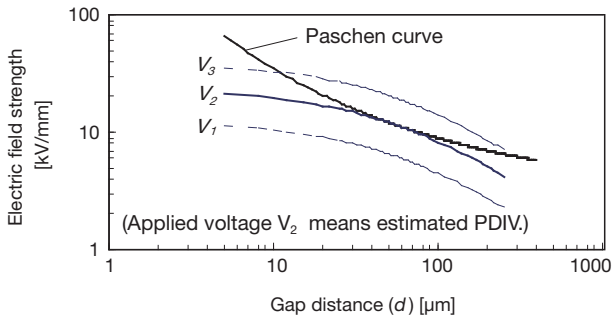**Figure 1　Computation model for the electric field.**

Figure 2　Electric field strength vs. gap distance.

In Figure 3, the relationship between the estimated PDIV and the insulation thickness is shown. The relative permittivity of the insulation layer was set to 4. In the figure, the calculated value according to the formula (1) which Dakin at al proposed was also shown.

$$V = 163 \, (t/\varepsilon_r)^{0.46} \, \cdots\cdots (1)$$

　　V : Partial discharge inception voltage[V_{rms}]
　　ε_r: Relative permittivity of Insulator
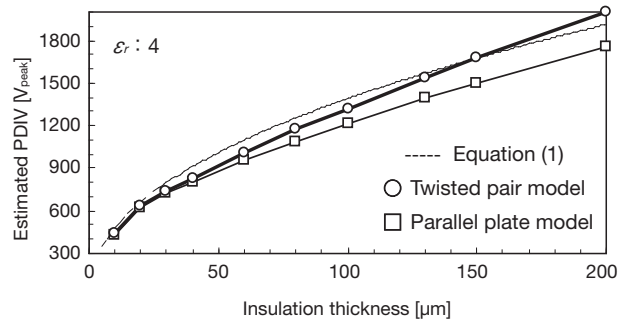　　t : Insulation thickness[μm]

Figure 3　Estimated PDIV vs. insulation thickness.

In any estimation, the results that the PDIV increases with the thicker insulation layer were obtained. This is qualitatively consistent with the empirical partial discharge phenomenon. The calculated value of formula (1) was in good agreement with the estimated value of the twisted pair model in the region of the insulation thickness of less than 30 μm. This is consistent with the experimental result[4] that the PDIV observed in the twisted enamel wire approximately agrees with the calculated value using formula (1). On the other hand, when the twisted pair model is compared with the parallel plate model, the difference in both estimated values appeared when the insulation thickness exceeds 40 μm. The difference became larger as the insulation thickness increases and the result when the estimated value from the parallel plate model is lower, was obtained. This is because the difference in the distribution of the electric field strength for both models occurs if the insulation layer is thick. In Figure 4, the difference in the distribution of the electric field of the air gap due to the insulation thickness is shown. In the case of an insulation thickness of 30 μm, the relationship between the gap distance and the electric field strength for both models reconciles well, but is slightly different in the case of 100 μm and the electric field strength values which are in contact with the Paschen curve values for a parallel plate model are larger. This is the reason why the PDIV for the parallel plate model is estimated smaller than the twisted pair model. Regarding this result, the shortest gap distance between wires is defined as d' and the relationship between d' and the PDIV is explained in addition.
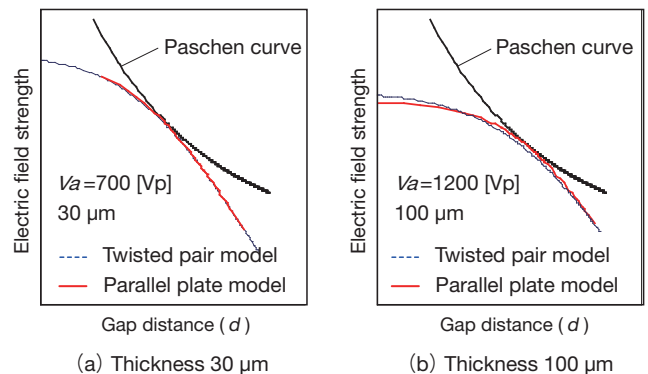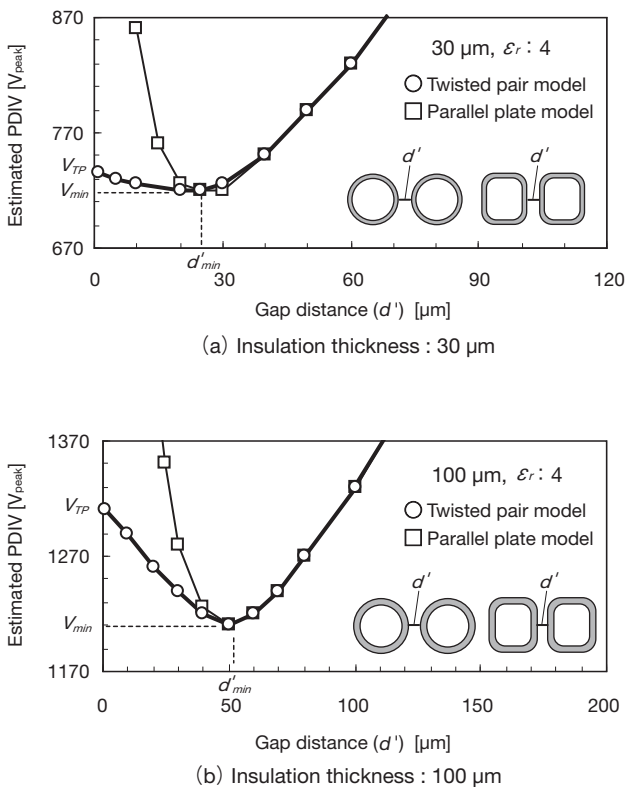

(a) Thickness 30 μm　　(b) Thickness 100 μm

Figure 4　Difference of electric field distribution due to insulation thickness.

In Figure 5, the relationship between the estimated PDIV of the twisted pair model and the parallel plate model and d' is shown. d' is set in the range from 1 to 120 μm, the insulation thickness is set to 30 μm and 100 μm and the relative permittivity is set to 4. From this figure, it is found that the PDIV changes depending on the d' and becomes the smallest value (V_{min}) at a certain gap distance. Also, as the insulation thickness increases, the gap distance (d'_{min}) from which V_{min} can be obtained, increases. In reality, in the case of the insulation thickness of 30 μm, V_{min}= 720 V is at d'_{min}=25 μm and in the case of the insulation thickness of 100 μm, V_{min}=1210 V is at d'_{min}=50 μm. These numbers are same for both the twisted pair model and the parallel plate model and are not dependent on the shape of the conductor within the scope of this study. In other words, if the insulation thickness and the permittivity are same, the estimated minimum PDIV will match. This is the reason why the electric field of the gap at d'_{min} in the twisted pair model is nearly a uniform electric field.

thickness is 100 μm. In other words, as the insulation thickness increases, ΔV increases. This explains the difference of the estimated PDIV in the case of the twisted pair model and the parallel plate model shown in Figure 3. At the same time, this result is suggesting that the PDIV which is observed in the twisted pair arranged for the wires to contact each other may not always agree with the minimum PDIV which is estimated by the insulation thickness and the permittivity. The determination of the gap distance between the wires is important in the evaluation and the estimation of the minimum PDIV which is critical from a practical viewpoint.

Table 1   Difference of the estimated PDIV.

Insulation Thickness [μm]	Estimated PDIV [V_{peak}]		ΔV ($=V_{TP}-V_{min}$)
	V_{TP} (PDIV of twisted pair)	V_{min} (Minimum PDIV)	
30	735	720	15
100	1310	1210	100

(a) Insulation thickness : 30 μm

(b) Insulation thickness : 100 μm

Figure 5   Estimated PDIV vs. gap distance.

Here, let us consider the difference of the estimated PDIV for the 2 models described before. The twisted pair model is applicable under the case of d'=1 in Figure 5. The estimated PDIV is set as V_{TP} at this time. The estimated PDIV of the parallel plate model is equal to V_{min}. Table 1 shows the comparison of V_{TP} and V_{min}. The difference of the estimated PDIV ($\Delta V = V_{TP}-V_{min}$) became 15 V if the insulation thickness is 30 μm and 100 V if the insulation

In this section, the PDIVs of the twisted pair model and of the parallel plate model are estimated using numerical calculation and in the case when the insulation thickness exceeds more than 40 μm, the difference in both the estimated values of the PDIVs occurred. It was shown that the reason was the difference of the distribution of the electric field and the importance to consider the gap distance between the wires when estimating the PDIV was described. It is considered that the findings which are obtained by this study give the beneficial information to the design of the insulation of the thick layer winding wires and to the evaluation of the partial discharge, especially for the purpose of the improvement of the PDIV.

2.2   Insulation Thickness and Permittivity Dependency of PDIV

As described in the previous section, the PDIV is dependent on the insulation thickness and the permittivity. Authors investigated these relationships using a twisted pair of the wires coated with various insulating materials.

In Table 2, the samples which were used in the experiment are shown. The diameter of the conductor is 1 mm, the thickness of the insulation layer(t) is from 29 to 107 μm and the relative permittivity(ε_r) is from 2.9 to 45. For the material of the insulation layer, the resins of Polyamide-imide(PAI), Polyether-ether-ketone(PEEK), Polyphenylene-sulfide(PPS) and Polyethylene-terephthalate(PET) are used. Sample A is an enameled wire with an insulation layer formed by baking varnished PAI resin on the conductor. Others are the extruded wires with the insulator which is formed by extruding on the conductor. For Sample 5, PEEK and PPS are laminated with the same thickness. The relative permittivity is calculated from the capacitance of the wire in the 100 Hz. 3531 Z HiTester (manufactured by HIOKI E.E. CORP.) was used for the measurement of the capacitance. For the measurement

of the PDIV, the twisted pair is used as the test specimen and the measurement was performed by the following method. The specimen is setup in a constant temperature and humidity chamber that is controlled at 25℃ and 50% relative humidity. The 50 Hz AC sine wave voltage was applied between the wires at a rate of 50 V/s and the input voltage when the discharge charge amount exceeds 10 pC is defined as the PDIV. For the detection of the partial discharge, KPD2050 (Manufactured by Kikusui Electronics Corp.) was used. Five measurements were carried repeatedly in one experiment and by using the data in the range from the 2nd to the 5th, the average, the maximum and the minimum of N=3 (3 experiments) were determined.

Table 2 Test samples.

sample	Conductor diameter	Insulation thickness (t) [μm]	Relative permittivity (ε_r)	Insulating material
1		36	4.5	PAI
2		29	2.9	PEEK
3	Φ 1 mm	36	3.1	PEEK
4		46	3.2	PPS
5		72	3.2	PEEK/PPS
6		107	3.6	PET

The testing results are shown in Table 3 and Figure 6. In these, the estimated PDIV which is obtained by the Paschen curve and formula (1) is also shown. The error bar which is shown in the figure represents the maximum and minimum value in the measured values. On the horizontal axis in the figure, the value which is twice the insulation thickness (the distance between conductors) divided by the relative permittivity was plotted. From this experiment, the result, that as the insulation thickness increases and also as the relative permittivity decreases, the PDIV increases, was obtained. As a matter of fact, it is found that, for example, from the comparison of the sample 4 and 5, the PDIV increases with the higher insulation thickness, and that from the comparison of sample 1 and sample 2 or 3, the PDIV increases with lower permittivity. The observed PDIV was in good agreement with the estimated value obtained by the Paschen curve and the value calculated by the formula (1) and the validity of the estimation of the PDIV described in the previous section was shown. More precisely, it can be said that the estimated value by the Paschen curve is close to the minimum observed PDIV. In this regard, it is estimated that in some cases, the PDIV is observed higher due to the insufficient supply of primary electrons. Because the formula (1) is also approximating to the measured result, it can be said that it is effective in the simple estimation of the PDIV. However, since the importance of knowing the minimum value of the PDIV is high, it is considered that the estimation using the Paschen curve is more appropriate in the insulation design of the winding wires.

Table 3 Test results.

sample	$2\,t/\varepsilon_r$	Measured PDIV [V_{peak}]		Estimated PDIV [V_{peak}]	
		Average	Minimum	Paschen curve	Equation (1)
1	16.0	775	728	750	823
2	20.0	830	788	830	912
3	23.2	902	849	860	977
4	28.8	1055	994	990	1078
5	45.0	1330	1245	1220	1325
6	58.8	1501	1445	1430	1506
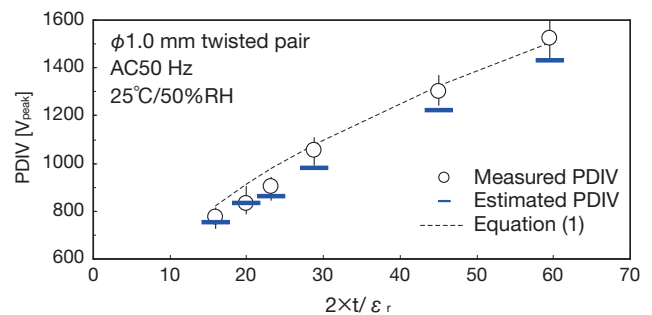
Figure 6 Thickness and relative permittivity dependence of PDIV.

In this section, the measurement results of the PDIV in 50 Hz AC voltage using a twisted pair of the wires coated with a variety of insulating materials were shown. The effect of the thicker insulation layer and the lower permittivity to the improvement of the PDIV was confirmed. Further, the observed PDIV was in good agreement with the value estimated by the Paschen curve and the electric field of the air gap. Therefore, the validity of the estimation using a numerical calculation was proved.

2.3 Effect of The Environment

Since the winding wires are used in a harsh environment, it is important for practical use to clarify the effect of the environment on the partial discharge and its generation mechanism[5]. In this section, the author's knowledge about the influence of the temperature and the humidity on the PDIV was described.

2.3.1 Temperature Dependency of The PDIV

By using the twisted pair wire coated with a variety of insulating materials, the temperature dependence of the PDIV was investigated. Three kinds of wires (Sample A-C) with different insulating materials were used for the test. Sample A is PAI which the permittivity property is improved, sample B is PAI and sample C is PEEK. The diameter of conductor is 1 mm and the insulation thickness is 30 μm. The twisted pair was used as the testing specimen and the PDIV measurement was performed by the following method. The specimen was set in a temperature controlled chamber. 50 Hz AC sine wave voltage is applied between the conductors at a rate of 50 V/sec and the voltage when the discharge charge amount exceeds

10 pC is defined as the PDIV. KPD2050 (manufactured by Kikusi Electronics Corp.) was used for the detection of the partial discharge. The measuring temperature is from 25℃ to 230℃. After reaching the predetermined temperature, the measurement was done quickly. Five measurements were performed at each temperature and the data in the range from the 2nd to the 5th are used and the average value of N=3 (3 experiments) was calculated.

Figure 7 shows the temperature dependence of the PDIV. In the figure, the retention ratio is shown in the case that the reference (100%) is the PDIV of each sample at 25℃. From this result, it is found that there is a tendency that as the temperature increases, the PDIV decreases and the decrease rate differs by insulating materials. It is considered that the reduction of the spark voltage caused by a change in the air density affect to the temperature dependence of the PDIV. For example, there is an experimental result[6] that the temperature dependence of the PDIV from room temperature to 80℃ in the air gap between the insulation sheets using CIGRE Method - Ⅱ electrodes can be explained mainly by the relative air density. So the temperature dependence from 25 to 230℃ observed in this experiment is considered from the viewpoint of the spark voltage of the air and the temperature dependence of the permittivity of insulating material.
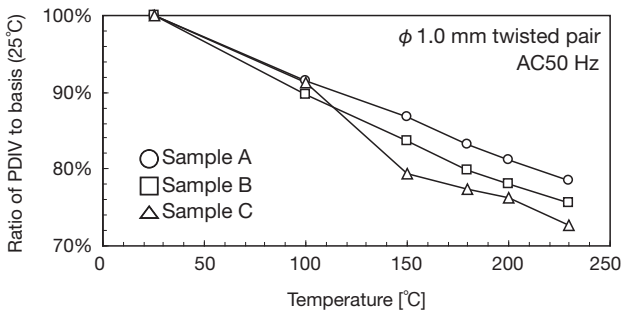

Figure 7   Temperature dependence of PDIV.

It is considered that the PDIV is determined by the relationship between the spark voltage of the gas indicated by the Paschen curve and the electric field strength in the air gap. The spark voltage V_s of the gas in the uniform electric field is represented by a product function of the pressure p [Torr] by gap distance d [m]. Here, it is possible to consider replacing the gas pressure p by the gas density of ρ [kg/m³].

$$V_s = f(pd) = f(\rho d) \cdots \cdots (2)$$

In addition, the density ρ is inversely proportion to the absolute temperature T [K] under a certain pressure from the equation of state of gas.

$$\rho T = \text{const.} \cdots \cdots \cdots (3)$$

From these relationships, it is believed that V_s is lowered due to the change in the gas density at high temperature. Therefore, the change in V_s with increasing temperature is estimated and the PDIV considered was therefore estimated using electric field analysis. In Figure 8, the estimation result of the temperature dependence of V_s is shown. The pressure is set as constant and the calculation example of the voltage between the gaps in the twisted pair is also shown in the figure. In the right region, i.e. in the gap distance that affects the PDIV essentially, the result that as the temperature increases, a V_s decreases was obtained.
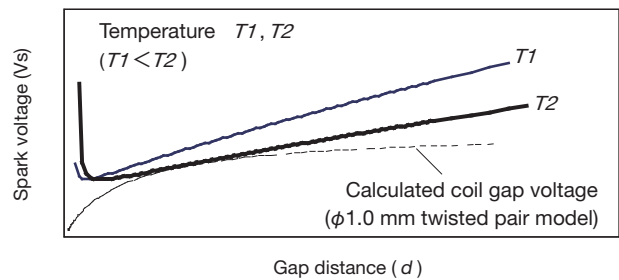

Figure 8   Estimation of temperature dependence of spark voltage.

Figure 9 shows the estimated result of the PDIV in consideration of the temperature dependence of V_s. In this estimation, it was assumed that there is no temperature dependence on the insulation thickness and the permittivity. In the figure, the actual measured values of sample A to C were also shown. It was indicated that there is a tendency where the estimated PDIV, in consideration of the temperature dependence, decreases as the temperature increases. Qualitatively, it indicated the same tendency as the actual measured value. However, to be precise, the divergence was seen for both at the temperature of more than 150℃ and the estimated value was estimated larger than the measured value. Especially, there is noticeable difference when compared with the sample B or C. That is, the difference between the insulating materials in the temperature dependence of the PDIV cannot be explained only by considering the temperature dependence of V_s.
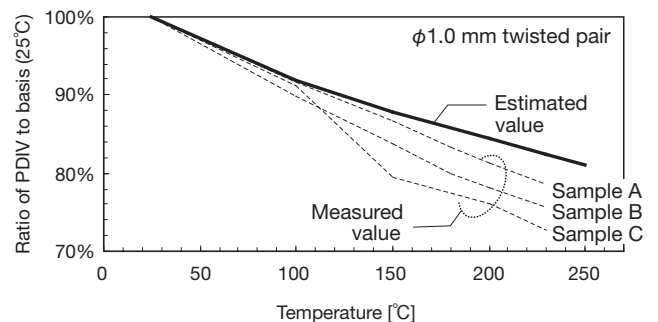

Figure 9   Estimated PDIV with a consideration of temperature dependence of V_s.

Next, the difference in the insulating materials is studied from the viewpoint of the temperature dependence of the permittivity. In Figure 10, the temperature dependence of the relative permittivity (ε_r) of each insulating material is shown. The relative permittivity was determined by the capacitance of the wires at 100 Hz. It can be seen from the figure that each insulating material has a different temperature dependence. On the basis of the value at 25℃, the permittivity of Sample A slightly increased at more than 150℃, the permittivity of Sample B increased linearly and the permittivity of Sample C increased rapidly at more than 150℃. In general, it is thought that because the sharing voltage of the air gap increases as the permittivity increases, the PDIV decreases. In another words, it is expected that the measured PDIV at high temperature is affected by the increase of ε_r in addition to the decrease of V_s described before.
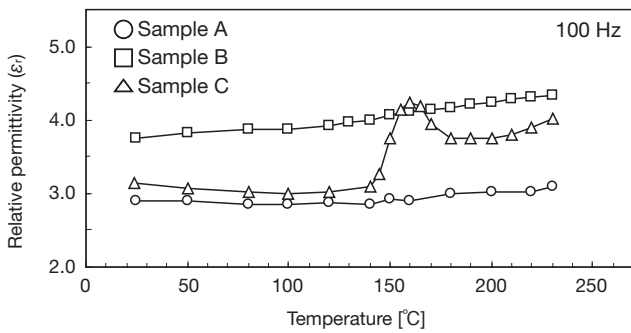

Figure 10 Temperature dependence of the permittivity.

In Figure 11, the estimated PDIV based on the temperature dependence of V_s and ε_r is shown. In any samples, the estimated value is in good agreement with the measured value and the difference between both values stayed less than 3%. From the above results, it was shown that the dominant factor that characterizes the observed temperature dependence of the PDIV is the spark voltage of the air and the temperature dependence of the permittivity of the insulating material.
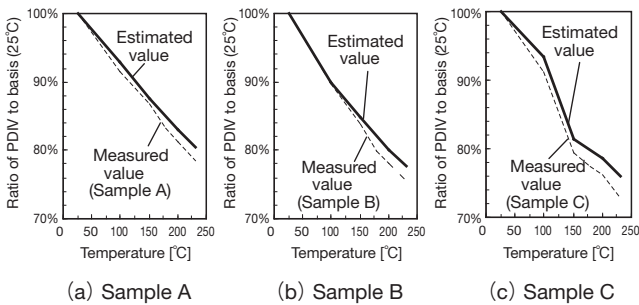

(a) Sample A (b) Sample B (c) Sample C

Figure 11 Estimated PDIV in consideration of the temperature dependency of V_s and ε.

In this section, the measurement result of the temperature dependence of the PDIV of the twisted pair using 50 Hz AC sine wave voltage was shown. It was confirmed that the PDIV reduces with increasing the temperature and it is concluded that the dominant factor is the temperature dependence of the spark voltage and the permittivity of the insulating materials. It is thought that the knowledge which was obtained by this study is useful specifically for the understanding of the partial discharge phenomenon of the winding wires which is used at high temperature environment such as in HV motor and in the design of insulator.

2.3.2 Humidity Dependency of The PDIV
The authors evaluated the humidity dependence of the PDIV in the 50 Hz AC voltage using the rectangular wires. Figure 12 shows the test specimen and the experimental method. The test specimen was prepared by contacting the flat face of two rectangular wires and fixing them by the resin clips. An air gap of parallel and plate shape between the wires is formed by sandwiching insulating spacer of 50 μm thickness. The effective length of the test specimen is 100 mm. The insulation thickness is 40 μm and the materials are Polyamide-imide(PAI) and Polyphenylene-sulfide (PPS). The measurement of the PDIV was conducted by the following method. The test specimen is placed in a temperature and humidity controlled chamber and the AC sine wave voltage is applied. The voltage when the discharge charge amount exceeds 10 pC is defined as the PDIV. The frequency of the voltage is 50 Hz and the increase rate of the voltage is 50 V/s. For the detection of the partial discharge, KPD2050 (Kikusui Electrons Corp.) was used. The measurement temperature is 25℃ and the relative humidity is between 50 and 95%. After stabilizing at a certain condition the measurement was taken quickly. Five measurements were taken repeatedly at each relative humidity. The data from in the range from the 2nd to the 5th are used and the average value of N=3 (3 experiments) was calculated.
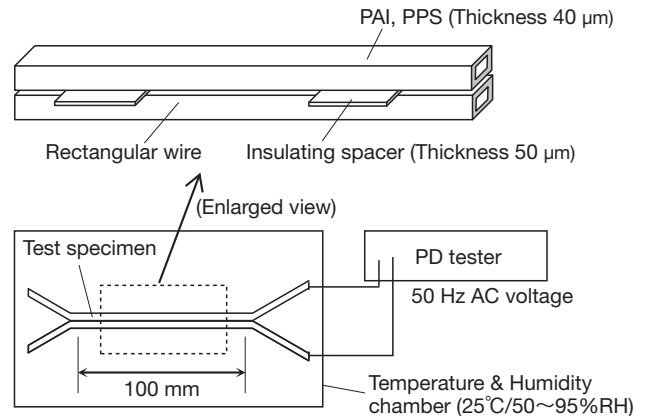

Figure 12 Specimen and testing method.

In Figure 13, the humidity dependence of the PDIV when the rectangular wire is used is shown. In the figure, the retention ratio in the case that the reference (100%) is the PDIV at 25℃/50% relative humidity is shown. In any cases, the humidity dependence was confirmed and the PDIV was reduced significantly at 95% relative humidity. The retention ratio at 95% relative humidity was 80% in the case of PPS and was 74% in the case of PAI. In Figure 14, the difference in the behavior of the partial discharge due to the relative humidity is shown. The discharge charge amount when the partial discharge started was about 100 pC at 50% relative humidity, but it was 10 pC at 95% relative humidity. In addition to the reduction of the PDIV, it is apparent that the discharge charge amount when the partial discharge starts is small.
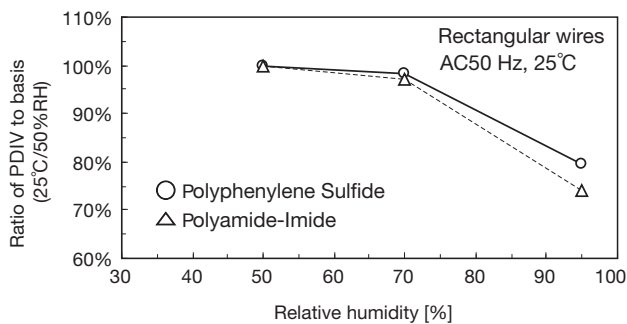

Figure 13 Relative humidity dependence of PDIV.
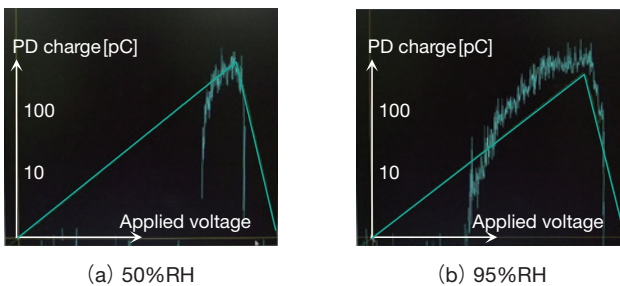

(a) 50%RH

(b) 95%RH

Figure 14 The difference of partial discharge behavior due to relative humidity.

The factor behind the reduction of the PDIV under the high humidity conditions is considered. With respect to the temperature dependence of the PDIV, many experimental results and models which explain it were reported. For example, they are the increase of the permittivity due to the water absorption of the insulation layer[7], the decrease of the insulation property of the air due to the increase of water content, the enhancement of the electric field due to the water droplet on the surface of the insulator[8] and the effect of the contaminants[9]. Among them, the investigation was performed in the PPS rectangular wires with respect to the possibility of the increase of the permittivity of the insulation layer. As a result, the change of the permittivity of PPS after 24 hours water soaking

stayed in about 3% increase in comparison to the value when it was left at the room temperature. The decrease of the PDIV due to the change in the permittivity is estimated as 1-2% and it cannot explain the observed experimental result. Therefore, with reference to the case reported to date, paying attention to the surface condition, the predicted effect of the surface contaminants especially on the electric property was investigated. At first, the substance adhering to the surface of the wire which is used for the measurement of the PDIV was identified by electron probe microanalyzer (EPMA). As the result, Na, K and Cl were detected. It is believed that these were adhering when the wires were touched by bare hand during sampling and etc. In the case that these are on the surface of insulator, it is known that they affect the electric conductivity of the surface in the wet state. For example, there are a number of case reports[10] regarding the insulation property of the insulator for the high-voltage power lines under the sea salt fouling environment. So, the hypothesis that the contaminants (adhering of Na, K, Cl and etc.) of the surface touched by bare hand affect the PDIV under high humidity environmental condition was made and it was verified by evaluating the temperature dependence of the PDIV using the wire for which the surface is cleaned and the adhered substance is removed and the wire which was touched by bare hand evenly after cleaning. The cleaning was performed by wiping off the moisture using clean rag after soaking the wires in the pure water. Note that EPMA testing confirmed that the contaminants described before were removed.

Figure 15 shows the humidity dependence of the PDIV in the case that the surface of the wire is cleaned by the pure water and in the case that the surface is touched by bare hand again. The insulation layer is PPS resin. In the case that the surface is washed by pure water, the clear humidity dependence was not observed and the PDIV is almost constant. On the other hand, in the case that the wire is touched by bare hand after washing, the humidity dependence was shown again and the PDIV reduced. From these results, it was believed that the contaminants of the wire surface, probably the presence of the contaminants containing Na, K, and Cl, strongly affected the humidity dependence of the PDIV. For the mechanism where the PDIV reduces under the high humidity environment, the increase of the air gap electric field due to the increase of the electric conductivity on the wire surface can be considered. In addition, because the decrease of the PDIV could not be recognized by washing the wire surface, it can be said that the effect of the change in the spark voltage due to the increase of the moisture content in the air did not appear clearly.
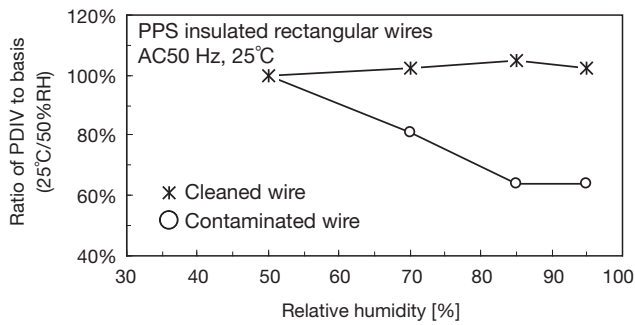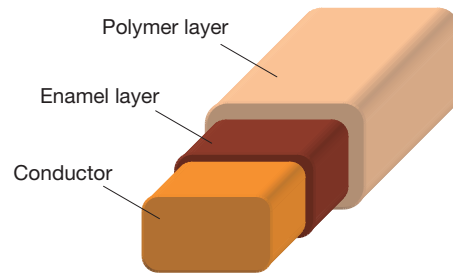
Figure 15 Effect of surface contaminants on the humidity dependence of the PDIV.

Figure 16 Developed structure of rectangular winding wire.

This section describes the measurement results of the humidity dependence of the PDIV at 50 Hz AC voltage using the specimen where two rectangular wires are arranged in parallel as shown in Figure 12. It was indicated that the possibility that the ionic contaminants present in the wire surface reduce the measured PDIV under high humidity environment is high. As described above, a variety of impact factors are considered for the humidity dependence of the PDIV and it is considered that more detailed study is required to elucidate the phenomenon.

## 3. EFFORT TOWARD HIGH PDIV WINDING WIRE

While hybrid vehicles(HV) and Electric Vehicles(EV) are growing rapidly, our company quickly worked on the high voltage of these driving motors and the strengthening of the insulator for the partial discharge. The rectangular winding wire having unprecedented structure has been developed.

In Figure 16, the structure of the rectangular winding wire for HV driving motor is shown. By introducing the rectangular conductor, high space factor is realized and also by increasing the insulation thickness, high PDIV was secured. The insulation layer has two layers structure and consists of an enamel layer and a thermoplastic resin layer provided on the outer periphery. Thick insulation which is difficult in the conventional enamel wires has been achieved with a high quality. For the application of the thermoplastic resin, the material which has excellent mechanical property, heat resistance and oil resistant in full consideration of the processing of the winding wires and the in-vehicle environment was selected. The excellent PDIV and workability of the developed rectangular winding wires support the technology revolution of a motor stator such as the abolition of the inter-layer insulation paper and the reduction of the coil end and contribute to the downsizing/weight reduction of the motor and the improvement of the fuel mileage.

In addition, the development of the enamel resin containing the air bubbles is being developed to reduce the permittivity of the insulator. By using this technology, the permittivity of the insulation layer can be reduced significantly. In Figure 17, the relationship between the enamel wire permittivity with PAI insulating material containing the air bubbles and the porosity. The permittivity can be reduced with the higher porosity. This technology is expected to be deployed to the other applications as well as the winding wires.
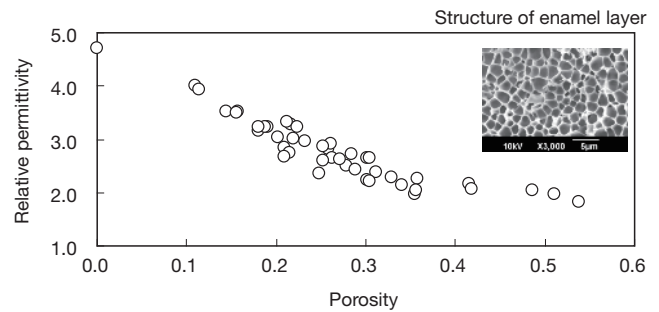
Figure 17 Relative permittivity of PAI vs. Porosity.

4. SUMMARY

By a numerical computation and an actual measurement of the partial discharge inception voltage(PDIV), the influence which the structure of the winding wires and the environmental condition give to the partial discharge property was investigated and the mechanism was considered. At first, the PDIVs of the twisted pair model and the parallel plate model are estimated by the Paschen curve and the numerical computation of the air gap electric field. As the result, when the insulation layer exceeds 40 μm, the difference of the estimated value for both cases appears and it was indicated that this is due to the difference of the electric field distribution of the air gap. It was suggested that there is a possibility that the observed PDIV in the twisted pair which the wires arranged in contact each other does not always agree with the minimum value estimated by the insulation thickness and the permittivity and it was described that the consideration of the gap distance is important when estimating and evaluating the minimum PDIV which is important in practical use.

Next, as a result of the PDIV being measured in the 50 Hz AC voltage using the wires of the twisted pair, it was confirmed that the estimated value and the measured value are in good agreement. From these, the validity of the PDIV estimation by a numerical computation and the effect of the thicker insulation layer and the lower permittivity are indicated quantitatively. Further, the effect the temperature and humidity environmental condition give to the PDIV when 50 Hz AC voltage is applied, was investigated. The PDIV of the twisted pair at 25-230℃ shows the clear temperature dependence and reduces with higher temperature. It was indicated that this dominant factor characterizing the temperature dependence is the spark voltage and the temperature dependence of the permittivity of the insulating material. Also, it was indicated that the PDIV of the rectangular wires arranged in contact reduces significantly and this is due to the ionic contaminants on the wire surface. In the end, regarding our effort to improve the partial discharge property of the winding wire, the rectangular winding wire for the HV driving motor and the technology to reduce the permittivity of the enamel wires was introduced.

5.　CONCLUSION

In this paper, the research results by the authors about the partial discharge phenomenon of the winding wires are reported mainly for the experimental result and the numerical computation. It is considered that the obtained knowledge gives the useful information for the evaluation and the understanding of the partial discharge of the winding wires used under the high voltage and a harsh environment, especially for the driving motor of the HV and EV, and the design of insulating materials.

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