The Development of Next-Generation Technologies in the Domain of Winding Wires of Main Electric Motors

Keiichi Tomizawa[*1], *Mamoru Shimada*[*1], *Keisuke Ikeda*[*1], *Daisuke Muto*[*1], *Hideo Fukuda*[*2]

ABSTRACT Recently, the number of hybrid electric vehicles (HEV) and of electric vehicles (EV) are growing rapidly. Motors integrated in these vehicles are required to be smaller in size and larger in the output power to improve the driving performance and the fuel efficiency. The winding wire applied to these motors is required to have an insulation coating with a higher insulation performance and conductors with lower loss. We have proved that the Partial Discharge Inception Voltage (PDIV) was greatly improved by introducing micro cellulars into the insulation coating and have succeeded in the development of an unprecedented insulation material with a very low permittivity. Further, we have found out that the segmented conductors could reduce the eddy current loss drastically and have examined the relation between the driving frequency and the effect in loss reduction to show there was a noticeable effect in the range of 1 kHz frequency and higher.

1. INTRODUCTION

Recently, driving motors integrated in vehicles such as hybrid electric vehicles (HEV) and electric vehicles (EV) are rapidly growing due to environment regulation conditions of each country such as the demand to reduce the CO_2 emission. A driving motor is a very important element directly influencing the driving performance and the fuel efficiency, which works not only as a driving power source during acceleration but also works as a generator during deceleration to charge a battery. The motor is required to improve its output level despite a size reduction and its higher performance. The situation requires further that a high operational voltage over 400 V is applied to meet the demand of a higher torque performance. In general, an inverter is integrated in a vehicle, which in turn can control the rotational speed with precision. However, a problem is observed when the coil insulation of the motor is damaged when subjected to a high voltage surge with a steep rise (that is the inverter surge).

We have started to work on an R&D on the partial discharge phenomenon and the damaged insulation caused by the inverter surge very early even in the winding wire industry. And as a result of our best effort to determine the mechanism and to improve the start voltage of partial discharge in the winding wire insulation coating, we have succeeded in the development[1)] of the High Voltage Winding Wire (HVWW), which is the world's first winding wire constructed in a hybrid insulation structure with an enameled layer (thermosetting resin) and an extruded layer (thermoplastic resin). In this paper, we report that aiming further improvements in resistive characteristics against the partial discharge, we have newly developed a method to introduce micro cellular into the insulation coating and have proved the excellent insulation properties of the coating containing the micro cellular.

Further, we also report that aiming at further improvement in the efficiency of motors, we have developed the divided segmented conductors applied to winding wire as a result of our R&D, which could reduce the loss caused by eddy currents.

[*1] Automotive Products & Electronics Laboratories, R&D Division
[*2] Technical Department 1, FURUKAWA MAGNET WIRE CO., LTD.

2. THE HIGHER WITHSTAND VOLTAGE WITH A LOW PERMITTIVITY INSULATION MATERIAL CONTAINING THE MICRO CELLULARS

2.1 Lowering the Permittivity of Insulation Materials

Aiming at the improvement of the resistive characteristics against the partial discharge, we have been working on lowering the permittivity of the insulation coating by introducing the air into the enameled resin, whose relative permittivity is 1.0. As a result of this action, we have succeeded in the development of an enameled wire coated with an enameled layer containing micro cellular based on our newly developed original composite of enameled resins. A sketch of the developed winding wire is shown in Figure 1.

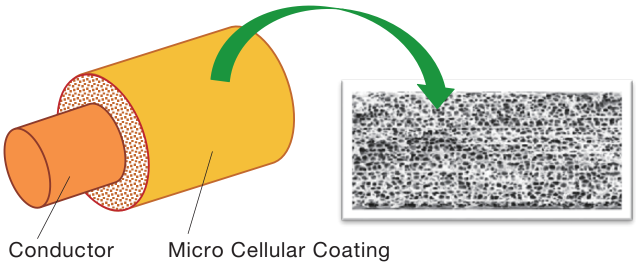

Figure 1 A sketch of the developed winding wire coated with the micro cellular film.

Applying the result of this developed composite, the relative permittivity of the insulation coating can be drastically reduced in comparison with actual general-purpose enameled wires.

The relative permittivity of the insulation resin made of the general-purpose polyamide-imide resin containing the micro cellular is shown in Figure 2 as a function of its porosity inside. The porosity means the cubic rate of micro cellular divided by the volume of insulation coating.

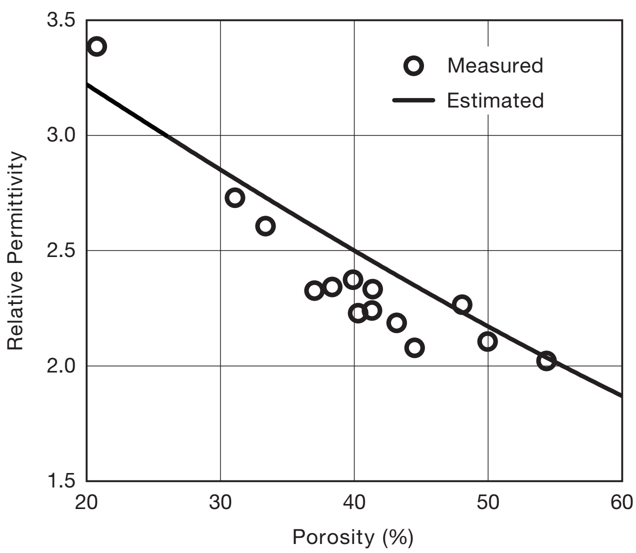

Figure 2 Relative permittivity of PAI (Poly Amide Imide) as a function of porosity.

The relation between the porosity and the relative permittivity was calculated from Equation (1), the equation of A. S. Windeler, which is commonly used for cross-linked insulation cables.

$$\frac{\varepsilon_i - \varepsilon_c}{\varepsilon_i - \varepsilon_a} = \frac{F}{100} \cdot \frac{3\varepsilon_c}{2\varepsilon_c + \varepsilon_a} \qquad (1)$$

ε_c: Effective relative permittivity of insulation resin containing the micro cellular

ε_i: Relative permittivity of insulation material (the relative permittivity of PAI, in this case)

ε_a: Relative permittivity of the cellular (air) (=1.0)

F: Capacity ratio of cellular (porosity %)

The solid line shown in Figure 2 shows the theoretical values calculated from this equation and each of the plotted points shows the actual measured value of the relative permittivity of the developed PAI (Poly Amide Imide) resin containing the micro cellular. It is confirmed that the developed resin can reduce the relative permittivity as much as expected because the actual measured values look almost same as the theoretical values mentioned above. As a result, the relative permittivity can be reduced by up to approximately 2.2 with the introduction of micro cellular up to 50 vol%.

2.2 The Temperature Dependence of the Relative Permittivity

Figure 3 shows the temperature dependence of the relative permittivity of the PAI resin containing micro cellular at 50 vol%, and whose relative permittivity at normal temperature is 2.2.

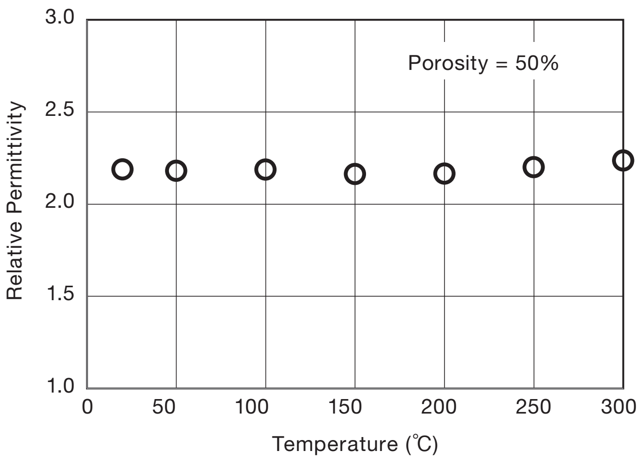

Figure 3 The Temperature dependence of the relative permittivity.

An automotive motor may be exposed to a high temperature environment. Therefore, it is also important that a winding wire applied to the motor keeps its relative permittivity stable and maintains the insulation performance even under the high temperature equivalent to which a vehicle may be exposed to. As a result of this measurement, it is discovered that the relative permittivity of the PAI resin containing the micro cellular did not change and was kept stable even at a temperature as high as 300°C. Based on what is mentioned above, it is proved that the PAI resin layer containing the micro cellulars has a very high and stable insulation performance as a winding wire material for the motor integrated in a vehicle even under the high temperature.

2.3 The Estimation of the Partial Discharge Inception Voltage (PDIV) and Its Verification

We have been estimating the PDIV using the Paschen curve, which indicates the electric field strength between the winding wires and the insulation performance of air to examine the difference against the actual measured values. Based on this examination, we have proved the validity of our theory[1)] that the discharge phenomenon would depend on the insulation property of the insulation coating. In this paper, based on the electric field analysis using the finite element method, we have evaluated the relation between the electric field strength in the air gap of a twisted pair and the distance of the gap to show the loaded voltage at which the Paschen curve matches the electric field strength as the estimated value of PDIV. Comparing the actual measured PDIV with the estimated value mentioned above, we have examined the net effect onto the PDIV caused by the lower permittivity of coating which was reduced with the introduction of micro cellular.

2.4 The Measurement of the Partial Discharge Inception Voltage (PDIV)

After baking the micro cellular PAI insulation layer onto the conductor to make the winding wire coated with the micro cellular insulation, we have measured its partial discharge inception voltage. The test sample for the evaluation was a twisted pair of winding wires coated with the micro cellular PAI insulation baked onto the conductor whose diameter was 1.0 mm and the film thickness of the insulation coating was 30 μm. Three levels of the porosity of micro cellular were prepared as 0%, 30% and 50%. The measurement of the PDIV was carried out in accordance with the following procedure. Setting the test sample in a constant temperature and humidity chamber controlled at the temperature of 25°C and the relative humidity of 50% and applying a 50 Hz sine-curve alternating current between the conductors at a 50 V/s of boosting rate, the applying voltage was measured to be the PDIV when the discharged quantity of electric charge became more than 10 pC. A KPD2050 (made by KIKUSUI ELECTRONICS CORP.) that was used to detect the partial discharge. The measurement was repeated 5 times on the same test sample in a single test. Those data at the 2nd time to the 5th time among the 5 data were adopted and averaged to be the data of N = 1. The measurement was carried out up to N = 3 and the average of the data from N = 1 to N = 3 was taken as the representative value. Further, the measurement was carried out in a thermostatic oven which could maintain the temperature from 25°C to 300°C to get the data of the temperature dependence (see 2.6) and also, in a desiccator which could maintain a constant decompression condition with a vacuum pump to get the atmospheric pressure dependence (see 2.7).

2.5 The Partial Discharge Inception Voltage as a Function of Porosity

Figure 4 shows the measured result of the PDIV at 25°C of the winding wire coated with micro cellular insulation whose porosity was set at 30% and 50%. And for the comparison, the measured result of a general-purpose enameled wire containing no micro cellular is shown together as 0% of the porosity;

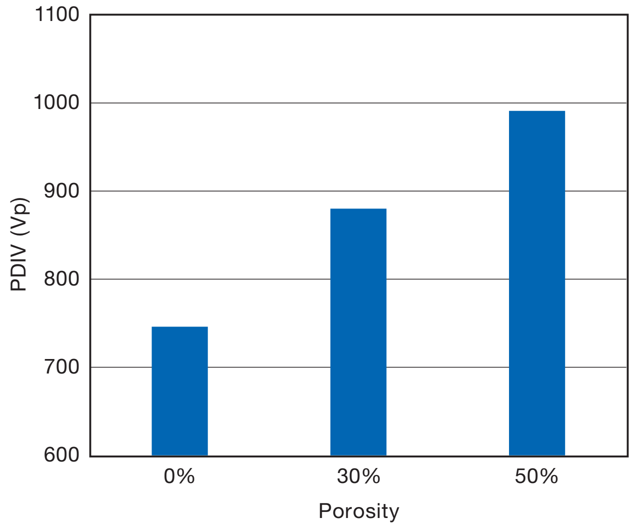

Figure 4 **The PDIV as a function of porosity.**

As a result of measuring the PDIV, a drastic improvement in the PDIV with the introduction of the micro cellular was confirmed in comparison with the present general-purpose enameled wire (0%). Further, a trend was found where the more the porosity was, the more the PDIV was improved. It was discovered that the PDIV of a winding wire coated with a micro cellular insulation of 50% porosity was improved by as much as 200 V_p in comparison with that of 0% porosity. This result shows that it is possible to improve the PDIV drastically by reducing the relative permittivity with the introduction of the micro cellular.

2.6 The Temperature Dependence of the Partial Discharge Inception Voltage

Figure 5 shows the relation between the PDIV and the environmental temperature when measuring a 1.0 mm winding wire coated with the micro cellular insulation of 50% porosity. In this figure, the rate (%) of PDIV at each temperature against the standard voltage at 25°C (100%) is shown as a retention rate. Further, estimated value of the PDIV calculated from the Paschen curve is also plotted together on the figure. The value of relative permittivity shown in Figure 3 was used to calculate the estimated value of PDIV. In this measured result, a trend is found out that the PDIV decreased along with the increase of the environmental temperature at the measurement. It was discovered that the value of PDIV decreased as much as approximately 30% under the environment of 300°C in comparison with that of 25°C. Further, it is also confirmed that the decreasing rate is quite similar to the estimated value calculated from the Paschen curve. This result has shown that even the PDIV of the coating containing the micro cellular could be estimated with the electric field strength and the Paschen curve under the high temperature environment same as mentioned in the past report[1].

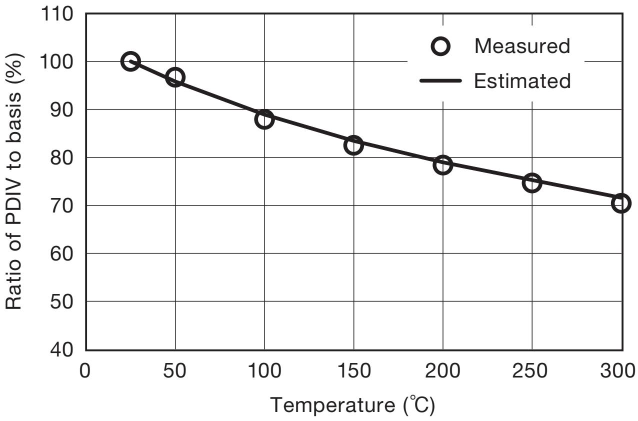

Figure 5 The temperature dependence of the PDIV.

2.7 The Atmospheric Pressure Dependence of the Partial Discharge Inception Voltage

It is well known that the PDIV is also changing with the atmospheric pressure[2] when it is measured because it is affected by the change of the air density. Figure 6 shows the relation between the PDIV and the environmental atmospheric pressure when measuring the 1.0 mm winding wire coated with the micro cellular insulation of 50% porosity. In this figure, the rate (%) of PDIV at each atmospheric pressure against the standard voltage at 25°C (100%) is shown. Further, the estimated values of PDIV calculated from the Paschen curve are also plotted together in the figure. The values of relative permittivity shown in Figure 3 were applied when calculating the estimated values.

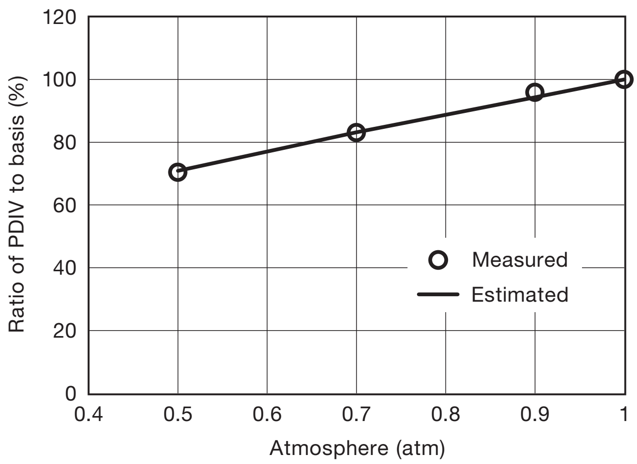

Figure 6 The atmospheric pressure dependence of the PDIV.

In this measurement result, a trend was found that the PDIV decreased along with the decrease of the atmosphere. It was discovered that the value of PDIV decreased as much as approximately 30% under the environment of 0.5 atm. which was a half of atmosphere. Further, it is also confirmed that the decreasing rate was quite similar to the estimated value calculated from the Paschen curve. This result has shown that even the PDIV of the coating containing the micro cellular under the lower pressure environment could be estimated as same as the theory indicated.

2.8 Problems to Practical Applications

As mentioned above, we have already shown the drastic improvement of insulation performance of the insulation coating with the introduction of the micro cellular. On the other hand, aiming at an early application to the actual automotive motor, we have planned to evaluate the mechanical properties which would influence the manufacturing process for a motor coil and also the long-term durability performance which is an important index of reliability of winding wires. From now on, we will continue the evaluation mentioned above to launch this next-generation winding wire early into the automotive motor market.

3. THE REDUCTION OF EDDY CURRENT LOSS WITH SEGMENTED CONDUCTORS

3.1 Classification of Motor Losses

From herein, we explain our activities to reduce losses with the improvement of conductor structure.

Figure 7 shows the diagram of losses occurring in a motor classified according to each of its main causes. At first, the losses can be classified into the loss occurring in a winding wire i.e. the copper loss and that occurring in a core i.e. the iron loss. Further, the copper loss can be classified into the Joule loss i.e. DC loss which occurs in proportion to the DC resistance when current flows in the winding wire and the eddy current loss i.e. eddy loss which occurs when the magnetic flux leaked from the core crosses with the winding wire. And, the iron loss can be also classified into the eddy current loss and the hysteresis loss[3].

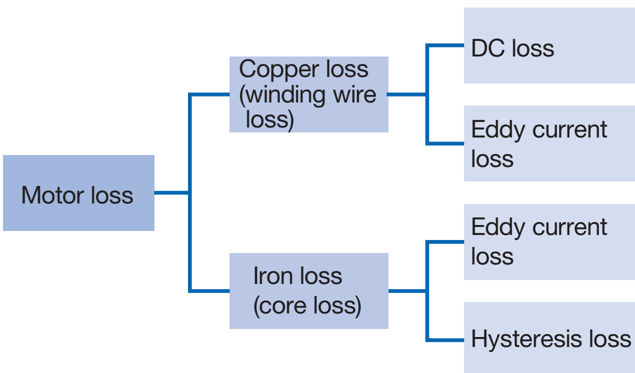

Figure 7 The classification of motor losses.

An equation is shown in Equation (2) to indicate the copper loss occurring in the conductor of the winding wires. W is the loss, S is the conductor cross section, I is the current value, t is the thickness of the conductors in the direction perpendicular to the magnetic flux, B is the amplitude of the interlinkage magnetic flux density, f is the frequency, ρ is a volume resistivity and k_e is a loss coefficient. The 1st term on the right side signifies the DC loss and is proportional to the square of the current value. The 2nd term on the right side signifies the eddy loss generated by the interlinkage magnetic flux, which is shown with the same equation[4] as that of the eddy current loss of iron loss.

$$W = \frac{L}{S}\rho I^2 + LSk_e\frac{(tBf)^2}{\rho} \qquad (2)$$

In general, the eddy loss per volume unit generated by an alternating magnetic field in the conductor is proportional to the square of the amplitude of interlinkage magnetic flux density, the square of the frequency and furthermore the square of the thickness of the conductors in the direction perpendicular to the magnetic flux. Therefore, the DC loss (the 1st term) will influence the whole loss relatively more if some large current flows when the rotational speed is low, on the other hand, the eddy loss (the 2nd term) will influence the whole loss relatively more when the rotational speed increases to make the frequency of the alternating magnetic field higher. At the very beginning when a round winding wire with a small size was commonly used, nobody paid attention to the eddy loss in the winding wire. However, recently along with the larger current and the higher voltage of an automotive motor, the use of a rectangular winding wire with a larger cross section has been increasing to reduce the DC loss. Because the larger the cross section of the winding wire is, the larger eddy current is generated, recently, the scale of this large loss has been considered a problem.

3.2 The Structure of Segmented Conductor Winding Wire

Figure 8 shows a sketch of the segmented conductor winding wire which we are developing.

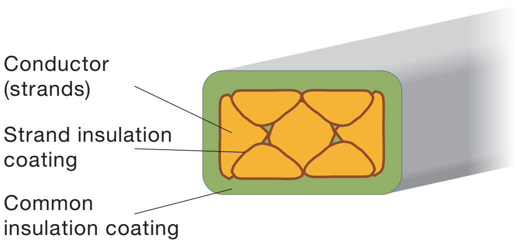

Figure 8 The structure of the segmented conductor winding wire.

This is an application of the twisted structure of Litz wires, which has been already used for transformers of electronic devices and the winding wire of a motor, but the shape of its cross section is rectangular to realize a higher space factor. Each strand has its strand insulation coating to prevent the electrical contact each other. Furthermore, the outside of the twisted strands is coated with a common insulation coating to ensure the dielectric strength. The conductor is constructed in a twisted structure not only to avoid the disintegrating strands during its manufacturing process but also have a uniform magnetic flux passing through each of the strands after being assembled in a motor. A gap always exists between a core and a stator of a motor. And, the leakage of magnetic flux is generated mainly in this gap. Therefore, it exists such a spatial distribution where the leakage magnetic flux, which causes the eddy current loss, becomes larger in the area near the rotor. Therefore, if the Litz wire (strands) is not twisted, the interlinked magnetic flux density will be different depending on the position of each strands in a cross section. As a result, the impedance of each strands will be different from each other to cause the increase the resistance of the whole winding wire. On the other hand, if the Litz wires is twisted, the position of each strands in the cross section will interchange each other along with the length of the winding wire to make the current flow in each strands uniform and the whole resistance of winding wire will be minimized.

3.3 The Effect on the Loss Reduction

Next, the effect of the segmented conductor winding wire in reducing the loss is explained here.

Figure 9 shows a sketch of the loss evaluation device.

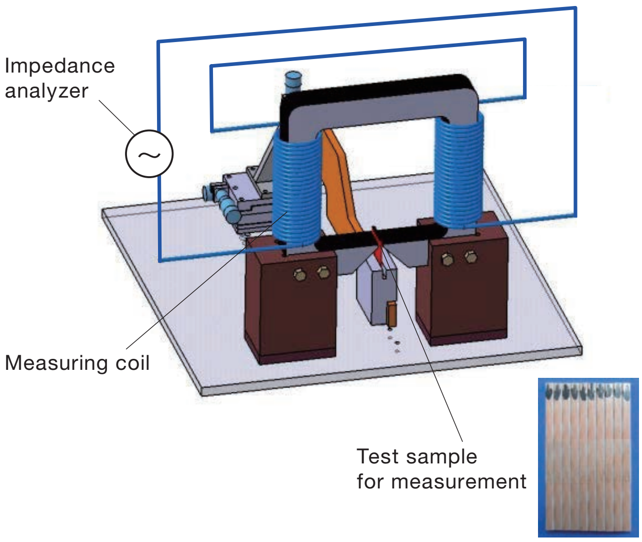

Figure 9 A sketch of the measuring device of the eddy loss in a conductor.

This measuring device is composed of a measuring coil which has a gap in its iron core and an impedance analyzer connected to the measuring coil. A test sample of the winding wire, which is the object of loss measurement and which is cut out from the winding wire in a short piece, is placed in the gap of an iron core. The impedance of the measuring coil when the test sample exists in the gap will differ from that when no test sample exists in the gap, that is, blank. The difference in the impedance is caused by the eddy current occurring in the test sample of the winding wire. The loss in the test sample can be calculated from the difference of resistance between the one when a test sample exists and the other when no test sample exists.

Figure 10 shows the loss of a segmented conductor winding wire and that of a common rectangular winding wire with the same conductor cross section area measured with this measuring device. The horizontal axis shows the frequency and the vertical axis shows the loss per each of winding wires.

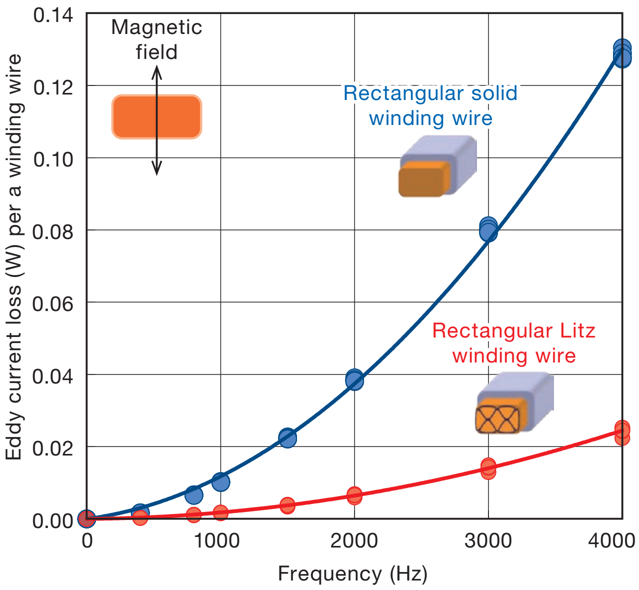

Figure 10 The comparison of the eddy current loss measured in a conductor of a solid winding wire and that of a Litz winding wire.

The calculated loss is proportional to the square of frequency, because only the eddy current loss is calculated in this measurement. The loss of the segmented conductor (Litz wire) winding wire is approximately 19% only of that of a solid rectangular winding wire. Based on the calculation of the 2nd term of Equation (2), the eddy current loss of the segmented conductor winding wire is equivalent to that of a common winding wire with a conductor of 43% in thickness.

As mentioned above, it was confirmed from the experimental test as well that the segmented conductor winding wire had a certain effect in reducing the eddy loss. On the other hand, the segmented conductor winding wire has such a disadvantage that the DC loss is larger than that of the solid rectangular winding wire because the conductor volume factor is made smaller than that of the solid rectangular winding wire because each of the strands are individually coated. Therefore, we simulated the segmented conductor winding wire to estimate the total effect of the loss reduction including the DC loss.

Figure 11 shows a range where the copper loss (the DC loss and the eddy current loss) is reduced and the other range where the copper loss increases on a plane by frequencies and current values, in case the present rectangular winding wire is replaced with the segmented conductor winding wire.

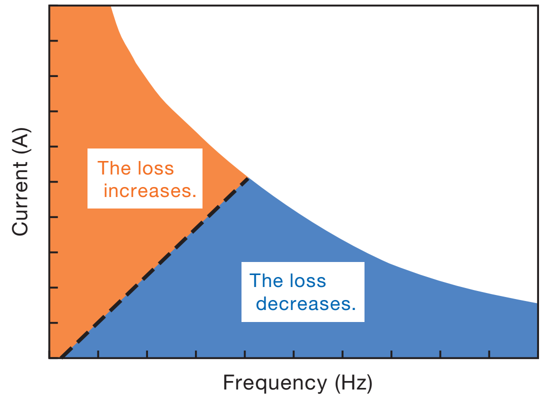

Figure 11 The decrease / increase of the copper loss of the segmented conductor winding wire on a plane by frequencies and currents.

In case of large currents but small frequencies, the ratio of the DC loss is larger, and the application of segmented conductor winding wires would rather increase the loss than reduce it. On the other hand, in case of large frequencies, the segmented conductor winding wire would reduce the copper loss because the ratio of the eddy loss is relatively large. The segmented conductor winding wire is expected to give a great advantage in size reduction of motors and so on, if a motor structure consists of a large rotational speed but a small current to make good use of such features of the segmented conductor winding wire as the low loss at the high rotational speed is realized.

3.4 Problems Toward Practical Applications

Aiming at practical applications, it is necessary for the replacement that the segmented conductor winding wire can be handled as easily as the present rectangular winding wire. When integrating the rectangular winding wire into a motor, usually, the winding wire is divided into short segments in length, formed in a U-shape, inserted into a slot of a core and welded together at each end of wire to be a coil[5]. Therefore, it is required for the segmented conductor winding wire to be easily bent for forming and welded for electrical connection as equivalent to a rectangular winding wire.

Figure 12 shows a result of an FEM analysis of deformed conductors when the segmented conductor winding wire is bent for forming.

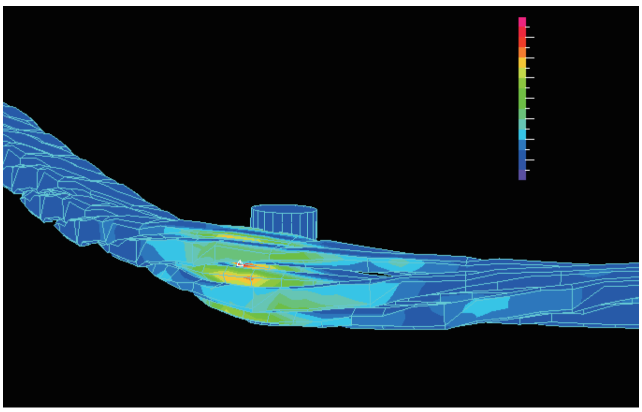

Figure 12 A result of an FEM analysis of bending the segmented conductors.

Some gaps were found out as a result of our analysis to be generated around the bent area to force the conductor to disintegrate. In our actual prototype winding wire, the phenomenon of disintegrating conductor was found out as same as the result of our analysis. That is to say, further efforts with development would be required, because it is difficult for the segmented conductor winding wire which is manufactured by simple twisting of strands to be formed by bending.

And, in general, when jointing a winding wire in a segmented coil with another winding wire, the conductors are welded to each other in such a method where a Tungsten Inert Gas (TIG) welding after mechanically removing the insulation at the end. The peripheral insulation of the segmented conductor winding wire can be mechanically removed in the same way as the rectangular winding wire, however, it is too difficult to remove the insulation between each strand. If conductors are welded together with the insulation remaining between each strand, the carbonized insulation material may remain in the welded area. Countermeasures against it are required because it may cause some defect.

We will make every effort to solve these remaining problems one by one to put the segmented conductor winding wire into a practical use, which is expected to reduce the loss drastically, and to contribute to the loss reduction in an automotive motor and to the higher fuel efficiency of an electric vehicle.

4. CONCLUSION

We have reported here effects and usefulness of two of the next-generation technologies for the winding wire of advanced motors based on not only our investigation but also our experiments and evaluation using the prototype test sample. One effect is to improve the partial discharge inception voltage with the application of a new insulation coating containing the micro cellular and another effect is to reduce the eddy current loss with the application of segmented conductors. As a result of our experiments, it was discovered that the insulation coating containing the micro cellular maintained its low relative permittivity even under such a severe condition of temperature and atmosphere of the automobiles environment. And, we have clarified that the eddy current loss was reduced in the segmented conductor winding wire in comparison with the present winding wire, although there were still some problems remaining when assembling it into a motor coil. The content of this paper is so noteworthy so that we expect more contribution to further technical innovations of motors in the field of automotive motors where the trend of size reduction and higher efficiency is promising to go faster. Now and in future, we are continuously focusing on the materials with a low relative permittivity and on the eddy current loss in a motor and concentrating our effort on the development of materials which will achieve the improvement of the performance of automotive motors.

REFERENCES

1) Muto, Ohya, Aoi and Ueno: "A Study on Partial Discharge Phenomena of Winding Wires", Furukawa Review No.45, 2014, pp. 13 - 21.
2) Wakimoto, Takahashi, Koda, Takizawa and Ishida: "A Study on High Voltage Insulation of the Motor for EV and HEV - Influence on PDIV in Consideration of the Vehicle Environment", DENSO Technical Review Vol.16 (2011), pp. 68 - 76 (in Japanese).
3) JMAG: "Introduction to the Designing Permanent Magnet Synchro-Motors", JSOL, (2016), pp. 219 (in Japanese).
4) M. Morimoto: "Introduction to Motor Engineering", Morikita Publishing Co., Ltd. (2013), pp. 56. (in Japanese).
5) Kaneiwa, Kato, Umeda, Takasaki, Kamiya and Mizutani: "Development of Motor - Stator for a Small-size Hybrid Electric Vehicle", DENSO Technical Review, Vol.19 (2014), pp. 58 - 59 (in Japanese).