Development of a Magnet Wire with Superior Inverter Surge Resistance

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ABSTRACT In recent years there is a trend for electrical equipment and industrial motors to be inverter controlled, as energy saving is promoted together with the downsizing and performance improvement of these equipment. While it has been suggested that excessive surges accompanied by inverter control adversely affect motor insulation systems, this does not make an exception for magnet wire. Thus magnet wires are required to have better resistance against inverter surges than before, because, when the wires are exposed to such voltages, degradation of the insulation layer is caused by corona discharge, unless sufficient insulation and creepage distance are provided between the wires. With respect to driving motors for electric vehicle (EV) and electric hybrid vehicle (EHV) also, similar phenomena are observable depending on the design of motors, thereby leading to a burgeoning demand for a magnet wire that is well adapted for inverter-controlled equipment.

To satisfy these demands, the authors have recently developed a new magnet wire with superior inverter surge resistance. Characteristics of this wire will be described in this report, whereby the life under high-frequency voltage has been improved significantly.

1. INTRODUCTION

In recent years there is a trend for electrical equipment and industrial motors to be inverter controlled, as energy saving is promoted together with the downsizing and performance improvement of these equipment. While it has been suggested that excessive surges generated by inverter-controlled equipment can enter into the motors to adversely affect their insulation systems, this does not make an exception for magnet wire. Thus, when the wires are exposed to such surges, degradation of the insulation layer is caused by corona discharge, unless sufficient insulation and creepage distance are provided between the wires. To prevent the corona discharge degradation due to surges, approaches to reduce such voltages based on motor design are oftentimes taken including changes of peripheral circuits. On the other hand, in order to reduce the size and cost of these motors, there is a demand for improving manufacturing efficiency of motors, including elimination of the inter-phase insulation paper between the wires. Therefore, magnet wires are required to have better resistance against inverter surge than before. With respect to driving motors for electric vehicle (EV) and electric hybrid vehicle (EHV) also, similar phenomena are observable depending on the design of motors, thereby leading to a burgeoning demand for a magnet wire that is well adapted for inverter-controlled equipment.

To satisfy these demands, the authors have recently developed a new enameled wire with superior inverter surge resistance. Characteristics of this wire will be described in this report, whereby the life under high-frequency voltage has been improved significantly.

2. DEVELOPMENT CONCEPT REGARDING INVERTER SURGE RESISTANCE

Surges of inverter-controlled motors can reach 1.5~2.0 times the input voltage, depending on the cable length between the inverter and the motor. Because such surges exceed the corona inception voltage of the magnet wire within the motors, corona discharge occurs in these wires, in case sufficient insulation reinforcements are not provided, producing adverse effects such as a substantial depletion of the insulation layer. Thus it is essential for inverter-controlled motors to improve the insulation reliability against surges.

Improvement techniques for inverter surge resistance of magnet wires come in two types. The first technique is to make the corona inception voltage higher. When the corona inception voltage of the wire insulation is improved to be higher than the inverter surge voltage (i.e., high-

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frequency impressed voltage), corona discharge does not occur extending the service life of the wire. The corona inception voltage V of an enameled wire is given by the experimental equation of Dakin [1] as shown below.

$$V = 163\ (t/\varepsilon)^{0.46} \qquad \text{(V)} \qquad (1)$$

where, t is the thickness of insulation layer in µm, and ε is permittivity.

It can be seen from the equation that the corona inception voltage can be maximized by reducing the permittivity of the insulation layer as low as possible, and by increasing the insulation layer thickness as large as possible. However, reduction of the permittivity is limited by the availability of appropriate resins and by the practical limit of engineering applicability; and increasing the insulation layer thickness may result in changing the motor design in view of slot fill factor.

The second technique aims at extending the life even in case of occurrence of corona discharge due to surges, and the technique is based on introducing insulation layers having corona discharge resistance. There are many examples reported, in which the resistance against inverter surges are provided by adding inorganic fillers to the organic enamel resin. Such techniques, however, result in a decrease in the flexibility of insulation layers, presenting a problem of insulation degradation under the influence of excessive stresses due to wire winding work.

In this development, we have studied the second technique mentioned above, i.e., insulation layers with resistance against inverter surges, carrying out development of insulation layer materials and investigation of application to enameled wires. Improvement of resistance against inverter surges can suppress insulation degradation due to the surges, thus improving insulation reliability even when exposed to excessive surges caused by inverter-controlled equipment. We have been successful, by dispersing inorganic particles into the enamel resin using a special process, in improving the inverter surge resistance, thereby also succeeding in solving the existing problem of degradation of this resistance after excessive mechanical stresses.

3. CHARACTERISTICS OF DEVELOPED WIRE

Table 1 shows the insulation layer structure of wire samples evaluated here.

3.1 Corona Inception Voltage

The corona inception voltage was measured using twisted samples under conditions of 50 Hz in frequency and 10 pC in electric charge detection limit. The results are shown in Table 2. The corona inception voltage of the developed wire is seen to be equivalent to that of the conventional wire, indicating no degradation due to the use of the developed resin.

Table 1 Insulation layer structure of wire samples evaluated.

Developed wire	Conventional wire (AIHPW)
Wire size: 0.9 mm Insulation layer: 30 µm thick	Wire size: 0.9 mm Insulation layer: 30 µm thick
Upper layer: Polyamideimide resin Lower layer: H-class resin including developed resin	Upper layer: Polyamideimide resin Lower layer: H-class polyester resin

Table 2 Corona inception voltages.

	Developed wire	Conventional wire (AIHPW)
Corona inception voltage (Vp), at 50 Hz and electric charge detection of 10 pC	805 V	798 V

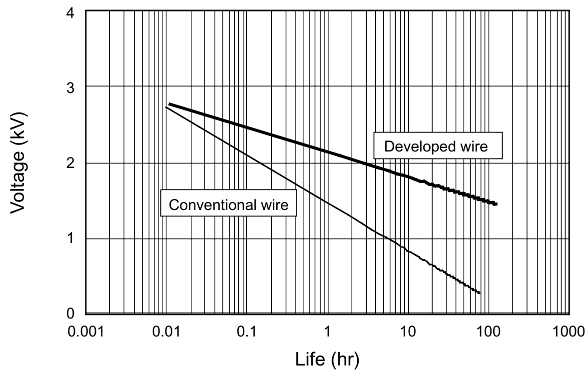

Figure 1 Comparison of V-t characteristics between the developed and conventional wires.

3.2 Evaluation of High-frequency Characteristics

To simulate the mechanical stresses due to elongation and deformation at the time of assembly into motors and insertion into slots, the wires are evaluated under an elongation of 5 %, 10 %, or 20 % depending on the circumstances. This time, the wires were twisted after being extended by 20 % --corresponding to about a half the breakage elongation-- to prepare test samples.

3.2.1 Sinusoidal Wave Life

The high-frequency characteristics of the conventional and developed wires were evaluated by measuring the time until breakdown (i.e., life) of twisted wire samples after 20 % elongation, on which a sinusoidal voltage of 10 kHz and in excess of the corona inception voltage was impressed. The results are shown in Figure 1. It has been shown that the developed wire has a life about 100 times the conventional wire under an impressed voltage of 1.5 kV. The main cause for the significant improvement of life, regardless of about the same insulation layer thickness and corona inception voltage in the case of the wire developed here, is thought to be that the speed of depletion due to corona discharge is suppressed by the newly developed resin layer, thereby significantly extending the time until breakdown.

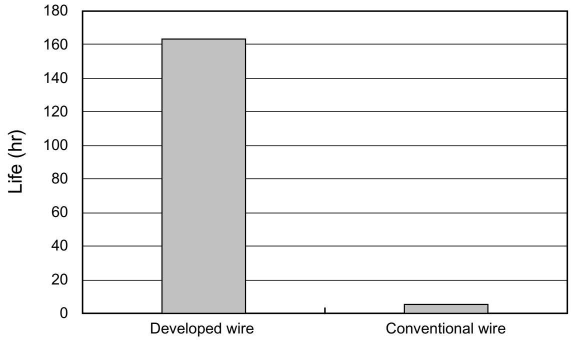

Figure 2 **Comparison of life under inverter surge between the developed and conventional wires.**

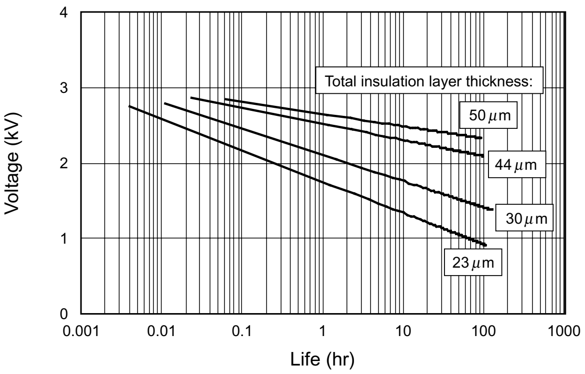

Figure 3 **Comparison of V-t characteristics of the developed wire with different insulation layer thicknesses.**

3.2.2 Life under Inverter Surge

The life under inverter surge was evaluated, using an industrial inverter commercially available, by measuring the time until breakdown of twisted wire samples, whereby the inverter output terminal and the sample were connected using a cable about 100 m in length, under conditions of an inverter input voltage of 480 V and a carrier frequency of 15 kHz, which resulted in a maximum voltage of 1.5 kV impressed on the sample. The results are shown in Figure 2. It has been shown that the developed wire has achieved a life improvement of 30 times over the conventional wire --a significant improvement. It should be noted that this improvement has been achieved using wire samples with 20 % elongation. It is therefore believed that the developed wire maintains this inverter surge resistance even in case of undergoing mechanical stresses during a winding process, thus overcoming conventional concerns.

3.2.3 Effects of Layer Thickness on High-frequency Life

Figure 3 shows the relationship, between the impressed voltage and the life under 10-kHz sinusoidal voltage, of the developed wires having insulation layers of different total thicknesses constituted by the newly developed resin. It can be seen that the lower the impressed voltage is the longer the life becomes, and there is a tendency in particular that as the layer thickness increases, the life extends significantly.

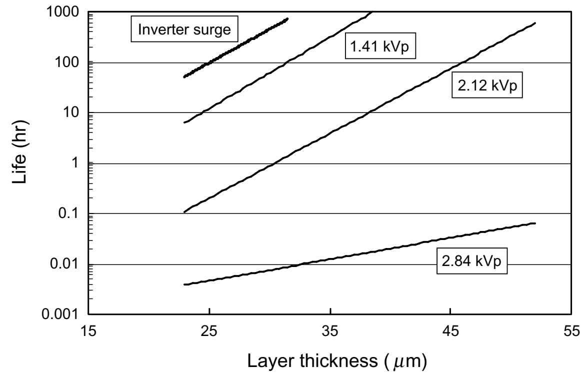

Figure 4 **Layer thickness dependence of the sinusoidal wave life under selected voltages and the life under inverter surge.**

Table 3 **Windability**

Item	Developed wire, Single, ϕ0.9 mm	AIHPW, Single, ϕ0.9 mm
Flexibility after 20 % elongation	2D	1D
NEMA heat shock test, 220°C × 30 min	OK	OK
Unidirectional abrasion (N)	20.0	15.5
Reciprocated abrasion (times)	210	205

In practical applications in inverter equipment, the carrier frequency, pulse frequency, surge voltage, etc. considerably change depending on the type of the inverter, so that the insulation reliability of the wire also changes depending on the environment of use. Figure 4 shows the layer thickness dependence of the sinusoidal wave life under selected voltages and the life under inverter surge. It can be seen that the logarithm of sinusoidal wave life is in a linear relationship with the layer thickness in the case of the same impressed voltage, and a similar tendency can be seen with the life under inverter surge. This fact suggests that a life under inverter surge can be predicted with a certain extent of accuracy based on the relationship of the sinusoidal wave life.

3.3 Windability

Table 3 shows the windability. When an automatic winding machine is used in the winding process of motor manufacturing, it is known that the wire undergoes elongation, bending, friction, etc. under a strong tension, so that the insulation layer is likely to be damaged. The wire developed here has, in comparison with the conventional wire, better abrasion characteristics, a smaller degree of flexibility degradation after 20 % elongation, and a satisfactory NEMA heat shock property. Thus the developed wire presents no problem of degradation in insulation properties at the time of winding processes, while this problem constituted a major concern for conventional wires that included inorganic fillers added.

Table 4 General characteristics.

Item	Developed wire, Single, ϕ0.9 mm	AIHPW, Single, ϕ0.9 mm
Finished size (mm)	0.956	0.956
Conductor size (mm)	0.896	0.896
Insulation layer thickness (μm)	0.030	0.030
Flexibility	1D, Good	1D, Good
Adhesion	Good	Good
Abrasion resistance (N)	20.0	15.5
Insulation breakdown voltage (kV)	13.5	13.3
Cut-through temperature (°C)	410	408
Heat shock, 220°C × 1 hr	1D, Good	1D, Good

3.4 General Characteristics

General characteristics of the developed wire are shown in Table 4. The developed wire has general characteristics equivalent to those of H-class conventional wires in terms of insulation breakdown voltage and adhesion, so that the wire is applicable to various industrial and automobile motors. Thus when used in such applications where concerns are raised about degradation of insulation reliability due to inverter driving, the wire is expected to offer high reliability.

4. IN CONCLUSION

1) The wire developed here has achieved an improvement in high-frequency life, thus offering superior resistance against inverter surges, in comparison with conventional wires.
2) Also, even after 20 % elongation, the wire improves in the life under inverter surges.
3) Basic characteristics of the developed wire are equivalent to those of conventional wires, so that the wire is applicable to various industrial and automobile motors.

REFERENCE

1) Dakin: IEEE, 5 (1959), 155