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Abstract. In the article test equipment is described for corona resistance testing of enameled winding wire samples. The primary element of equipment is generator producing test voltage with necessary waveform and magnitude according to the required PWM. Test conditions are accurately simulated by operational loads on a winding insulation (simultaneous impact of temperature and corona discharges). Obtained results of average time to breakdown show that the enamel insulation modified by silicon nanoparticles has a maximum corona resistance.

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### **I. Introduction**

Recent advances in the development field of power semiconductors and the method of pulse-width modulation allowed increasing significantly the frequency of switching operations (up to 20 kHz), minimizing power losses, and improving the performance of variable frequency drive [1]. However, increasing the switching speed reduced the rise time of the voltage pulses, which had a negative impact on the transition processes in the inverter – power cable – motor circuit. Impedance mismatches between the inverter, cable and motor excited wave processes in the cable and signal reflection phenomenon that resulted in overvoltages at the motor terminals [2–4]. Such electrical loads tightened operation conditions of VFD insulation system and, first of all, turn-to-turn insulation as the weakest element of the winding insulation. Corona discharges leading to accelerated aging of the insulation and further breakdown began appearing in voids and air gaps [5–7]. Currently, there are some standardized methods to determine the electrical, mechanical and thermal properties of the winding wire insulation. Unfortunately, there is no detailed information about any method to determine the enamel insulation resistance to the effect of corona discharges. In this regard, a reasonable choice of enameled wires for use in low-voltage machine windings with frequency regulation system is complicated. The aim of this work is to develop equipment for determining the enameled wire insulation resistance to the effect of operating loads in the VFD.

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#### II. Theory

Total operational impacts causing aging of the insulation is varied and complex, but in many cases the main reason of aging is the high electric field. The main negative factors in the VFD resulting in overvoltage appearance in LV windings are:

- high slew rate (du/dt) – high rate of inverter output voltage rise has a negative impact on the cable insulation and its winding by small distances between inverter and motor.

- overvoltages at the motor terminals - it is the result of occurring wave phenomena being sometimes called "The long transmission line effect ", "The reflected wave effect" or "The standing wave effect".

- additional losses in a motor and feeder – the higher harmonics of voltage and current lead to additional losses in feeder, motor core and winding, especially in the rotor "squirrel cage".

The destructive effect of surface discharges is a result of heating impact, charged particle bombardment (generally, electrons), the impact of chemically active products formed during the surface discharge effect, as well as impulse waves and radiation.

The effect of these factors causes erosion (destruction of the surface with material entrainment), as well as structural changes (degradation, cross-linking of the polymer chains). Erosion can be caused by the following reasons:

a) oxidation of polymers by highly reactive radicals existing only in the discharge area;

b) reactions of polymer microradicals formed under the influence of a discharge, with oxygen of gaseous atmosphere or another active material arisen as a result of the surface discharges;

c) the dielectric surface bombardment by electrons and ions.

Ozone formation is typical of discharges in the air. Ozone is very corrosive, easily oxidize. In an enclosed space ozone formation is only a transitional phenomenon. Ozone oxidizes air nitrogen, after a while ozone disappears and nitrogen oxide stays. Various stable and unstable nitrogen bonds are formed by discharges in the void filled with air.

The mechanical and electrical insulation properties are sharply deteriorated because melting, emission, carbonization and chemical decomposition occurs in the field of surface discharges effect. Conductivity and lose factor of electrical insulating material increase because of rising the temperature that enhance the local heating.

Above factors have an effect together with increased temperature. Based on these conditions, tests of enameled wire must adequately reproduce the thermal and electrical loads on winding.

#### III. Test method

Sample is the standard twisted pair placed in heat chamber. Tests are carried out at a temperature of heat resistance class [7]. High-frequency electric loads are created on the twisted pair insulation using specially designed equipment (Figure 1). Criterion is the average time to insulation breakdown.



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Figure 1 shows equipment schematic structure forming the test voltage. Further, the operating principle of equipment is stated. Generator plate A1 generates a pulse signal with amplitude  $Ua = \pm 1200 V$  feeding the test sample in the heat chamber by the high-voltage wires. Generator plate is powered by the voltage Us = 48 V from module power supply A2 through circuit breaker assembly FU1.

Accumulated counter timer A3 is activated by synchronous power supply to the generator plate and test initiation. Time is calculated until control voltage of 48 V supplies the counter. The threshold level of circuit breaker is selected so that the input current is increased in the feed network by sample breakdown and circuit breaker FU1 breaks the circuit. Tests are broken off and the accumulated counter timer A3 stops counting. Equipment turn on / off is made by the S1. The equipment construction according to the current structure provides the simplest implementation.

Generator plate schematic is shown in Fig. 2. The scheme operational principle is stated below. A rectangular voltage formation with required PWM law is realized by the processor module A1. This solution is the most ideal for solving single tasks in the case of laboratory research. Module is powered by a galvanically isolated power supply DA2. Generated signals are transmitted to the following stages via photo coupler DA1. The galvanic isolation of the processor module allows providing the equipment resistance to interference. Driver DA3 separates signals on two channels and enters a pause between control pulses of 0.4 us by the power transistors. Drivers of control transistors VT1 and VT2 are implemented on chips DA4 and DA5 respectively. Switching circuits are identical and correspond to the standard ones recommended by manufacturer. Consider the example of driver work on the circuit DA4. Switching on is carried out by LED through a resistor R1. Chain C10, R5, VD3 protects the transistor VT1 against overcurrent, including short circuit. Resistor R1 limits the switching speed of transistor and protects the output stage circuit DA4 against overcurrent. Diode VD1 and resistor R7 provide protection of transistor gate against overvoltage and increase resistance to interference. Diode VD5 provides a path flow of reverse current when the transistor VT1 is off. The power stage is built by the scheme of circuit transformer with a common point. This scheme enables efficient operation of equipment at a low supply voltage. Transformer T1 increases the test voltage up to  $\pm 1200$  V, and provides galvanic isolation of equipment from high-voltage circuit. The output voltage is supplied to pins 3 and 4 of the connector X1. Supply voltage 48V is supplied to the generator plate through the terminals 1 and 2 of connector X1.



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## IV. EXPERIMENTAL RESULTS

The general scheme of tests is shown in Figure 3.



Figure 3. Block-scheme of high-voltage test equipment.

During the tests were obtained values of the mean time to breakdown samples wires with enamel isolation of various types. Samples were tested as in the initial state and after impregnation with impregnating materials. For each experiment was tested at least 20 samples. Summarized results are presented in Table 1.

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Wire insulation type	Impregnating	Average time to
	compound type	breakdown <b>t</b> <sub>br</sub> , s
1 layer (inner) – 3-hydroxiethylcyanurate varnish,	Without IC	9509
comprising at least 0.1 volume percent of silicon	КО-916К	10664
nanoparticles,	KP-50	14728
2 layer (outer) – polyamide imide varnish	KP -55-5	11412
1 layer (inner) – polyester varnish , 2 layer (outer) – polyamide imide varnish	Without IC	2009
	КО-916К	1286
	KP -50	1278
	KP -55-5	1192
Polyester varnish	Without IC	2337
	КО-916К	1085
	KP -50	1736
	KP -55-5	1812

Table 1. Determination of average time to wire twists breakdown by high voltage tests

# V. Conclusion

1. Tests on the high voltage laboratory bench allow producing the whole range of operating loads, closest to the real operation of the VFD winding with PWM. In this case, temperature, electrical voltage, corona discharges influence on sample.

2. Developed equipment generates electrical impulses exciting appearance of stable corona discharge across the twisted part of the sample during the entire experiment. The value and shape of electrical impulses adequately reproduce overvoltages caused by the PWM operation: an alternating voltage with the amplitude of 1200 V, frequency of 400 Hz with the quantization voltage frequency (modulation) of 5 kHz (the duration of the wave front), with the rate of pulse rise 4 ms.

3. Wire with two-layer insulation modified by silicon nanoparticles has the greatest time to a breakdown. It is apparently associated with non-traditional mechanism of wire insulation destruction modified by nanoagents. In case of conventional wire aging, corona discharges cause material

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destruction processes leading to the polymer chains break and the formation of free radicals and the volatile decomposition products. It results in relatively rapid insulation breakdown. But in the case of corona resistance wires, nanoparticles put into the enamel insulation have a strong interaction between the particles (bond strength) by the corona resistance development. Thus, it creates a kind of protective layer slowing the insulation breakdown during the material degradation.

### References

- [1] Melfi M, Sung A M J, Bell S, Skibinski G L 1998 Industry Applications, IEEE Transac-tions on p 766 - 775
- [2] Stone G C, Culbert I M, Lloyd B A 2007 Cement Indus-try Technical Conference Record, IEEE, p 187 – 192
- [3] Bogh D, Coffee J, Stone G, Custodio J 2006 Industry Applications, IEEE Transactions on p 148 154
- [4] Fenger M, Campbell, S R, Pedersen J 2003 Industry Applications Magazine, IEEE p 22-31
- [5] USSR copyright certificate №536443, MIIK5 G01R31/00, published 25.11.1976
- [6] Pulse width modulation simulator for testing insulating materials. US Patent No. 6051980, Is-sued on April 18, 2000.
- [7] Leonov A P, Red'ko V V, Soldatenko E Yu 2014 20<sup>th</sup> International Conference for Students and Young Scientists: Modern Techniques and Technologies (MTT'2014), Tomsk, Russia Vol. 66