Barbara FLORKOWSKA[1], Marek FLORKOWSKI[2], Paweł ZYDROŃ[1], Józef ROEHRICH[1]

AGH University of Science and Technology, Krakow, Poland[1]
ABB Corporate Research Center, Krakow, Poland[2]

doi:10.15199/48.2016.10.05

Experimental evaluation of breakdown voltage and life time for models of the low voltage electrical motors windings

***Abstract**. Modern electric motors of small power are often supplied with electronic power converters producing PWM voltages. For this reason, it is necessary to study the properties of winding insulation of these motors using pulse voltages with variable rise times and switching frequencies. The paper describes the results of investigations of magnet wires insulation with different diameters in a standardized model samples, for the assessment of their resistance to exposure on pulse voltages.*

Streszczenie**. Współczesne silniki elektryczne małych mocy są często zasilane z przekształtników energoelektronicznych wytwarzających napięcia typu PWM. Z tego powodu zachodzi konieczność badania właściwości izolacji uzwojeń tych silników z zastosowaniem napięć impulsowych o zmiennych czasach narastania oraz częstotliwościach kluczowania. Artykuł opisuje wyniki badania izolacji drutów nawojowych o różnych średnicach w standaryzowanych próbkach modelowych, dla oceny ich odporności na narażenia napięciami impulsowymi. **(Eksperymentalna ewaluacja napięcia przebicia i czasu życia dla modeli uzwojeń niskonapięciowych silników elektrycznych.)

Keywords: electric motors, low voltage windings, breakdown voltage, twisted-pair
Słowa kluczowe: silniki elektryczne, uzwojenia niskonapięciowe, napięcie przebicia, para skręcona

Introduction

Power electronic switching devices used in construction of voltage inverters are the dominant technology applied for modern low voltage electric motor drives. Because of many advantages low voltage induction motors are usually controlled by PWM (Pulse Width Modulation) voltages which produce very fast slopes and overvoltages, as result of several synergistic reasons that lead to many undesirable effects [1-9]. Such working conditions strongly influence on motor insulating system, the inception and dynamics of partial discharges developing in insulation of windings, and also on the breakdown voltage of insulation [7-14]. For this reason the influence of fast rising, high frequency pulse voltages is a topic problem for researches in the area of new materials for magnet wires insulation [13-17].

In laboratory experiments with twisted-pair (TP) model samples [18] the impact of the construction of samples and parameters of external stresses on the breakdown voltage and time to breakdown have been researched.

Controlled parameters of the test were: wire diameter, number of turns in TP sample, the type of test voltage (AC, pulse-like PWM voltage), voltage pulse repetition/switching frequency (up to 10 kHz), pulse rise time.

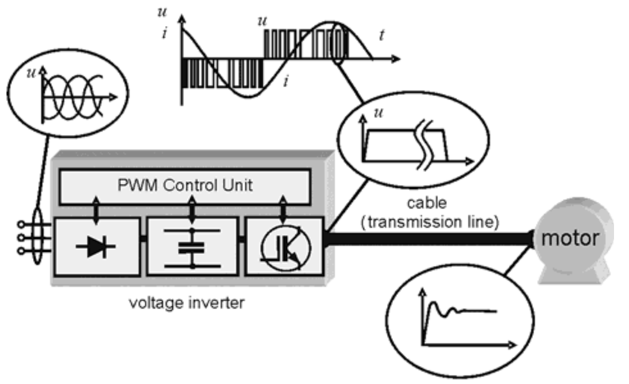

Fig. 1. Path and mechanism of overvoltage generation for *inverter-cable-motor* configuration

Described investigations do not belong to the tests listed in the relevant standard documents [19-22]. Expanding the scope of researches demonstrate that these factors may be important to assess the resistance of the windings wires on working stresses and their appropriate selection for specific applications.

Voltage stresses in electric motor insulation system

Random wound windings of low-voltage, low-power motors are made from round, enameled magnet wire. One turn consists of several spools of wire. As turns are randomly distributed, they can be in a close proximity to a number of other turns. Throughout the axial length of the coils, wires can migrate during manufacturing and take new positions with respect to other coils. When migration occurs, as the result electrical stresses between turns can increase.

The stator can be either dipped in resin or vacuum-pressure impregnated. In impregnation process, the resin fills the pockets and seals any openings present in the end windings. However, wires may be loose and vibrate with respect to each other, depending upon the resin treatment. This mainly happens when the motor is controlled by ASD, and the insulation is stressed by overvoltages of several hundred volts.

During working conditions, the electrical stresses will be created in the following locations in the insulating system: between conductors in different phases or phase-to-phase (U_{PP}), between turn-to-turn (U_{CC}), and between a phase conductor and ground (U_{PG}) – Figure 2.

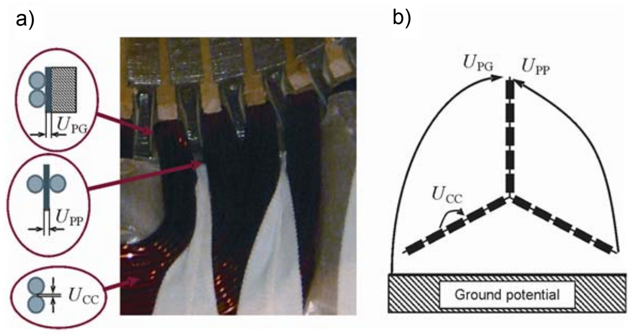

Fig. 2. Electrical stresses of motor insulating system [5]: a) insulating system of inverter fed motor b) voltages for star-connected motor: $U_{P\text{-}P}$ – phase-to-phase voltage, U_{CC} – conductor-to-conductor voltage, U_{PG} – phase-to-ground voltage

Voltages stressing the elements of insulation are:
- the maximum voltage stress on the phase-to-phase

insulation,
- the maximum voltage stress on the conductor-to-conductor insulation,
- the maximum voltage stress on the phase-to-ground insulation.

In the conventional 50/60 Hz motors rated up to 575 V the phase-to-phase insulation must withstand 575 V_{rms}, whereas the ground insulation must withstand 332 V_{rms} [23]. The calculation of maximum voltage stress for turn insulation is complicated because the adjacent of the turn-to-turn is random. In the worst case one can assume the voltage stress to be 575 V. In this type of motors the voltage stress does not cause the deterioration processes in their insulation materials. In the inverter-fed motors deterioration processes are possible due to generation of surge over-voltages on the motor insulation system.

Evaluation of breakdown voltages for twisted-pair models representing motor windings insulation

The assessment of insulation quality of enameled wires was based on a comparison of the breakdown voltage of standardized twisted-pair samples [18] with wires different diameters (signed individually as TPx.x, TPx.xC, and TPx.xCC; where x.x is a diameter of wire and only samples with CC index had corona resistant CR enamel insulation), containing various number of twists *ts*: 1, 3, 5, 10 and 15 (Fig. 3) tested at sinusoidal voltage and pulse voltages.

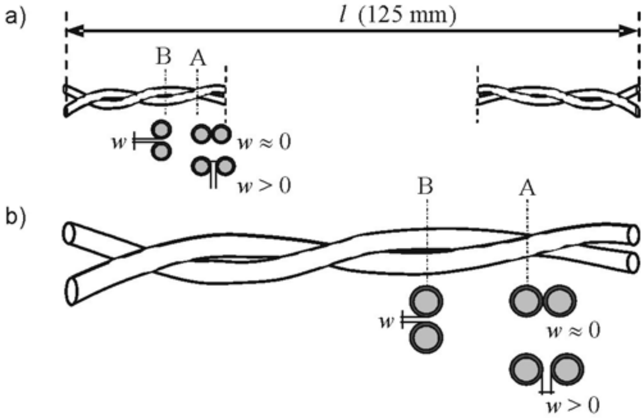

Fig. 3. Geometry of standardized twisted-pair (TP) samples

During laboratory researches the following voltage sources were used.

I. The sinusoidal voltage (50 Hz) source was applied as a reference and denoted as VSIN50.

II. Semi-square voltage SSV

As a SSV source, the HV amplifier TREK 20/20B controlled by a programmable function generator Analogic 2030 was used. The parameters of this source are:
- voltage range of the amplifier is 40 $kV_{p\text{-}p}$,
- frequency in the range from 0 to 500 Hz,
- maximum voltage slew rate 350V/μs.

To control the rise time t_r of the pulse voltage, the capacitor C_0 was connected in parallel with the tested samples. The total capacitance of the test sample and the capacitance C_0 were set at about 1000 pF (the capacitance of test sample was from 20 pF to 50 pF). It enabled to form the slew-rates of trapezoidal voltage t_{r1} = 1 kV/160μs and t_{r2} = 1kV/5.8 μs, then the following notation is used for different parameters of semi-square test voltages:
- SSV1 – t_{r1} = 1kV/160 μs f = 50 Hz
- SSV2 – t_{r2} = 1 kV/5.8 μs f = 50 Hz
- SSV3 – t_{r2} = 1kV/5.8 μs f = 500 Hz

III. PWM-like voltage – type PV1

The first PWM like voltage source was the pulse generator with the following parameters:
- the maximum voltage up to 4 $kV_{p\text{-}p}$,
- repetition/switching frequency from 50 Hz to 10 kHz,
- the voltage slew rate 1 kV/μs.

IV. PWM-like voltage type – PV2

The second PWM-like voltage source was the pulse generator with following parameters:
- the maximum voltage 6 $kV_{p\text{-}p}$,
- bipolar or unipolar output configuration,
- impulse repetition/switching frequency up to 6 kHz (1.5 kHz in long-term tests),
- the voltage rise time of the generator is controlled by changing of output circuit parameters value in the range from 800 ns to 3 μs.

The corresponding configurations mentioned in the text, depending on the rise time and frequency, are denoted as PV2-1, PV2-2, etc.

The breakdown voltages U_{BD} at AC voltage for samples with wires diameters 0.315 mm (TP0.3) and 0.8 mm (TP0.8) are shown in Table 1 and in Figure 4.

Table 1. Breakdown voltage U_{BD} at AC voltage for samples TP0.3 and TP0.8 for a different number of twists *ts*

Sample type	Breakdown voltage U_{BD} [kV] at AC voltage				
	ts = 1	*ts* = 3	*ts* = 5	*ts* = 10	*ts* = 15
TP0.3	11	10.2	10.0	9	8
TP0.8	21.0	20.0	19.6	17.5	17.2

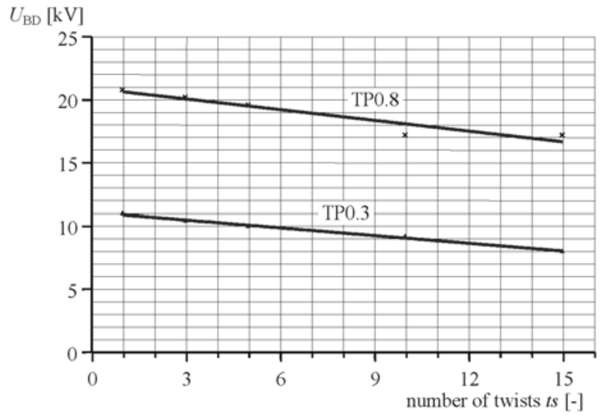

Fig. 4. The dependence of breakdown voltage U_{BD} on the number of twists in samples TP 0.3, TP 0.8 (AC voltage)

Two indicators were used for assessment of test parameters on breakdown voltage of TP samples:
- a ratio of breakdown voltage at *ts* =1 to *ts* = 15:

$$k_{BD,ts} = \frac{U_{BDts1}}{U_{BDts15}} \tag{1}$$

for samples TP0.3 and TP0.8 approx. equals to 1.4,
- a ratio of breakdown voltage at TP0.8 to TP0.3;

$$k_{BD,TP} = \frac{U_{BD,08}}{U_{BD,03}} \tag{2}$$

is for *ts* = 10 approximately equal to $k_{BD,TP}$ = 2.

The results of breakdown voltage evaluation for SSV and VSIN50 (as reference) voltage sources are shown in Tables 2 and 3, and also on Figures 5 and 6.

Table 2. The breakdown voltage U_{BD} of TP0.3C samples at SSV and VSIN50 with various rise time and frequency

Number of twists *ts* [-]	Breakdown voltage U_{BD} [kV]			
	SSV1	SSV2	SSV3	VSIN50
1	12.8	11.2	8.0	16.5
3	10.6	8.4	6.6	14.0
5	7.8	7.2	4.8	11.4
10	6.4	6.2	4.5	9.0
15	6.2	6.0	4.5	8.1

Table 3. The breakdown voltage U_{BD} of TP0.8CC samples at SSV and VSIN50 with various rise time and frequency

Number of twists *ts* [-]	Breakdown voltage U_{BD} [kV]			
	SSV1	SSV2	SSV3	VSIN50
1		20.0	16.8	25.0
3	20.0	17.6	14.6	21.4
5	17.2	14.0	13.0	19.6
10	12.6	12.0	10.6	14.6
15	10.5	10.0	9.0	12.0

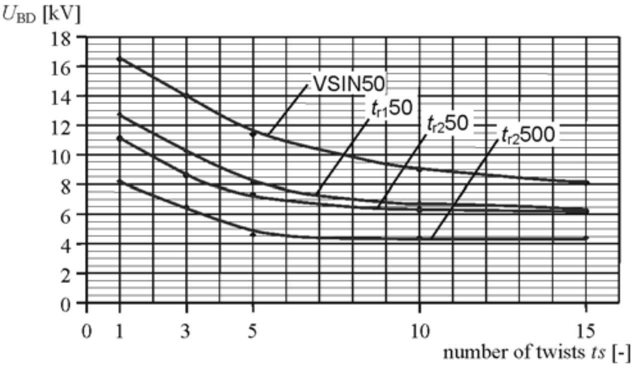

Fig. 5. The dependence of breakdown voltage U_{BD} of TP0.3C samples on number of twists *ts* at voltage VSIN50 and semi-square voltages SSV: 1) t_{r1}, 50 Hz, 2) t_{r2} 50 Hz, 3) t_{r2} 500 Hz

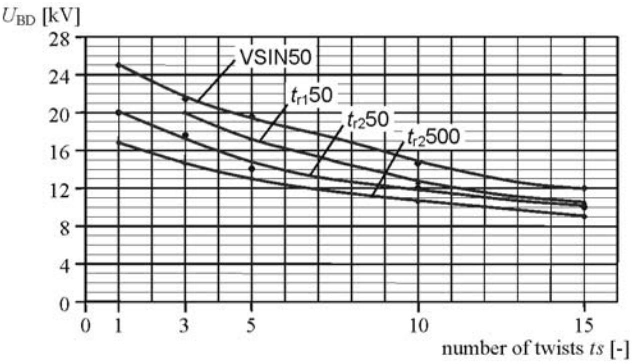

Fig. 6. The breakdown voltage U_{BD} vs. number of twists *ts* for TP0.8CC samples at voltage VSIN50 and semi-square voltages SSV: 1) t_{r1}, 50 Hz, 2) t_{r2} 50 Hz, 3) t_{r2} 500 Hz

The following influence of voltage SSV rise time on breakdown voltage of the TP samples was observed:

- when rise time t_r is shorter, the breakdown voltage is smaller, i.e.:

  $t_{r2} < t_{r1}$ then $U_{BD}\,\mathrm{SSV}t_{r2} < U_{BD}\,\mathrm{SSV}t_{r1}$
- further increase of frequency of voltage SSV will lead to the decrease of breakdown voltage U_{BD}:

  $U_{BD}\,\mathrm{SSV}t_{r2}\,(500\ \mathrm{Hz}) < U_{BD}\,\mathrm{SSV}t_{r2}(50\mathrm{Hz})$
- breakdown voltage at SSV is smaller than at sinusoidal voltage:

  $U_{BD}\,\mathrm{SSV} < U_{BD}\,\mathrm{VSIN50}$
- there is a distinct impact of the number of twists *ts* on the breakdown voltage U_{BD} for ts = 1÷3, but in the range ts = 10÷15 this influence is practically not visible. One may notice, that breakdown voltage U_{BD} in the case of ts = 1 is much higher than for ts = 15:

  $U_{BD}\,\mathrm{SSV}_{ts=15} < U_{BD}\,\mathrm{SSV}_{ts=1}$

Characteristic indicators k_{BD}, defined as a ratio between breakdown voltage at ts = 1 to breakdown voltage at ts = 15 are presented in Table 4.

Table 4. Definitions and values of k_{BD} indicators (notation in Table as above)

Selected characteristic indicators	TP0.3	TP0.8CC
$k_{BD}SSV_{tr1}(50) = \frac{U_{BD}tr_1, ts=1}{U_{BD}tr_1, ts=15}$	2.1	2.0
$k_{BD}SSV_{tr2}(50) = \frac{U_{BD}tr_2, ts=1}{U_{BD}tr_2, ts=15}$	1.9	2.0
$k_{BD}SSV_{tr2}(500) = \frac{U_{BD}tr_2\,500, ts=1}{U_{BD}tr_2\,500, ts=15}$	1.8	1.8

The indicator defined as a ratio of breakdown voltage at sinusoidal voltage VSIN50 to breakdown voltage at semi-square voltage SSV3:

$$k_{BD,V} = \frac{U_{\mathrm{BD,VSIN50}}}{U_{\mathrm{BD,SSV3}}} \tag{3}$$

is for TP0.3C sample with ts = 10, equal to $k_{BD,V}$ = 2, and for TP0.8CC sample equal to $k_{BD,V}$ = 1.45.

Breakdown voltage goes up with the increasing wires diameter as a result of electric field stress distributions changes (maximum electric field stress at wire surface decreases with diameter increasing). It can be noticed that application of CC type insulation (corona resistant CR enamels) significantly influences on increasing of breakdown voltage value (Fig. 7, sample TP0.8CC).

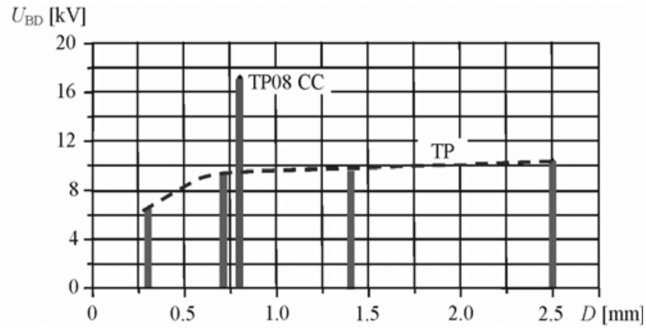

Fig. 7. Comparison of breakdown voltage at SSV for different wires diameters D of TP samples (ts = 10)

Evaluation of time to breakdown for twisted pair models

An important indicator of the quality of magnet wires insulation is the lifetime, that could be determined by the time to breakdown t_{BD} at the constant value of the test voltage. Such experiments were performed on TP samples with different twist number, subjected to PWM-like voltage with magnitude $U_{p\text{-}p}$ = 5 kV, rise time of pulses 800 ns, repetitive rate 50 Hz and 1500 Hz, namely:

- PWM voltage at 50 Hz, denoted PV2-50
- PWM voltage at 1500 Hz, denoted PV2-1500

The experimental results obtained for two kinds of samples TP0.3 and TP0.5 are shown in Table 5.

Table 5. Time to breakdown t_{BD} of TP0.3 and TP0.5 samples at PWM-like voltage $U_{p\text{-}p}$= 5 kV, at 50 Hz and 1500 Hz

Number of twists ts [-]	Time to breakdown t_{BD} [min]			
	TP0.3		TP0.5	
	PWM 50 Hz	PWM 1500 Hz	PWM 50 Hz	PWM 1500 Hz
1	110	19	140	23
3	85	15	124	20
5	73	7	116	13
10	44	6	90	12
15	25	4	62	9

Figure 8 shows the relationship between time to breakdown t_{BD} and number of twists ts for repetition rate 50 Hz and 1500 Hz of PWM-like voltage.

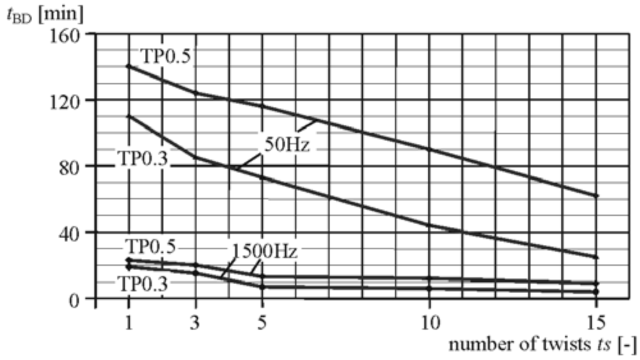

Fig. 8. The relationship between time to breakdown t_{BD} and number of twists ts at PWM-like voltage $U_{p\text{-}p}$= 5 kV, for 50 Hz and 1500 Hz

The time to breakdown t_{BD} of TP samples at PWM-like voltage depends on:

- diameter of wires – time t_{BD} is longer for wires with bigger diameter,
- repetition rate of voltage – at 1500 Hz time t_{BD} is much shorter than at 50 Hz, for example for TP0.5 (ts = 10) the indicator k_{BD}:

(4)
$$k_{BD,f} = \frac{t_{BD,50}}{t_{BD,1500}}$$

at ts = 10 is approximately equal to $k_{BD,f}$ = 8.

Comparison of time to breakdown t_{BD} of TP samples with different diameter of the wires: 0.31 mm, 0.56 mm, 0.8 mm C and 0.8 mm CC with constant number of twists ts =10 at PWM 1500 Hz, 5 kV, is summarized in Table 6 and in Figure 9.

Table 6. Time to breakdown t_{BD} for TP samples with different diameter of wires, test voltage 5 kV, ts = 10, 1500 Hz

t_{BD} [min]			
D [mm]			
TP0.3	TP0.5	TP0.8	TP0.8CC
6	12	55	240

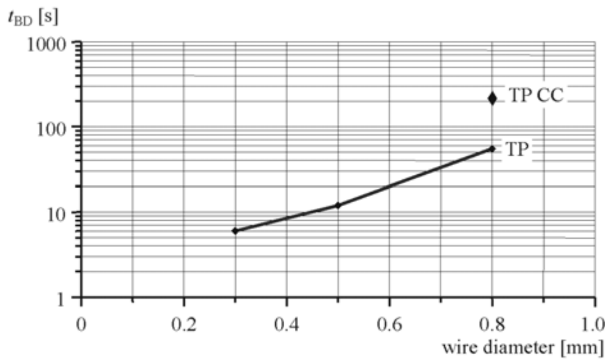

Fig. 9. Comparison of time to breakdown t_{BD} at PWM-like voltage 5 kV, 1500 Hz for different wires diameter (ts = 10)

The indicator exhibiting the ratio of time to breakdown at ts =1 to t_{BD} at ts =15, at f = 50 Hz is equal to:

(5)
$$kt_{BD,ts} = \frac{t_{BD}(ts1)}{t_{BD}(ts15)}$$

and for samples TP0.3 equals to $kt_{BD,ts}$ = 4, and for samples TP0.5 $kt_{BD,ts}$ = 2.3.

At the frequency 1500 Hz the indicator $kt_{BD,ts}$ for samples TP0.3 and TP0.8 yields respectively 2.9 and 4.0.

The measurements results of t_{BD} at the stress exhibiting short rise time (PWM-like voltage PV3, 1500 Hz, t_r = 800 ns) referred to sinusoidal voltage AC (VSIN50) are shown in Table 7 and in Figure 10. They illustrate meaningful influence of PWM stresses for endurance reduction of magnet wires. At the test voltage $U_{p\text{-}p}$ = 5kV and number of twists ts =10, the time to breakdown t_{BD} at PWM 50Hz is approximately 15 times shorter than at VSIN50 voltage.

Table 7. Time to breakdown t_{BD} for TP0.5 at PWM50 and VSIN50, $U_{p\text{-}p}$= 5 kV

Voltage	t_{BD} [h]				
	Number of twists ts [-]				
	1	3	5	10	15
PWM50	3.0	2.0	1.7	1.5	1.0
VSIN50	19.0	17.5	18.0	15.0	13.0

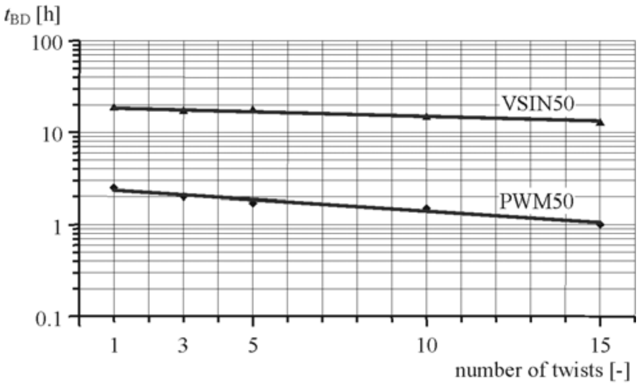

Fig. 10. Comparison of time to breakdown at PWM50 and VSIN50 voltage $U_{p\text{-}p}$= 5 kV, TP0.5

The indicator exhibiting the ratio of time to breakdown at PWM-like voltage to time to breakdown at sinusoidal voltage is equal to:

(6)
$$k_{BD,V} = \frac{t_{BD\_PWM}}{t_{BD\_VSIN50}}$$

for different number of twists in TP samples, is equal approximately to 0.1.

Summary and conclusions

It is known that pulse voltages produce stresses causing lower endurance of enameled magnet wires than at the sinusoidal voltage. Additionally, an increase of pulse voltage steepness and increase of frequency will enhance that effect. For this reason new insulating materials are introduced for increasing reliability of the electric motors driven from modern power inverters. Standardized methods of magnet wires insulation testing are used for assessment of their long-term insulating properties. Tests described in the paper have shown that consideration of additional factors widens the scope of information on the causes of damages of windings in operation.

The results of experiments revealed the impact of PWM-like voltages on the basic parameters describing the models representing motor windings insulation systems, like a breakdown voltage U_{BD} and time to breakdown t_{BD}.

Summarizing:
- Pulse (PWM-like) voltages produce stresses which shorten the life of enameled wires insulation.
- Breakdown voltage at pulse voltages is lower than at sinusoidal one, independent of the type of wires in the sample and number of twists.
- If the pulse rise time is shorter, the observed effect is stronger.
- Increase of the repetition/switching frequency of voltage pulses will lead to further decrease of breakdown voltage.
- The design and manufacturing of TP samples has impact on results of experiments, particularly in the comparative study. For this reason, special attention should be paid to proper model sample preparation.
- In TP samples with different number of twists, the number of contact spots between the twisted wires will be also different. The enameled wires may contain manufacturing defects like: inhomogeneous insulation thickness and gaseous micro-inclusions in the insulation. Those defects are distributed along the wire length. Both have influence on the breakdown voltage U_{BD} and PD mechanism. It was observed that the breakdown voltage drops with a higher number of twists in TP sample. This effect is caused mainly by higher number of contact spots in the sample. The decrease of breakdown voltage with an increase of twists, thus with higher number of contacts spots in samples, can be caused by higher probability of weak points along the wire lengths in the sample.
- In the case of bigger wire diameter in TP samples, the electric field distribution is more homogeneous and at the same test voltage, in samples with smaller diameter the electric field strength at the surface is higher. This effect and the smaller insulation thickness for those wires result in a shorter time to breakdown for samples with smaller diameter.
- Application of CC type insulation (*Corona Resistant* CR enamels) in magnet wires has significant influence on increasing of breakdown voltage.

The results of described experimental studies of magnet wires showed high sensitivity to changing parameters of the test. It follows that there is the need to maintain high repeatability of the basic parameters used in the sample tests. In the absence of a comprehensive and detailed standardization the results of materials and TP samples researches obtained in different laboratories may be not comparable. Additional statistical indicators (for example proposed in the paper) support proper evaluation of experimental data and assessment of insulation properties.

Authors:
prof. dr hab. inż. Barbara Florkowska, dr hab. inż. Paweł Zydroń prof. n. AGH; dr inż. Józef Roehrich, Akademia Górniczo-Hutnicza im. St. Staszica w Krakowie, al. Mickiewicza 30, 30-059 Kraków, Poland; e-mail: beflor@agh.edu.pl, pzydron@agh.edu.pl; roehrich @agh.edu.pl; dr hab. inż. Marek Florkowski,, ABB Corporate Research Center, ul. Starowiślna 13a, 31-038 Kraków, Poland, e-mail: marek.florkowski@pl.abb.com

REFERENCES

[1] Bonnett A. H., Analysis of the impact of pulse-width modulated inverter voltage wave forms on ac induction motors, IEEE Annual Pulp & Paper Ind. Techn. Conf., 1994, 68-75
[2] Oliver J. A., Stone G.C., Implications for the applications of adjustable speed drive electronics to motor stator winding insulation, *IEEE El. Insul. Mag*., (1995), 32-36
[3] Kerkman R. J., Leggate D., Skibinski G., Interaction of drive modulation and cable parameters on AC motor transients, *IEEE Trans. Ind. Appl*., 33 (1997), no. 3, 722-731
[4] Yin W., Failure mechanisms of winding insulation in inverter-feed motors, IEEE Electr. Insul. Mag., 13 (1997), no. 6, 18-23
[5] Kaufhold M., Aninger H., Berth M., Speck J., Eberhardt M., Electrical stress and failure mechanism of the winding insulation in PWM-inverter-fed low voltage induction motors, *IEEE Trans. Industr. Electron*., 47 (2000), 396-402
[6] Glinka T., Kulesz B.: Wyładowania niezupełne w izolacji zwojowej silników indukcyjnych zasilanych z falowników PWM, *Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Polit. Wrocławskiej*, 49 (2000), 96-103
[7] Wheeler J. C. G., Effects of converter pulses on the electrical insulation in low and medium voltage motors, *IEEE Electr. Insul. Mag*., 21 (2005), No. 2, 22-29
[8] Haq S.U., Jayaram S.H., Cherney E.A., Insulation problems in medium-voltage stator coils under fast repetitive voltage pulses, *IEEE Trans. Industry Appl*., 44 (2008), no 4, 1004-1012
[9] Florkowska B., Florkowski M., Furgał J., Roehrich J., Zydroń P., The voltage stresses of insulation systems under PWM inverter supplies, 2009 IEEE CEIDP Annual Report, 648-651
[10] Cavallini A, Fabiani D., Montanari G.C., Power electronics and electrical insulation systems – Part 1: Phenomenology overview, *IEEE Electr. Insul. Mag*., 26 (2010), no. 3, 7-15
[11] Florkowska B., Florkowski M., Furgał J., Pająk P., Roehrich J., Zydroń P., Influence of fast switching phenomena on electrical insulation systems, *Przegląd Elektrotechniczny*, 86 (2010), nr 4, 158-161
[12] Florkowska B., Zydroń P., Florkowski M., Effects of inverter pulses on the electrical insulation system of motors, IEEE Int. Symp. Industrial Electronics, Gdańsk, 2011, 573-578
[13] Florkowska B., Florkowski M., Furgał J., Roehrich J., Zydroń P., Impact of fast transient phenomena on electrical insulation systems, AGH Press, Kraków, 2012
[14] Florkowska B., Florkowski M,, Roehrich J., Zydroń P., Modelling of degradation process of electrical insulation systems due to inverter pulses, *Przegląd Elektrotechniczny*, 90 (2014), nr 12, 320-324
[15] Wang P., Cavallini A., Montanari G.C., The influence of repetitive square wave voltage parameters on enameled wire endurance, *IEEE Trans. Dielectr. Electr. Insul*., 21 (2014), no. 3, 1276-1284
[16] Manh Quan Nguyen, Malec D., Mary D., Werynski P., Gornicka B., Therese L., Guillot, P., Silica nanofilled varnish designed for electrical insulation of low voltage inverter-fed motors, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 5, 2010, pp. 1349-1356
[17] Hoang A.T, Hammarström T. J., Bengtsson T., Serdyuk Y.V., Gubański S.M., Partial discharge behavior of a newly developed enamel insulation at various voltage rise times, Proc. ISEIM'2014, 241-244
[18] IEC 60851-5 ed. 4.0 (2008-07): Winding wires – Test methods – Part 5: Electrical properties
[19] IEC 60034-18-41 (2012) Rotating electrical machines - Part 18-41: Qualification and type tests for Type I electrical insulation systems used in rotating electrical machines fed from voltage converters
[20] IEC 60034-18-42 TS ed 1.0 (2008): Rotating electrical machines – Part 18-42: Qualification and acceptance tests for partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters
[21] IEC/TS 61934 ed. 2.0 (2011-04): Electrical insulating materials and systems – Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses
[22] IEC 62068-1 ed. 1.0 (2003-07): Electrical insulation systems – Electrical stresses produced by repetitive impulses – Part 1: General method of evaluation of electrical endurance
[23] Stone G., Culbert M., Lloyd B.A., Stator insulation problems associated with low voltage and medium voltage PWM drives, IEEE Cement Industry Technical Conference, 2007