Selected Diagnostic Methods of Electrical Machines Operating in Industrial Conditions

Marcin Barański, Adam Decner and **Artur Polak**
Institute of Electrical Drives and Machines KOMEL
188 Rozdzienskiego Ave
40-203 Katowice, Poland

ABSTRACT

The article proposes a series of tests on the groundwall insulation, utilizing the dc voltage and consisting of three related procedures. After running the tests, the obtained data are analyzed and insulation is graded in accordance with proposed criteria. These criteria are presented in the paper. The method has been illustrated by real-life example of electrical machine tests' results. The article describes the turn-to-turn insulation substitute circuit and results of simulations and measurements. There is shown a new diagnostic method to determinate condition of this insulation. The suggested method can be used in any kind of machine and it is easy to use. The most commonly damaged machine parts, except the insulation, are bearings, so the authors decided to mention in the article, about vibration measurements.

Index Terms - **Rotating machine insulation testing, vibration measurement.**

1 INTRODUCTION

ELECTRICAL machines, which operate in a majority of factories like cement plants, chemical plants, steel plants are subjected to a considerable influence of conditions in their location. During the time of repairs, diagnostic tests of electrical machines are carried out. Some of the tested motors have built-in heating systems which limit the absorption of moisture by the insulation of the windings, whereas others have no such heating systems and that is reflected in the received results. Many different testing methods of groundwall and turn-to-turn insulation are described in literature [1-12]. But in this article authors describe very easy to use and inexpensive method of tests on the groundwall insulation, which is recommended to use after each repair of the machine. This recommendation is placed in Polish Standard [13]. Method of testing the turn-to-turn insulation is newly developed. Statistics of machines failures show that the most frequent (about 85%) are damages of windings and bearings [2].

Vibrations in electrical machines are undesirable, their high level, higher than the acceptable level, is considered to be a symptom of failure. Ignoring these symptoms entails a real risk of a catastrophic failure, where costs can often exceed the cost of the drive. The task of vibration diagnostics is to collect and process the information about degree of components' deterioration. The majority of vibration diagnostic for electrical machines is based on measurements which are done with external sensors connected to complicated and expensive meters or analyzers which are dedicated for this purpose. In such situations, mounting of vibration sensor is often problematic, because the machine is rarely designed by the manufacturer for this purpose. Methods for detection of increased levels of vibration in classical electrical machines encountered in industrial applications is well known and described in the literature [1, 14, 15]. Authors decided to focus on a relatively new issue - the problem of vibration in machines with permanent magnets.

The other method newly developed by the authors described in this article for detecting vibrations in electrical machines with permanent magnets is a measurement system that does not require the use of sensors. Excitation circuit and armature winding perform a function of the vibration sensor at the same time. Vibration measuring sensors are used ones, for scaling the measurement. Vibration measurement with this method can be performed on-line during normal operation of the machine [16-19].

2 ASSESSMENT OF INSULATION DEGREE OF DEGRADATION

The DC voltage diagnostic tests of insulation in electrical machines are the simplest method of testing. The method consists of three tests:

- designating the characteristic of $R_{60} = f(U)$, if possible - range of voltage from 0 up to $2U_N$,
- characteristic of leakage current i_p after the nominal voltage is connected on the absolutely discharged winding,
- charging the winding to the nominal voltage, then disconnecting the source of voltage and fault to frame the capacitance of winding for the time t_z, and next opening the circuit and recording the characteristic of the recovery voltage on the insulation of the stator winding $U_{od}(t)$.

The first two tests are commonly used in periodical tests of insulation, because this is required in the instructions of operation. However, the range of these tests is usually limited to 500 V, 1000 V or 2500 V, sometimes 5000 V.

Manuscript received on 5 February 2014, in final form 21 March 2014, accepted 21 March 2014.

DOI 10.1109/TDEI.2014.004602

In the suggested program of tests, the range of the tests is extended to designate the characteristic $R_{60} = f(U)$ in the range of voltage up to $2U_N$, and the characteristic of the leakage current $i_p = f(t)$ by the nominal voltage.

The third test, the recovery voltage, is the most important test in the diagnostics of the technical condition of insulation and estimating the rate of its deterioration.

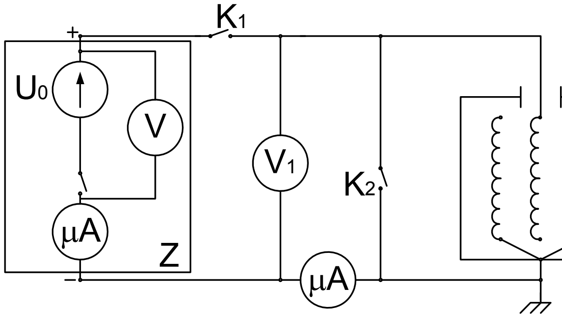


Figure 1. Scheme of circuit connections for the diagnostics of the groundwall insulation.

The tests are made in a circuit as shown in Figure 1. The basic elements of this circuit are a regulated DC supply (U_0), a micro ammeter, a voltmeter and switches allowing the implementing of particular tests [1, 23 – 27].

On the basis of the measurements, the following characteristics and parameters of insulation are calculated:

- a chart of insulation resistance $R_{60} = f(U)$ in the voltage range from 0 to $2U_N$, from which the resistance of insulation by the nominal voltage is calculated,
- from the extrapolation of curve $R_{60} = f(U)$ the level of the breakdown voltage U_p is estimated,
- a chart of recovery voltage $U_{od} = f(t)$ on insulation which shows the time of recovery and the maximum value of the recovery voltage,
- absorbency index i_{p15}/i_{p60},
- the level of fluctuation of the leakage current i_{p60min} and i_{p60max} in the time over 60 s from the moment of connecting the voltage.

Criteria are based on curves and parameters presented in Table 1 and are assigned ranks from 5 to 0:

5 – excellent insulation (new),
4 – good insulation (voltage restoration and resistance parameters are lessened),
3 – satisfactory insulation (voltage recovery parameters are low, this points to high degree of wear or dirtied insulation),
2 – less than satisfactory insulation (voltage is not recovered even if short-circuit time is equal to 1 s., degree of wear or dirt is high),
1 – unsatisfactory insulation, real hazard of insulation grounding exists,
0 – permanent insulation damage (grounding, turn short-circuiting), emergency, degree of insulation wear equal to 100%.

Parameters characterising insulation's technical condition are set out in Table 1.

Basing on the value of the insulation resistance it is possible to check whether the insulation is wet or not, but it is impossible to estimate the degree of its degradation.

Table 1. Assessment of electrical machines windings insulation system technical conditions – ranking system.

No.	Parameter of insulation		Evaluation of condition of insulation					
			5	4	3	2	1	0
1	Breakdown voltage U_p/U_N		>3	>3	>2	~1.5	~1	~1
2	Resistance R_{60N}/U_N [kΩ/V]	for $U_N = 6$ kV	>50	>20	>10	>10	>10	<3
		for $U_N < 1$ kV	>50	>20	>10	>3	>1	<1
3a	Time of fault t_z [s]	for $U_N = 6$ kV	30	30	30	1	1	0
		for $U_N < 6$kV	10	10	10	1	0	0
3b	Maximum value of recovery voltage $U_{od\,max}/U_0$		>0.1	≥0.1	≥0.05	≥0.01	0	0
	Time of recovery voltage t_{od} [s]	for $U_N = 6$ kV	>240	>120	>30	~10	0	0
		for $U_N < 1$ kV	>120	>60	>15	~5	0	0
4	fluctuation level of leakage current by voltage U_N $\frac{i_{p60\,max} - i_{p60\,min}}{i_{p60\,mean}}$		<0.5	<1	>1	>1	>2	0
5	absorbency index i_{p15}/i_{p60}	for $U_N = 6$ kV	>1.5	>1.2	>1	1	1	1
		for $U_N < 1$ kV	>1.3	>1.1	>1	1	1	1

2.1 DIAGNOSTIC TEST OF WINDINGS' GROUNDWALL INSULATION IN INDUSTRIAL PLANT

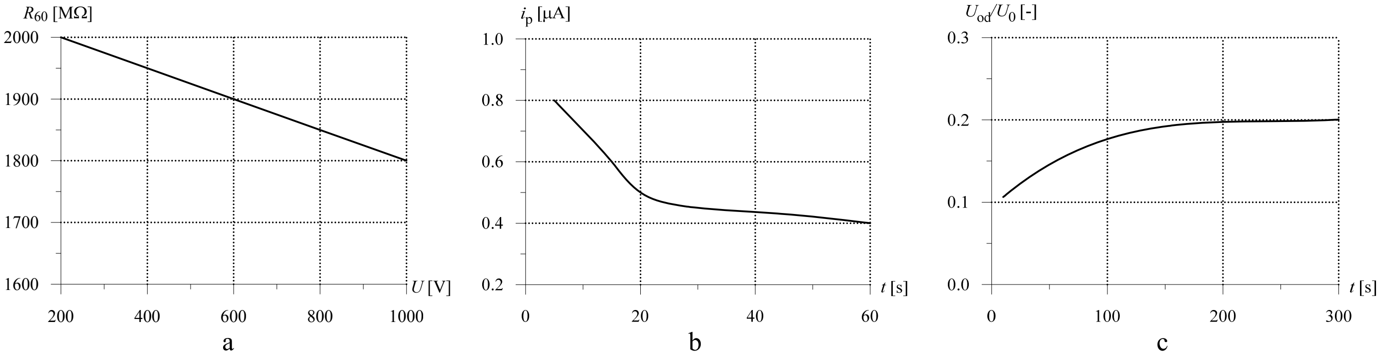
The following machines were tested:

- 4 synchronous motors, MC 325-12/12 type, rated at: 7000 kW; 6 kV; 828 A, 500 rpm; $\cos\varphi = 0.85$; excitation: 155 V; 266 A.
- 8 DC generators, P21-35-17K type, rated at: 4150 kW; 730 V; 5670 A; 500 rpm;
- 8 DC motors, 2PP3000/40 type, rated at: 3250 kW; 730 V; 4780 A; 55/110 rpm; excitation: 110/220 V.

These machines were manufactured from 1970 to 1973 and they are installed in a steel plant plate mill in Poland. They have been operating since 1974, i.e. windings insulation has been made of micafolium, temperature class B. Some of the tested machines have undergone major repairs (rewinding).

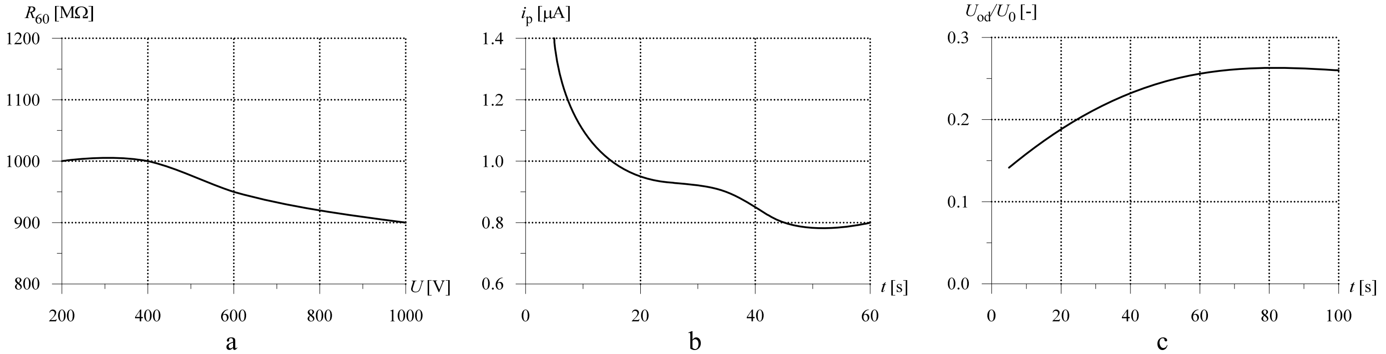
The evaluation of the breakdown voltage is a very important parameter of the diagnostics. The breakdown voltage $U_p \leq U_N$ can be found in degraded insulation of windings of DC machines. Basing on the value of the insulation resistance it is possible to check whether the insulation is bad or not, but it is impossible to estimate the degree of its degradation. Wet insulation is very difficult to be classified. First, it must be desiccated, and then the diagnostic tests must be made. If a motor is placed in a considerably dry room, and the insulation is absorbing the moisture and its resistance is decreasing, shows that the degree of degradation is significant.

The diagnostic tests of electrical machines in one of the Silesian factories have been conducted systematically during each major repair time. The Figures below show the results of tests of insulation in DC generators, of the nominal voltage $U_N = 730$ V. The nominal power of these machines is $P_N = 4150$ kW. Each generator has different insulation's technical condition. It is presented in Figures 2–6. Table 2 shows results of diagnostic tests made in 2000, 2005 and 2010.



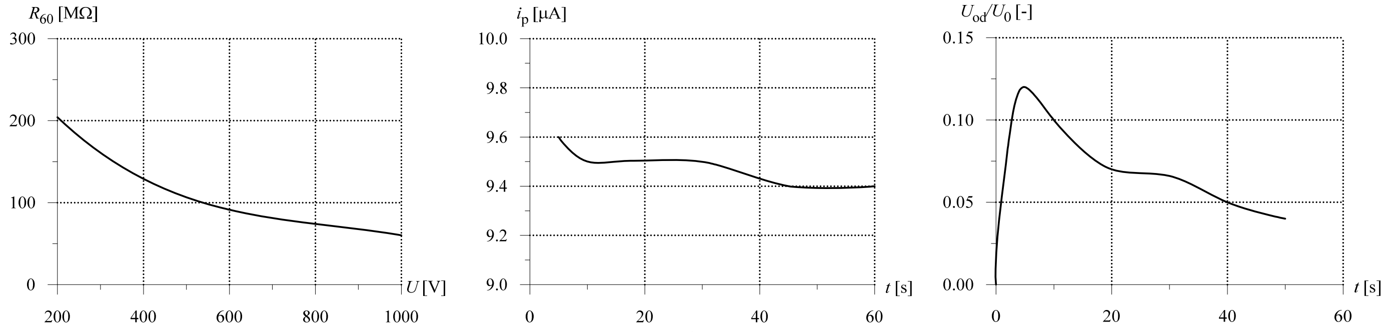
a b c

Figure 2. Rating – "5" – excellent insulation
a) curve $R_{60} = f(U)$, $R_{60} = 1863$ MΩ at $U = U_N$, b) curve $i_p = f(t)$ at $U_0 = 750$ V, $i_{15}/i_{60} = 1.6$,
c) curve $U_{od} = f(t)$ at $U_0 = 750$ V, $t_z = 30$ s. Recovery voltage parameters: $t_{od} = 240$ s; $U_{odmax} = 150$V.



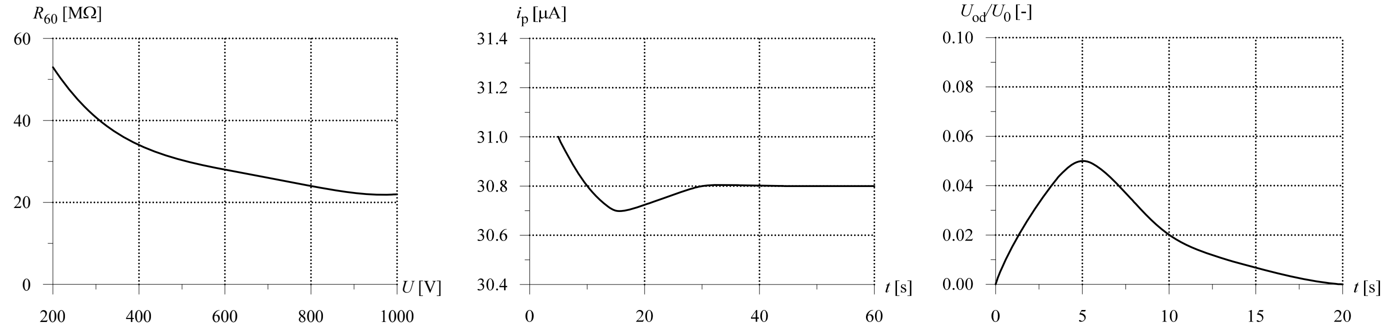
a b c

Figure 3. Rating – "4" – good insulation
a) curve $R_{60} = f(U)$, $R_{60} = 930$ MΩ at $U = U_N$, b) curve $i_p = f(t)$ at $U_0 = 750$ V, $i_{15}/i_{60} = 1.25$,
c) curve $U_{od} = f(t)$ at $U_0 = 750$ V, $t_z = 30$ s. Recovery voltage parameters: $t_{od} = 70$ s; $U_{odmax} = 195$ V.



a b c

Figure 4. Rating – "3" – satisfactory insulation
a) curve $R_{60} = f(U)$, $R_{60} = 79$ MΩ at $U = U_N$, b) curve $i_p = f(t)$ at $U_0 = 750$ V, $i_{15}/i_{60} = 1.01$,
c) curve $U_{od} = f(t)$ at $U_0 = 750$ V, $t_z = 10$ s. Recovery voltage parameters: $t_{od} = 5$ s.; $U_{odmax} = 90$ V.



a b c

Figure 5. Rating – "2" – less than satisfactory insulation
a) curve $R_{60} = f(U)$, $R_{60} = 25$ MΩ at $U = U_N$, b) curve $i_p = f(t)$ at $U_0 = 750$ V, $i_{15}/i_{60} = 1.0$,
c) curve $U_{od} = f(t)$ at $U_0 = 750$ V, $t_z = 1$ s. Recovery voltage parameters: $t_{od} < 5$ s.; $U_{odmax} = 38$ V.

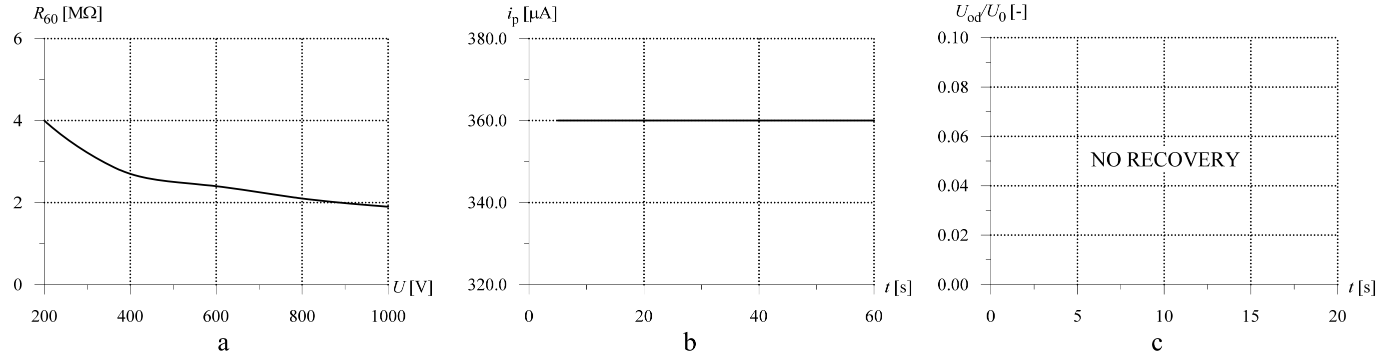


Figure 6. Rating – "1" – unsatisfactory insulation
a) curve $R_{60} = f(U)$, $R_{60} = 2.2$ MΩ at $U = U_N$, b) curve $i_p = f(t)$ at $U_0 = 750$ V, $i_{15}/i_{60} = 1.0$,
c) curve $U_{od} = f(t)$ at $U_0 = 750$ V, $t_z = 1$ s. Recovery voltage parameters: $t_{od} = 0$ s.; $U_{odmax} = 0$ V.

Table 2. Assessment of electrical machines windings insulation system technical conditions – ranking system.

Synchronous motor type MC 325 – 12/12				
No	Serial number	Technical condition of insulation 2000/2005/2010		
		Stator	Rotor	
1	…887	4/4/4	4/3/3	
2	…052	4/4/4	2/4/3	
3	…244	4/4/3.5	3/3/2	
4	…107	4/4/4	1/3/4	
DC generator type P21-35-17K				
No	Serial number	Technical condition of insulation 2000/2005/2010		
		Rotor	Stator	
		A1A2	B1C2	F1F2
1	…054	1/4/2	1/5/2	3/4/3
2	…888	1/5/2	1/5/2	4/5/2
3	…013	1/1/5	1/1/2	2/2/4
4	…053	3/1/5	2/1/2.5	5/4/4
5	…889	1/5/4	1/5/4	2/5/4
6	…299	4/3/2	5/3/2	4/3/2
7	…108	3/2/5	3/1/4	4/2/4
8	…014	2/1/5	2/3/2	4/4/4
DC motor type 2PP3000/40				
No	Serial number	Technical condition of insulation 2000/2005/2010		
		Rotor	Stator	
		A1A2	B1C2	F1F2
1	…161	4/5/5	4/5/5	4/4/4
2	…160	4/5/4	4/4/5	3/4/4
3	…486	5/5/5	5/5/5	5/4/4
4	…487	3/3/5	5/4/5	5/4/5
5	…305	1/5/4	5/4/5	5/4/5
6	…306	5/5/4	5/5/4	5/4/4
7	…630	5/5/4	5/5/4	5/4/4
8	…631	5/5/5	5/5/4	5/4/5

In the Table 2 the technical condition of insulation system is presented. The notification is corresponding to Table 1. For each type of machines the results are presented separately for each kind of winding (stator, rotor, armature – A1A2, field – F1F2, compensation – B1C2).

2.2 DETERMINATION OF TURN-TO-TURN INSULATION CONDITION

Several coils were tested in order to develop a method of determining the technical condition of turn-to-turn insulation. The insulation of these coils was in good and in bad condition. The method is the subject of patent application [28].

The coils were taken from high voltage motor (Figure 7). The coil was placed in the air. Resistance, inductance, capacitance and insulation resistance of each coil were measured. Measurements were taken at $\vartheta = 20°C$.

Voltage measurements were performed by recording its waveform at the terminals of the coil when interrupting the current of the same value 0.1 I_N. Recording of the voltage waveform was performed by a digital scope. The measurement result is shown in Figure 8.

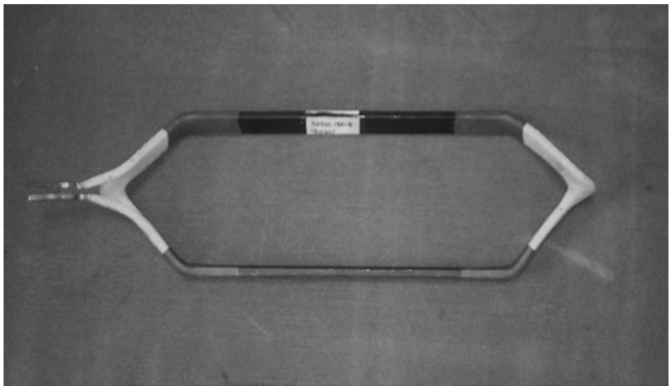


Figure 7. View of tested new coil.

The following were chosen for comparison:
- the frequency of oscillation,
- the shape of voltage waveform at the terminals of the coil,
- the logarithmic damping decrement (Λ).

The logarithmic damping decrement is defined as (1):

$$\Lambda = \ln\left(\frac{A_n}{A_{n+1}}\right) \tag{1}$$

where:

A_n – amplitude of peak n,
A_{n+1} – amplitude of peak n+1.

The results of comparative tests for the motor coil are summarized in Table 3.

Labeled in this table:
- U – the mean value of the supply voltage,
- I – the mean value of the current flowing in the circuit,
- f_p – the frequency observed during measurements of the real object,
- U_p – the maximum value of voltage excited at the terminals of the coil during the measurement of the real object.

Table 3. Results and measurements for coil new and used.

U	I	f_p	U_p	Λ	Coil
V	A	kHz	V	–	status
0.150	2.10	541.0	240	0.16	new
0.175	2.10	737.6	210	0.35	used
0.175	2.10	725.0	210	0.33	used

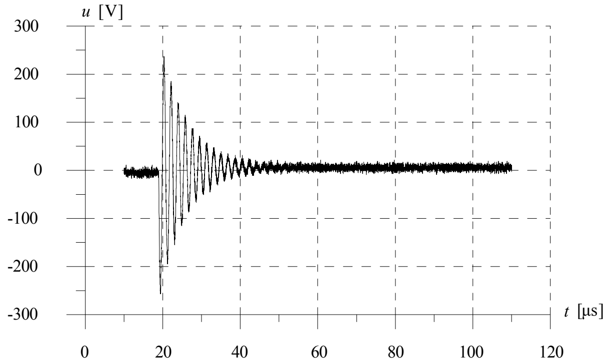


Figure 8. The result of the measurement made for the motor coil.

Another study carried out on a new coil, where a short-circuit was simulated. On the nose of the coil, a part of the bandage was cut out, fragments of copper wires isolation were removed and additional resistance R_D of variable value was merged. The value of resistance R_D simulated the aging of the insulation. Examples of the results of measurements of excited voltage for the intact coil and the short-circuit with resistance R_D = 1 kΩ are shown in Figures 9 and 10. Example of the results of measurements of excited voltage for the coil with old and used insulation is shown in Figure 11.

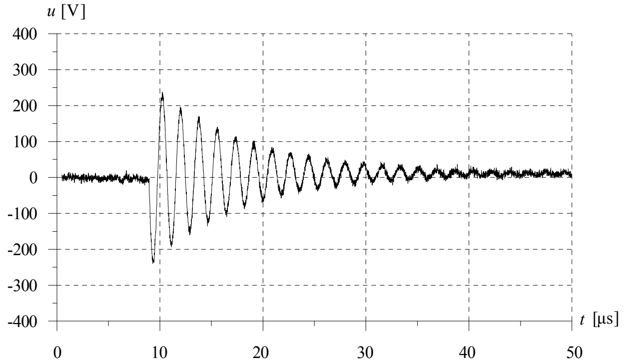


Figure 9. The waveform of excited voltage on the terminals of the intact coil: f = 541 kHz, Λ = 0.16.

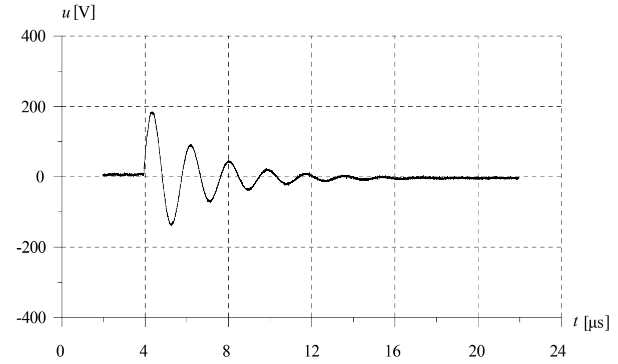


Figure 10. The waveform of excited voltage on the terminals of the coil after shorting 1/3 turns by resistance R_D = 1 kΩ: f = 543 kHz, Λ = 0.54.

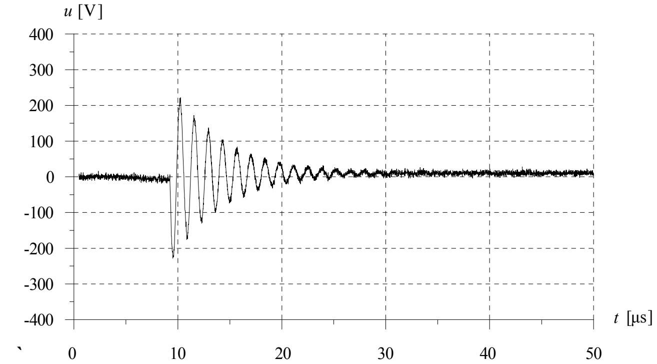


Figure 11. The waveform of induced voltage on the terminals of the intact coil with old insulation: f = 737.6 kHz, Λ = 0.35.

The results of the measurement frequency for different values of resistance R_D are summarized in Table 4.

Table 4. Measurements of the frequency of voltage generated at different values of resistance R_D and damping decrement Λ.

No	R_D	f	Λ	comments
	kΩ	kHz		
1	—	541	0.16	Intact insulation
2	100000	598	0.18	
3	10000	595	0.18	
4	1000	586	0.20	
5	100	588	0.19	
6	10	587	0.21	
7	1	543	0.54	

3 VIBRATION DIAGNOSIS

Progress in recent years in the field of production technology and dissemination of magnetic materials caused that significant part of traction drives (electromobility) are machines excited by permanent magnets. Their features are the reasons of their popularity: high efficiency, high power density, high torque overload, very good control and relatively simple construction. A very high torque can be reached in a wide range of machine speed by proper control.

There are many adverse effects that appear in machines with permanent magnets, due to their construction. For example, this adverse effect is force reacting on the individual machines parts. An example of these phenomena is magnetic strain, which occurs when the machine is energized or not. That effect does not occur in induction machines or in machines with electromagnetic excitation.

Those phenomena are reflected in vibrations. Vibrations emitted by the electric drive depend on the construction of a bearing and the kind of a supply. The authors concentrate on the vibration diagnostics of the machines excited by permanent magnets. Properly performed diagnosis is a very important issue for each drive [29–31].

Currently, in each industrial plant, almost each electric drive requires periodic vibration diagnostics. With every year the popularity of the machines with permanent magnets (PM) is increasing. This kind of machines are very responsive to vibrations. When some object is vibrating in the vicinity of a PM machine the measurement of eg. winding resistance become impossible because of disruptions (Figure 12). The electromotive force (EMF) is induced when the machine with permanent magnets is vibrating. That EMF introduces distortions and the measurement of winding resistance is impossible.

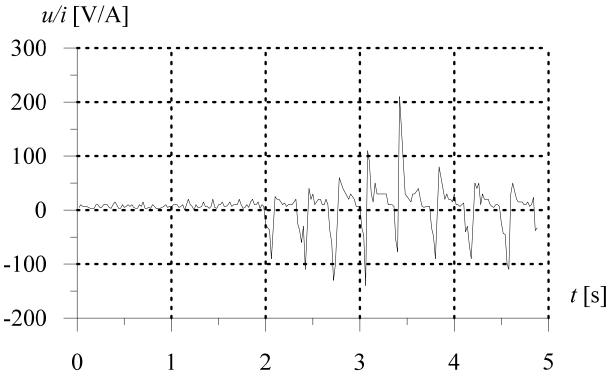


Figure 12. Distortions during the resistance measurements.

The equivalent circuit of the winding is shown in Figure 13. The circuit includes additional EMF ($e(t)$) which introduces noise into the circuit, and prevents measurements from being made using classical measuring equipment.

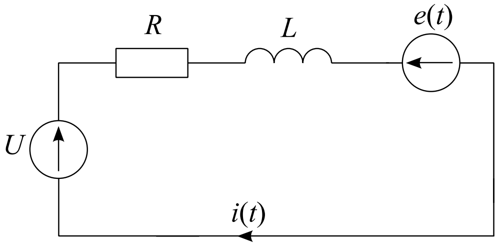


Figure 13. The equivalent circuit of the winding including additional EMF – $e(t)$.

Parameters of equivalent circuit:

- U – DC voltage source,
- R – resistance of winding,
- L – inductance of winding,
- $e(t)$ – additional EMF,
- $i(t)$ – current in the circuit.

3.1 PM GENERATOR AS VIBRATION SENSOR

When the problem was analysed a similarity between PM machine and electrodynamic sensor which is used to measure vibrations has been observed. The method of determining the technical condition of PM electrical machine based on its own signals is the subject of patent application No P.405669 [16].

This diagnostic method of electric machines excited by permanent magnets, which have a number of poles pairs p and work with the rotational speed n, includes recording a waveform of voltage or current of diagnosed machine, perform frequency analysis and separation the frequencies f_1 and f_2 defined by equations (2) and (3).

$$f_1 = \frac{(p+1)\cdot f}{p} \tag{2}$$

$$f_2 = \frac{(p-1)\cdot f}{p} \tag{3}$$

where: f_1, f_2 – searched frequencies, p – number of pole pairs, f – first harmonic frequency of tested generator.

3.2 COMPUTER SIMULATIONS AND LABORATORY TEST RESULTS OF PM GENERATOR WITH UNBALANCE AS A SOURCE OF VIBRATION

The physical model to provide analysis of vibrations was developed using the equivalent circuit shown in Figure 14. All the parameters were determined using the circuit method, base formulas and machine design data [32].

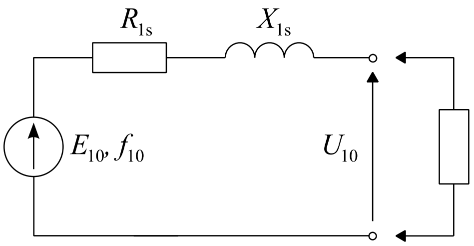


Figure 14. Equivalent circuit of PM generator.

Equivalent circuit parameters:

- E_{10} – electromotive force generated by rotating permanent magnets,
- f_{10} – frequency of the generated voltage,
- R_{1s} – phase resistance of stator winding,
- X_{1s} – synchronous reactance of the stator winding,
- U_{10} – generated voltage on idle run,
- Z_1 – load impedance.

Simulations and laboratory tests described in the article were performed for PM generator: U_N = 40 V, I_N = 17.2 A, P_N = 1.2 kW, n_N = 1000 rpm. These machines are commonly used in small wind turbines.

The waveform voltage of the generator, which is not supplied but under the influence of the forced oscillations, is presented in Figure 15. Vibrations were forced by placing the test generator on common frame with induction motor, which has had mounted unbalance on the shaft. Machines were not coupled. Both machines have the same number of pairs of poles. Powered motor was a source of vibration for the generator with permanent magnets. The EMF was induced on the generator terminals, which was recorded.

The voltage waveform of the computer simulations of the generator, which is not supplied but under the influence of the forced oscillations is presented in Figure 16. Comparing Figures 15 and 16 it can be seen that the real voltage induced in the winding of the generator coincides largely with the result of the simulation.

The frequencies f_1 and f_2 for tested generator were calculated using formulae (2) and (3). These frequencies are detectable when the rotating parts of machine are unbalanced. The vibrations were generated by making the shaft unbalanced. The generator was rotating with nominal speed. The FFT analysis was performed for EMF obtained as a result of simulations and measurements. The results of FFT analysis for simulation and for measurement are presented in Figure 17. Fundamental frequency f and the frequencies f_1 and f_2 are marked. The frequency spectrum of the real object is different from the simulation. The reason of the difference is that the simulation model assumes an ideal machine, a fully symmetrical. The real machine is not perfect, unfortunately.

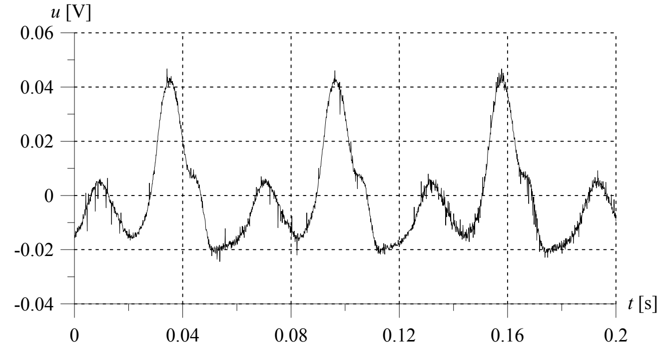


Figure 15. The waveform of the induced EMF - the real measurement.

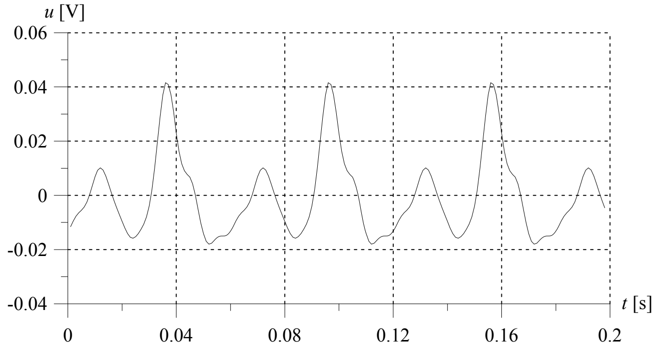


Figure 16. The waveform of the induced EMF - the result of simulation.

Table 5. Comparison of simulation results and laboratory tests

	f Hz	f_1 Hz	f_2 Hz
Formulas (2) and (3)	50.00	33.33	66.67
	49.70	33.13	66.27
	49.55	33.03	66.07
Simulations	49.70	33.16	66.23
Laboratory tests	49.55	33.27	65.86

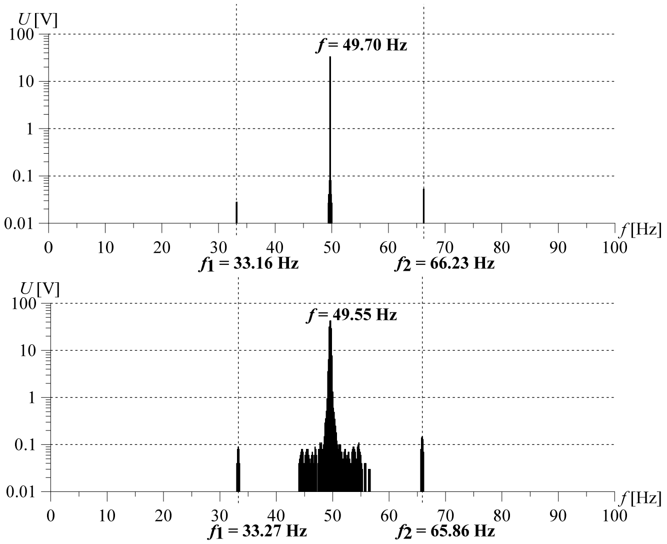


Figure 17. Frequency spectrums of induced voltage of the generator - the results of the simulation and real measurement.

4 CONCLUSIONS

By analyzing the results of the diagnostics of insulation of the motors installed in the industrial plant, the life expectancy of a motor can be estimated. The services responsible for repairing motors can estimate the time and ranges of future repairs on the basis of the results. By collecting and comparing the received results in a way that is similar to those presented in the article, can be seen the tendencies of changes and their intensity.

The frequency of generated voltage depends solely on the parameters of the winding, not on the supply.

A comprehensive and unified method for diagnosing the technical condition of winding insulation, which can be used in practice with no need to build complex industrial measuring and testing equipment, was developed.

The proposed methodology of testing the winding insulation by interrupting the current flowing through the windings is subject to the following evaluation criteria and conditions:

- an interrupted current 5 - 10% of the nominal current of the machine,
- access to each phase separately if possible,
- the increase of the excited voltage frequency by 5% comparing with the value of frequency registered on the coil in good condition reveals the deterioration of the turn-to-turn insulation,
- a change of the shape of excited voltage waveform demonstrates the deterioration of the turn-to-turn insulation.

The calculations, simulations and tests confirm the effectiveness of new vibration diagnostic method for generators excited by permanent magnets, where vibrations were created as a result of unbalance (Table 5). The analysis shows the possibility to use the machine with permanent magnets as a vibration sensor for itself. This approach is innovative and customizable. The method does not require to use the expensive sensors and diagnostician does not care about their assembly, which in some cases is an important issue. Using additional equipment for FFT analysis of the voltage or current signal the method allows on-line diagnostics also. It is quite essential for the wind power plant where, for various reasons, admittance is rather difficult [33]. Other mechanical sources of harmonics in electrical machines, which may become active during the operation of the machine with permanent magnets will be analyzed by the authors in future works.

ACKNOWLEDGMENT

The scientific work was financed from the funds for science in 2013-2015 as research project no. 413/L-4/2012 2012 named “Vibroacoustic diagnostic method of traction permanent magnets motors and generators based on the own signals“ realized in Institute of Electrical Drives and Machines “KOMEL”.

REFERENCES

[1] T. Glinka, “Diagnostic tests of electrical machines in industry”, Research and Development Centre of Electrical Machines KOMEL, Katowice, 2002. (in Polish)
[2] A. Decner and A. Polak, “Diagnostic tests of Turn-to-turn insulation”, International Conference on Electrical Machines, Roma, 2010.
[3] IEEE Std 43-2000. IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

[4] X. Zeng, Y. Xu and Y. Wang, "Some Novel Techniques for Insulation Parameters Measurement and Petersen-Coil Control in Distribution Systems," IEEE Trans. Industr. Electron., Vol. 57, No. 4, pp. 1445 - 1451, 2010.

[5] "IEEE Guide for Induction Machinery Maintenance Testing and Failure Analysis," IEEE Standard 1415™-2006, 2007.

[6] A. H. Bonnett and G. C. Soukup, "Causes and analysis of stator and rotor failures in three-phase induction motors," IEEE Trans. Ind. Appl., Vol. 28, No. 4, pp. 921–937, 1992.

[7] O. V. Thorsen and M. Dalva, "Failure identification and analysis for high voltage induction motors in the petrochemical industry," IEEE Trans. Ind. Appl., Vol. 35, No. 4, pp. 810-818, 1999.

[8] M. T. Tallam, S.B. Lee, G.C. Stone, G. B. Kliman, J.Yoo, T.G. Habetler and R.G. Harley, "A Survey of Methods for Detection of Stator-Related Faults in Induction Machines," IEEE Trans. Industry Appl., Vol. 43, No. 4, 2007.

[9] W. McDermid and J. C. Bromley, "Monitoring rotating machine insulation with the CEA PDA through the use of directional couplers", IEEE Electrical,/Electronics Insul. Conf., Chicago, USA, p.120, 1985.

[10] S. U. Haq and T. Bashir, "Evaluation of Induction Motor Groundwall Insulation using Infrared Thermography," 2nd Int'l. Conf. Emerging Technologies Peshawar, Pakistan, pp. 416-420, 2006.

[11] A. H. Bonnett and G. C. Soukup, "Causes and analysis of stator and rotor failures in three-phase induction motors," IEEE Trans. Ind. Appl., Vol. 28, No. 4, pp. 921–937, 1992.

[12] O. V. Thorsen and M. Dalva, "Failure identification and analysis for high voltage induction motors in the petrochemical industry", IEEE Trans. Ind. Appl., Vol. 35, No. 4, pp. 810-818, 1999.

[13] PN-E-04700:1998: Devices and electrical circuits in electrical power engineering objects. Guiding rules of making after montage receipt tests. (in Polish)

[14] IEC 60034-14 Rotating electrical machines. Mechanical vibration of certain machines with shaft heights 56 mm and higher – Measurement, evaluation and limits of vibration severity.

[15] ISO7919 Mechanical vibration of non-reciprocating machines - Measurements on rotating shafts and evaluation criteria.

[16] M. Barański and T. Glinka, "Vibration diagnostic method of permanent magnets generators – detecting of vibrations caused by unbalance", PL Patent application P.405669 (in Polish).

[17] M. Barański, A. Polak and A. Decner, "Bearings vibration diagnosis based on hodograph X", Poland, Przegląd Elektrotechniczny, pp. 10-12, 2014 (in Polish).

[18] M. Barański, "Multiaxial Vibration Analyzer with SV06A Module, Data Acquisition System (Personal Daq 300) and LabView as a Graphical Programming Environment", Master dissertation, Gliwice, Poland, 2010, (in Polish).

[19] M. Barański and A. Decner, "The vibration acceleration $a_y = f(a_x)$ function as a tool to determining the bearing technical condition", Electrical Machines – Trans. J., Katowice, Poland, pp. 1-4, 2012, (in Polish).

[20] M. Tsypkin, "Induction Motor Condition Monitoring: Vibration Analysis Technique – a Practical Implementation". IEEE, Int'l. Electric Machines & Drives Conference, Canada, pp. 406-411, 2011.

[21] M. Tsypkin, "Vibration analysis of induction motors with pulsating electromagnetic torque", 20th Annual Meeting of the Vibration Institute, St. Louis, Missouri, USA, pp. 169-178, 1996.

[22] M. Tsypkin, "Induction Motor Condition Monitoring: Slip Frequency and Pole Pass Frequency – a Clarification of Definitions," Vibration Institute Proceedings. National Technical Training Symposium and Annual Meeting, Oak Brook Illinois, pp. 75-81, 2010.

[23] T. Glinka, A. Polak and A. Decner, "Degradation of winding insulation of electrical machines caused by the time of exploitation". Electrotechnical News, 7-8/2005, Warsaw, 2005, (in Polish).

[24] T. Glinka, A. Polak and A. Decner, "Degradation of winding insulation of electrical machines caused by the time of exploitation", Electrical Machines – Trans. J., 74/2006, Research and Development Centre of Electrical Machines KOMEL, Katowice, pp. 51-56, 2006, (in Polish).

[25] A. Decner and B. Picheta, "The diagnostic of insulation using dc-voltage method in the cement plat *Nowiny*", Electrical Machines – Trans. J., 74/2006, Research and Development Centre of Electrical Machines KOMEL, Katowice, pp. 57-61, 2006, (in Polish).

[26] A. Decner and A. Polak, "Wear estimation criteria of turn to turn insulation", Electrical Machines – Trans. J., 81/2009, Research and Development Centre of Electrical Machines KOMEL, Katowice, pp. 51-53, 2009, (in Polish).

[27] A. Decner, T. Glinka and A. Polak, "Observation of the aging process of electrical machines windings insulation using the method of dc voltage", Published by University of West Bohemia in Pilsen, Pilzen, 2007.

[28] Patent Application P 382388, "Measurement system and method for testing turn-to-turn insulation", Research and Development Centre of Electrical Machines KOMEL, 10.05.2007, (in Polish).

[29] D. Torregrossa, "Multiphysics finite-element modeling for vibration and acoustic analysis of permanent magnet synchronous machine", IEEE Trans. Energy Conversion, pp. 490-500, 2011.

[30] R. Islam, "Analytical model for predicting noise and vibration in permanent-magnet synchronous motors", IEEE Trans. Industry Appl., pp. 2346-2354, 2010.

[31] S. Lakshmikanth, K.R. Natraj and K.R. Rekha, "Noise and vibration reduction in permanent magnet synchronous motors – a review", Int'l. J. Electrical and Computer Eng., p.405, 2012.

[32] P. Pistelok and T. Kądziołka, "New series of high efficiency 2 pole synchronous generator with permanent magnet", Electrical Machines – Trans. J., Katowice, Poland, pp. 65-69, 2013, (in Polish).

[33] S. Nandi and H.A. Toliyat, "Condition monitoring and fault diagnosis of electrical machines–a review", Industry Applications Conf., pp. 197-204, 1999.

Marcin Barański was born in Czeladź, Poland, on 2 January 1981. He graduated from the Silesian University of Technology in Gliwice, Faculty of Electrical Engineering. He has been working in the Institute of Electrical Drives and Machines KOMEL, Katowice, Poland from 2006. He works in the Laboratory of Electrical Machines where he is Research and Technical Expert. Author of technical papers and patent applications. Member of IEEE.

Adam Decner was born in Katowice, Poland in 1974. He graduated from the Silesian University of Technology in 1999. He defended his Ph.D. dissertation at Wroclaw University of Technology in November 2009. He has been working in the Institute of Electrical Drives and Machines KOMEL, Katowice, Poland from 1996. He works in the Laboratory of Electrical Machines. He pursues research in the laboratory and works as consulting expert for industry.

Artur Polak was born in Zawiercie, Poland in 1968. He graduated from the Silesian University of Technology in 1994. He defended his doctoral dissertation at Gliwice Silesian University of Technology in 2000. He has been working in the Institute of Electrical Drives and Machines KOMEL, Katowice, Poland from 1994. He works in the Laboratory of Electrical Machines where he is head of the Laboratory.