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PM Electrical Machines Diagnostic - Methods Selected

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***Abstract*—**This paper presents a several diagnostic methods designed to electrical machines especially for permanent magnets (PM) machines. Those machines are commonly used in small wind and water systems and vehicles drives. Those methods are preferred by the author in periodic diagnostic of electrical machines. The special attention should be paid to diagnostic method of turn-to-turn insulation and vibrations. Both of those methods were created in Institute of Electrical Drives and Machines Komel. The vibration diagnostic method is the main thesis of author's doctoral dissertation. This is method of determination the technical condition of PM electrical machine basing on its own signals is the subject of patent application No P.405669. Specific structural properties of machines excited by permanent magnets are used in this method - electromotive force (EMF) generated due to vibrations. There was analysed number of publications which describe vibration diagnostic methods and tests of electrical machines with permanent magnets and there was no method found to determine the technical condition of such machine basing on their own signals.

***Keywords*—**Electrical vehicle, generator, main insulation, permanent magnet, thermography, turn-to- traction drive, turn insulation, vibrations.

I. Introduction

EVOLUTION in last years in the magnetic materials production technology and dissemination field caused that traction drives (electromobility) significant part are machines with permanent magnets (Figs. 1 and 2). Machines like those are used in small wind or water systems too. Their main of advantages are the reasons of their popularity: very good control, high efficiency, high power density, high torque overload and relatively simple construction (Table I). A very high torque can be reached in a wide range of machine speed by proper control.

TABLE I
Comparison of Electrical Machines

Type of electical motor	Lift	P[kW]	n [1/min]	η [%]	m [kg]
Asynchronous motor	200	30.0	1472	92.5	265
DC motor	160	34.7	1560	88.5	247
PM motor	160	31.2	1500	91.8	110

Those electric machines are subjected to a considerable influence of conditions in their location. During the time of repairs, diagnostic tests of electrical machines are carried out.

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Fig. 1 Komel's traction motor of type: SMwsPA132S4

Fig. 2 Fiat Panda with Komel's traction motor – research and development project no. NR01-0084-10

Currently, each an important electric drive requires periodic diagnostic. Periodic testing of electrical machines is designed to prevent major accidents which generate high costs associated with the stopping of the machine (production costs) and repair costs.

The most commonly damaged machine parts are: degradation of insulation and bearings faults, so the author decided to mention in the article, about: insulation and vibration diagnostic methods and thermography tests.

II. The Diagnostic Method of Main Insulation

The dc voltage diagnostic main insulation method in electrical machines used by the author is the simplest testing method [1], [2]. The method consists of three tests:

- the $R_{60} = f(U)$ characteristic, if possible - voltage range from 0 up to $2U_N$,
- the leakage current i_p characteristic after the nominal voltage is connected on the absolutely discharged winding,
- charging the winding to the nominal voltage, then disconnecting the voltage source and fault to frame the

winding capacitance for the time t_z, and next opening the circuit and recording the voltage rebuilding characteristic on the stator winding insulation U_{od} *(t)*.

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

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

The third test – the voltage rebuilding testing is the most important test in the diagnostics of the technical condition of insulation and estimating the rate of its wear.

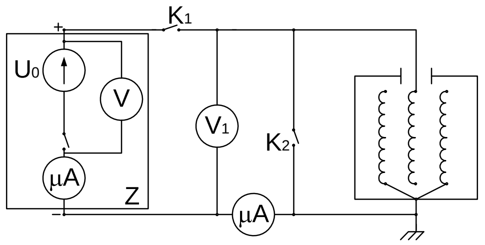

Fig. 3 Circuit connections schema for the technical condition of main insulation diagnostic

TABLE II
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]	U_N=6kV	>50	>20	>10	>10	>10	<3
		U_N<1kV	>50	>20	>10	>3	>1	<1
3a	Fault time t_z [s]	U_N=6kV	30	30	30	1	1	0
		U_N<6kV	10	10	10	1	0	0
3b	Rebuilt voltage maximum value $U_{od\,max}/U_o$		>0,1	≥0,1	≥0,05	≥0,01	0	0
	Rebuilding voltage time t_{od} [s]	U_N =6kV	>240	>120	>30	~10	0	0
		U_N <1kV	>120	>60	>15	~5	0	0
4	Leakage current fluctuation level by voltage U_N $\frac{i_{p60\,max} - i_{p60\,min}}{i_{p60\,śr}}$		<0,5	<1	>1	>1	>2	0
5	Absorbency index i_{p15}/i_{p60}	U_N=6kV	>1,5	>1,2	>1	1	1	1
		U_N<1kV	>1,3	>1,1	>1	1	1	1

The tests are made in a circuit as shown in Fig. 3. Criteria are based on curves and parameters presented in Table II and are assigned ranks from 5 to 0:

- 5 – excellent insulation (new),
- 4 – good insulation,
- 3 – satisfactory insulation,
- 2 – less than satisfactory insulation,
- 1 – unsatisfactory insulation,
- 0 – permanent insulation damage.

In Figs. 4 and. 5 present waveforms of rebuilding voltage of machines in good and bad technical condition of main insulation.

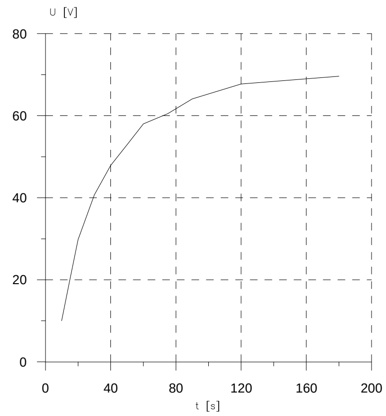

Fig. 4 Waveform of rebuilding voltage of motor with good main insulation

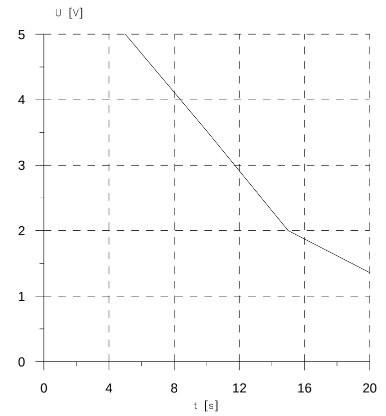

Fig. 5 Waveform of rebuilding voltage of motor with bad main insulation

III. THE DIAGNOSTIC METHOD OF TURN-TO-TURN INSULATION

The method of determining the technical condition of turn-to-turn insulation preferred by the author, based on the comparison of two voltage waveforms [3]. Voltage waveforms are compared of machine one type. First waveform is the base and it's from good condition machine (Fig. 6). Second it's from tested machine (Fig. 7).

The following parameters of waveforms are chosen for comparison:

- the oscillation frequency,
- the voltage waveform shape at the coil terminals,
- logarithmic dumping decrement Λ (1).

$$\Lambda = \ln \frac{A_n}{A_{n+1}} \tag{1}$$

where: A_n – is the peek n amplitude, A_{n+1} – is the peek n+1 amplitude.

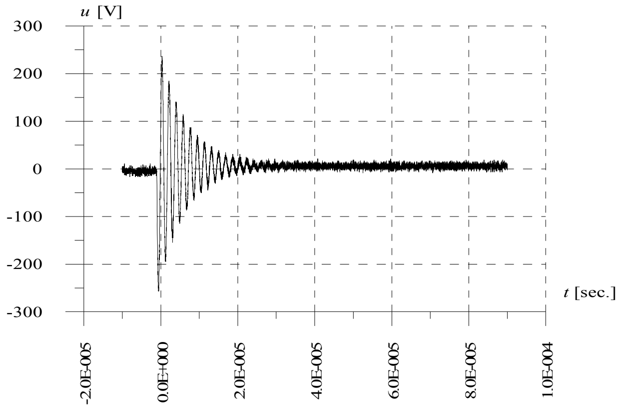

Fig. 6 Voltage waveform of machine in good technical condition

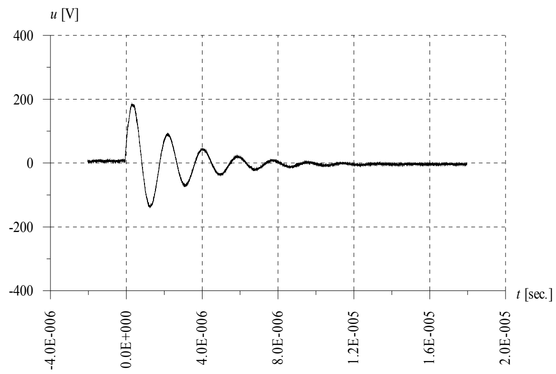

Fig. 7 Voltage waveform of machine in bad technical condition

IV. The Thermography Tests

Thermography based on the detection of infrared radiation emitted by objects with a temperature above absolute zero. Thermography converts this radiation into visible light, resulting in a thermal image. This is a temperature field map of the object's surface which is made possible the power of radiation depends on the bodies radiant property. Such tests can be performed using thermography cameras (Fig. 8). Nowadays, thermovision allows the test object temperature distribution digital recording. This "temperature map" is interpreted graphically. The object thermal image is seen on the viewfinder because all temperatures are assigned to a different color. In practice, data is stored as a temperature map. The same object may look different depending on the adopted color-scale and relationship to temperature scale. Thermography system is special kind of thermometer that can measure temperature from a distance, in one moment in many places. Thermography is noninvasive and effective diagnostic method. Using the thermovision cameras obtain temperature field's tested object picture. Remote measurement with resolution depends on the transducer type in the camera, of which the current standard is 0.1°C. The main advantage of method is that the measurements are made during normal work [4]-[6].

To accurately measure the temperature distribution on the electrical machines body, it is necessary to separate the wished sources influence from disturbances that have to be compensated. In order to do this automatically, the camera must be informed of the following parameters:

- the temperature of atmosphere,
- the distance between the camera and object,
- the humidity,
- the object emissivity.

Fig. 8 Thermography camera

Thermal tests are characterized by high accuracy of measurements and may be applied to different types of electrical machines tests. Thermal camera may be used in some tests, such as:

A. The Test of Phase Continuity (Fig. 9)

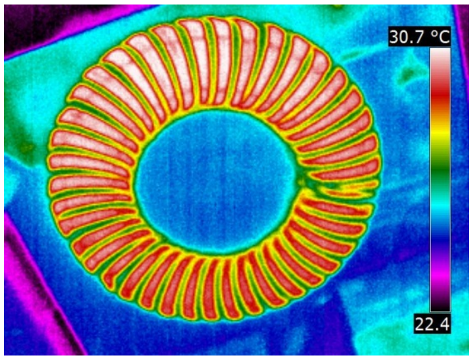

Fig. 9 Thermal image of axial fluke Komel's generator winding

B. The Test of Winding Connection (Fig. 10)

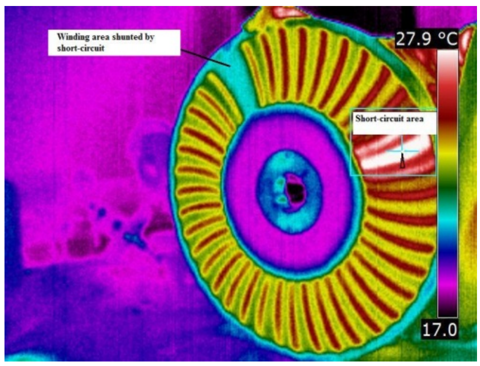

Fig. 10 Thermograph of axial fluke generator broken winding

C. The Test of Cooling Duct (Fig. 11)

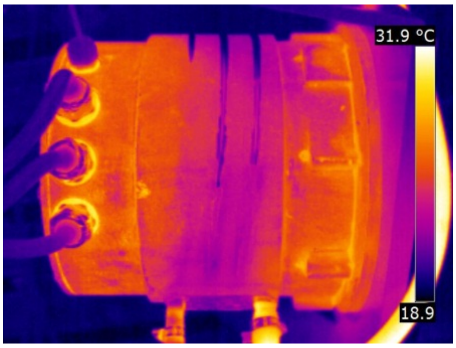

Fig. 11 Thermal image cooling duct of motor of type SMwsPA132S4

D. The Test Determine Bearing Mountings Overheating (Fig. 12)

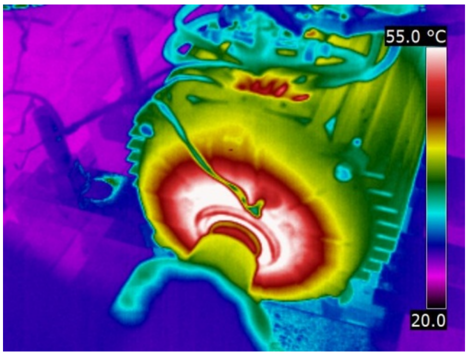

Fig. 12 Thermograph of PM machine heating of bearing

V. The Vibrations Diagnostic Method

Vibrations in electrical machines are undesirable, their high level, higher than the acceptable level, is considered to be a failure symptom. Ignoring these symptoms entails a real catastrophic failure risk, which costs can often exceed the drive cost. Vibrations, which are always accompanied by rotating machines work cause gradual degradation of the unit some component. Vibration diagnostics task is to collect the information about components wear degree. Depending on the tested machines aim of test and type, it is very essential which waveform (accelerations, velocities or displacements) have to be recorded. The vibration velocity RMS value is dedicated for determination of overall rotary machine assessment. It reflects the destructive energy. However, if it is wanted to know the vibration cause it is necessary to conduct a detailed vibration spectrum analysis, which is transformation of the waveform in time domain to the frequency domain. Knowing the machine basic operating parameters and construction, each component of vibration spectrum could be attributed to these elements or states [7]-[9]. Electrical machines vibration diagnostic majority is based on measurements which are done with external sensors connected to dedicated complicated and expensive meters or analyzers. In such solutions, vibration sensor mounting is often problematic, because the machine is rarely designed by the manufacturer for this purpose. Mounting affects the frequency response of the measurement signal. Additionally, it is needed to pay special attention for the measuring circuit separation from any kind of interference, which could result in incorrect measure [10], [11].

In this work author presents a new diagnostic method of vibration designed machines with permanent magnets (PM). Those machines are commonly used in small wind or water systems and vehicles drives. This is very innovative and unique method. Specific machines excited by permanent magnets structural properties are used in this method - electromotive force (EMF) generated due to vibrations. This method based on the frequency spectrum analysis of machine own signal. Author analysed number of publications which describe vibration electrical machines diagnostic methods and tests and there was no method found to determine the technical condition of such machine basing on their own signals. The method of determination the technical condition of PM electrical machine basing on its own signals is the subject of patent application No P.405669 [12], and it is the main thesis of author’s doctoral dissertation.

The method main advantage is that the measurement system does not require sensors for measuring vibration. Excitation circuit and armature winding perform a function of the vibration sensor at the same time. Vibration measurement with this method can be performed on-line during normal machine operation [13]-[16].

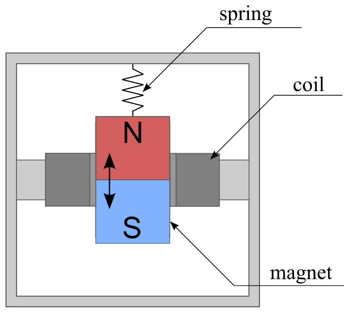

Fig. 13 The electrodynamic sensor

There are some similarities can be noted when the comparison of PM machine (Fig. 14) with electrodynamic sensor (Fig. 13):

- a similar structure – permanent magnets and coils (winding). While the sensor is exposed to the vibrations an EMF is generated. That EMF signal can be used for vibration analysis,
- greater number of turns and pole pairs makes the signal greater. That means the sensitivity is dependent on the number of turns in the coil – in analogy to the electrodynamic sensor.

The most important mechanical sources of harmonics that may occur during the operation of the machine:

- unbalance,
- radial or axial asymmetry between the stator and the rotor,
- bearing damage.

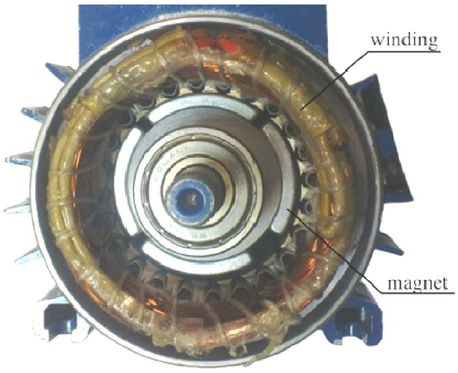

Fig. 14 Permanent machine

In this article the author presents vibration diagnostic method of permanent magnets machines – detecting of vibrations caused by unbalance. This is especially important in wind system.

This PM electric machine diagnostic method, which has a number of poles pairs p and works with the rotational speed n, includes registration a voltage or current waveform of diagnosed machine, perform frequency analysis and separation the frequencies f_1 and f_2 defined by (2) and (3).

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

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

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

Laboratory tests presented in the article below were made for Komel's PM generator of type: PMGhR90X – 6M, and parameters: U_N = 40 V, I_N = 17,2 A, P_N = 1,2 kW, n_N = 1000 rpm. Those machines are commonly used in small wind systems.

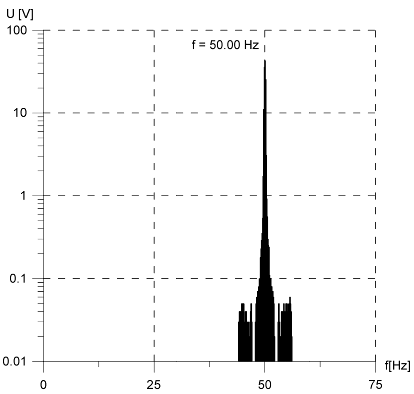

Fig. 15 Frequency analysis of good technical condition PM machine voltage

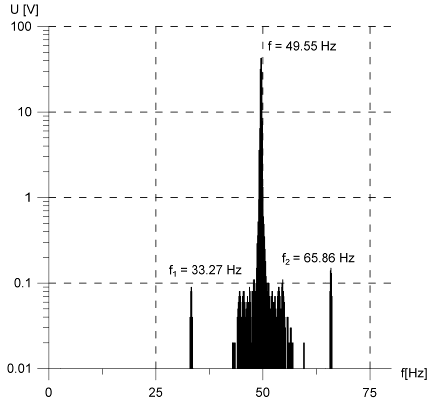

Fig. 16 Frequency analysis of bad technical condition PM machine voltage

TABLE III
COMPARISON OF SIMULATION RESULTS AND LABORATORY TESTS

	f [Hz]	f_1 [Hz]	f_2 [Hz]
Formulas (1) and (2)	49.55	33.03	66.07
Laboratory tests	49.55	33.27	65.86

The calculations and tests (Figs. 15, 16, Table III) confirm the effectiveness of new vibration diagnostic method for machines excited by permanent magnets, where vibrations were created as a result of unbalance. The analysis shows the possibility to use the machine with permanent magnets as a vibration sensor for itself. This approach is innovative and custom. The author never encountered such an application for PM machines, where the assessment of the intensity of the vibration a specific properties of the machine are used.

VI. SUMMARY

In this article author presents of insulation and vibration diagnostic methods and thermography tests. Methods describe commonly damages of electrical machines. All of them are used to electrical machine tests by the author. The method of diagnostic of main insulation is a simple and very effective. Criteria of this method are very clearly and easy to measure.

The diagnostic method of turn-to-turn insulation based on comparison of waveforms is very simply too.

Thermography is very effective and noninvasive diagnostic method. Is special kind of thermometer that can measure temperature from a distance, in one moment in many places. It can be using in tests of: cooling ducts, connections, phase continuity or heating.

Author presents also new vibration method. This 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 admittance is difficult for various reasons. Other mechanical sources of harmonics in electrical machines, which may occur during the operation of the PM machine will be analyzed by the author in future works.

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He has worked in the Institute of Electrical Drives and Machines KOMEL, Katowice, Poland from 2006. Author of patent applications and technical papers: "Thermographic diagnostic of electrical machines"(Roma, Italy, ICEM, 2010), "Noninvasive and invasive methods of squirrel cage's bars diagnostic" (Ponta Delgada, Portugal, XIICLEEE, 2011), "Bearings vibration diagnosis based on hodograph XY" (Poland, Przegląd Elektrotechniczny, 2014).Now, he is a manager of project: "Vibroacoustic diagnostic method of traction permanent magnets motors and generators based on the own signals".