Marcin BARAŃSKI

VIBRATION INCREASE LEVEL PROBLEM CAUSED LOAD ASYMMETRY OF PM GENERATOR

Streszczenie

The paper presents a new vibration diagnostic method designed for permanent magnets (PM) generators with point operation asymmetry. Those machines are commonly used in small wind or water systems. The described method is very innovative and unique. Specific structural properties of machines excited by permanent magnets are used in this method - electromotive force (EMF) generated due to vibrations. In this article several issues will be discussed: the similarity of permanent magnet machines to vibration sensor, calculations, results of simulation and laboratory tests. The method is the subject of patent application [1]-[2].

INTRODUCTION

Progress in recent years in the production technology and dissemination of magnetic materials field caused that significant part of renewable energy systems are PM machines. Machines like those are used in small wind or water industry systems and by individual customers too. Main of PM generator advantages are the reasons of their popularity: high efficiency, high power density, high torque overload, very good control and relatively simple construction. Table 1 contains the comparison of catalogue parameters of several types of electrical machines [3].

Tab. 1. *The comparison of parameters of electrical machines.*

Type of machine	Asynchronous	DC	PM
Frame size	200	160	160
Power [kW]	30,0	34,7	31,2
Speed [1/min]	1472	1560	1500
Efficiency [%]	92,5	88,5	91,8
Mass [kg]	265	247	110

Generators excited by permanent magnets have a lot of advantages, but can't forget about one of the drawbacks: increase of vibration level for load asymmetry. It is result of electromagnetic torque pulsations appearance – see figures 2–3. This is a very unfavorable phenomenon. A long exploitation of machine in this state can lead to the degradation of individual components. Ignoring these symptoms entails a real risk of a catastrophic failure, where costs can often exceed the cost of the drive [3], [7], [12], [14]-[15].

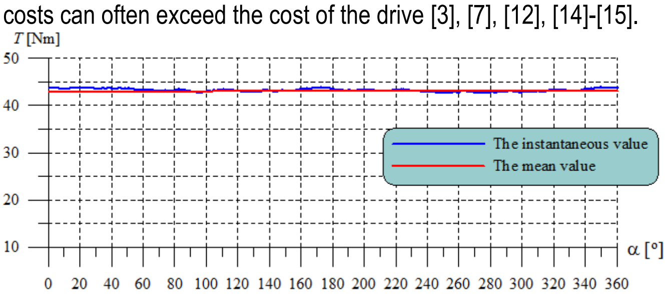

Fig. 1. *The waveform of electromagnetic torque for generator loaded symmetrically.*

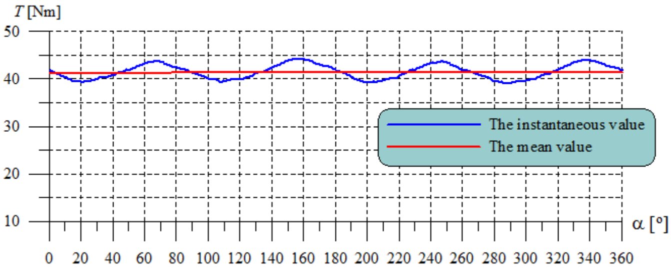

Fig. 2. *The waveform of electromagnetic torque for generator loaded asymmetrically (the current in one phase I = 0,75 I_n).*

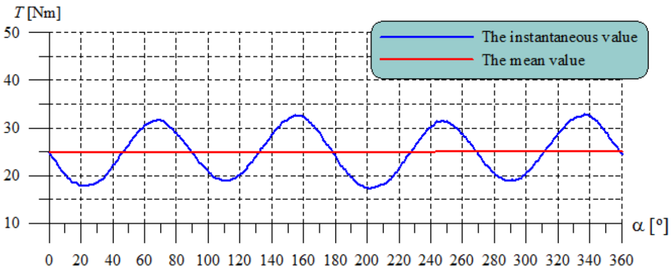

Fig. 3. *The waveform of electromagnetic torque for generator loaded asymmetrically (the break in one phase).*

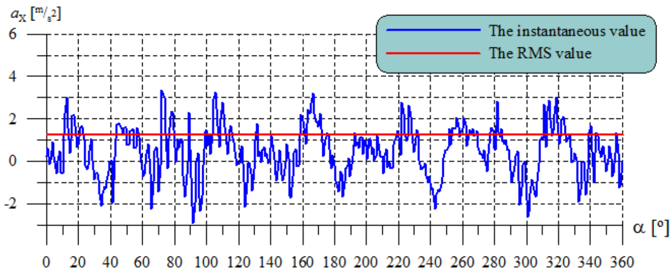

Fig. 4. *The waveform of vibration acceleration for generator loaded symmetrically.*

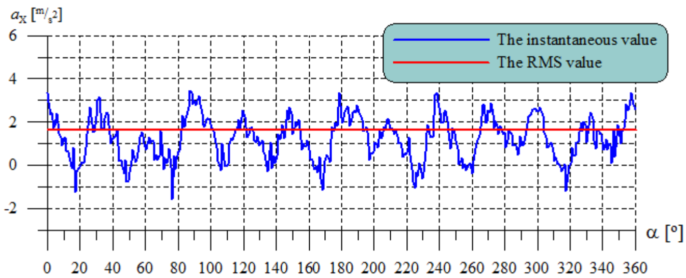

Fig. 5. *The waveform of vibration acceleration for generator loaded asymmetrically (the current in one phase I = 0,75 I_n).*

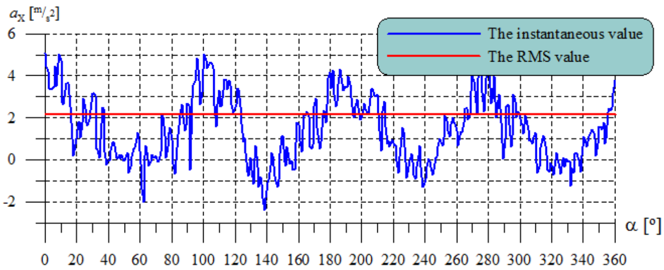

Fig. 6. The waveform of vibration acceleration for generator loaded asymmetrically (the break in one phase).

Tab. 2. The influence of electromagnetic torque pulsation on the increase in level of vibration of generator SMzsg132M-4

Load state of generator	T [Nm]	T_{pp} [Nm]	a [m/s²]	a_{max} [m/s²]
Symmetry $I = I_n$	43,0	1,2	1,3	3,2
The current in one phase $I = 0{,}75\ I_n$	41,3	5,0	1,6	3,4
The break in one phase $I = 0$	24,9	15,0	2,2	5,0

In Figures 1–6 and in Table 2 can be observed the influence of load asymmetry on the increase in level of vibration and electromagnetic torque waveform. The level of vibration and torque pulsation increase with the increase of load assymetry.

1. THE ESSENCE OF DIAGNOSTIC METHOD

A common diagnostic method of electrical machines vibration measuring is a direct measurement of acceleration or velocity by mechanical-electrical sensors.

The sensor with a piezoelectric element is used to measure of acceleration of vibration. The magnetic – electric sensor (permanent magnet and coil) is used to measure of vibration speed. The vibration measurement consists in applying a sensor to the measuring point, for example to the bearing shield of generator. Vibration is usually measured in three directions: x – horizontal, y – vertical and z – longitudinal. Vibration diagnostics is mainly based on measurements using dedicated, complicated and expensive apparatus [1]-[6], [8].

If the vibration exceed the limit values according to the norms and manual instructions, the registered signal is frequency analyzed, what is transformation of the waveform in time domain to the frequency domain. By measuring the vibrations need to pay attention on correct sensor mounting, it often creates problems because the machine is rarely adapted for this. The method of sensor mounting influences on the band frequency of measurement signal [3]. Additionally, it should pay particular attention to the separation of the measuring circuit from any kind of distortions, it may cause incorrect indications of apparatus.

In the wind energy systems, where the PM generator is housed in the gondola, and in the water systems, where generator with turbine is sunk in the water, the direct vibration measure by sensors is difficult or impossible. There is therefore a need for a different way of generators vibration diagnostic without using electromechanical sensors [3]-[6].

When the measurements of the generator load asymmetry was performed, it's noted an increase the level of vibrations – it can be observed in table 2. It shows that the load asymmetry of generator with permanent magnets generated vibration, these inducted voltage or current harmonics in the windings expressed by equation (1). It occurred the idea that, for the generators excited by permanent magnets, working in hard conditions, where vibration measurement is difficult, to vibration diagnostic use harmonic analysis of voltage or current. Specific structural properties of machines excited by permanent magnets are used in this method - electromotive force (EMF) generated due to vibrations [3]-[6].

$$f_k = (2k-1)\frac{n\,p}{20} \qquad (1)$$

where:

f_k – kth harmonic,
p – pole pairs number,
n – rotational speed,
k – natural number.

2. GENERATOR PM AS A VIBRATION SENSOR

PM machine is similar to electro-dynamic sensor of vibration. The sensor has a simple construction – a permanent magnet hanged on a spring inside a coil. The permanent magnet moves inside the coil and generates a voltage on terminals of the coil. The voltage signal is proportional to vibrations. There are also constructions where a coil moves and the permanent magnet is fixed rigidly to the chassis. Electrical machine with permanent magnets has 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 electro-dynamic sensor. The external supply is no required to generation measuring signal.

To verify this phenomenon the non-powered and idle machine was tested on the vibration table. In figure 7 present the frequency analysis of phase and phase to phase voltages and vibration sensor signal. The induced of voltages confirms the theory to use the machine with permanent magnets as a vibration sensor for itself. However the measuring signal must be extract from operating signal, which can cause some difficulties. The value of measuring signal to operating signal is relative small and therefore can't be relied upon.

To signals selection author use frequency analysis, however, keep in mind that a lot of PM machine operates with the inverters and is needed filtration of signals [3], [9]-[11].

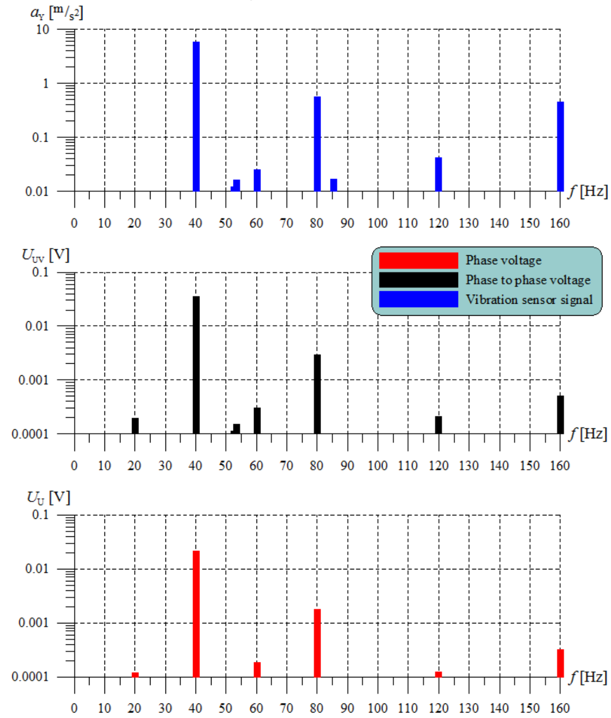

Fig. 7. The frequency analysis of signals: own and vibration sensor –static tests on the vibration table.

3. THE CALCULATIONS, SIMULATIONS AND LABORATORY TESTS RESULTS

Calculations, simulations and laboratory tests described in the article were made for PM generator of type: PMzsg132M-4 – 6M, and parameters: P_N = 6,5 kW, U_N = 82 V, I_N = 55,9 A, n_N = 1500 1/min, T_N = 41,4 Nm. This machine has a stator with skew and number of slots Q = 36. The rotor has permanent magnets mounted on the surface (SPM).

Computer simulations were performed using an Ansys Maxwell program on field model. The program uses for calculations the finite element method and Maxwell's equations. It is used for analysis of two and three dimensional electromagnetic fields of low frequency. Can be used to solve issues of constant and variable magnetic field. It can be caused by time-varying electric current in winding or varying position of permanent magnets. The calculations can be made for linear and nonlinear materials [3], [13].

For measuring, recording and analyzing of results the virtual measuring instruments made in LabView environment were used.

Below in figures 8–11 and tables 3–5 presents simulations and laboratory tests results of current of tested generator (one rotation).

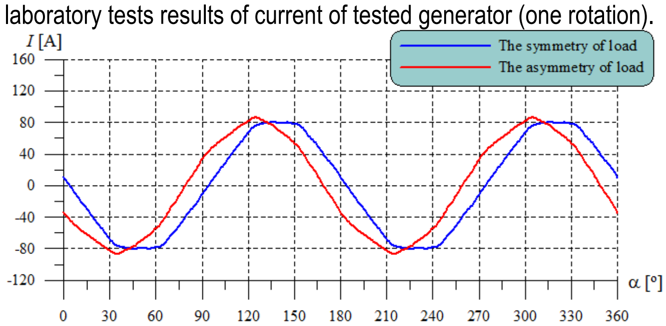

Fig. 8. The waveforms of generator current with symmetry and asymmetry point operation – the result of simulation.

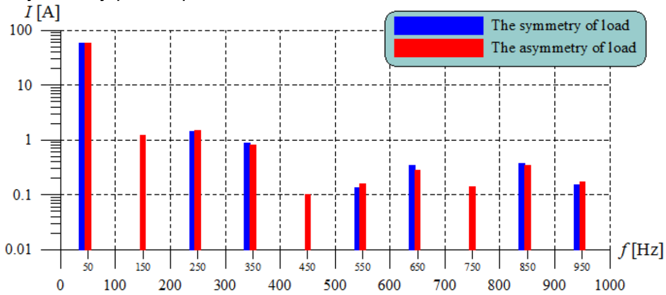

Fig. 9. The frequency analysis of generator current with symmetry and asymmetry point operation – the result of simulation.

Tab. 3. The frequency analysis of generator current with symmetry and asymmetry point operation – the result of simulation.

kth harmonic (1)	I_1 [mA]	I_2 [mA]	I_3 [mA]
Load symmetry	4,0	1,0	1,0
Load asymmetry	1197,9	100,9	137,6

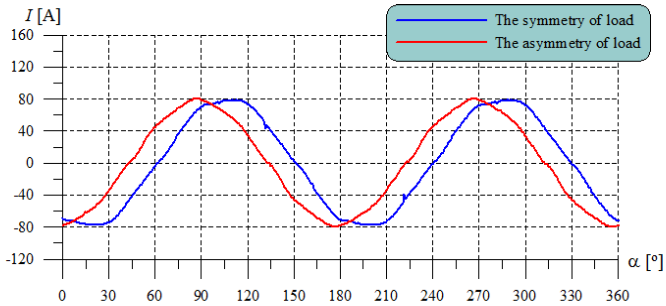

Fig. 10. The waveforms of generator current with symmetry and asymmetry point operation – the result of laboratory tests.

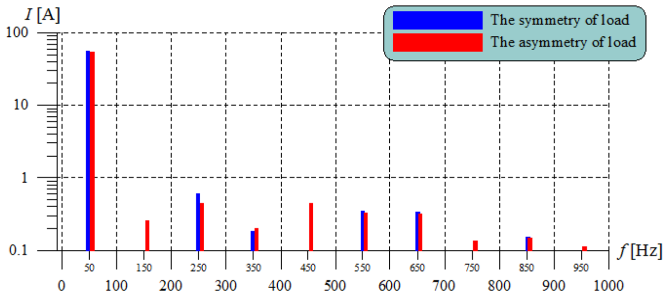

Fig. 11. The frequency analysis of generator current with symmetry and asymmetry point operation – the result of laboratory tests.

Tab. 4. The frequency analysis of generator current with symmetry and asymmetry point operation – the result of laboratory tests.

kth harmonic (1)	I_1 [mA]	I_2 [mA]	I_3 [mA]
Load symmetry	38,0	31,0	27,0
Load asymmetry	253,0	448,0	135,0

Tab. 5. The frequency analysis of generator current with symmetry and asymmetry point operation – the comparison of calculations, simulations and laboratory tests results.

	n [1/min]	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
Simulations	1500,0	150,1	450,1	750,1
Tests	1504,8	150,3	450,6	751,0
Calculation	1500,0	150,0	450,0	750,0
	1504,8	150,5	451,4	752,4

In the analysis of above results can be observed the convergence of simulated and recordered waveforms of voltage and current. The results of simulations and laboratory tests present an increase of level of the same frequencies in the asymmetry states. Obtained frequencies don't differ from the calculations (1) – the difference is less than 0,15 %. According to the author is it a very good result. The values of magnitudes are different, but in case of simulations the considered electrical machine is ideal. Whereas in reality there are a number of additional frequencies, resulting from the asymmetry of machine construction. Both in the case of simulation and the laboratory tests can be obtained several to several tenfold increase of level concerned frequencies.

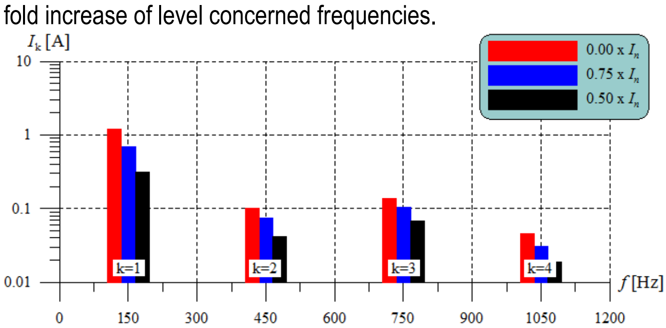

Fig. 12. The frequency analysis of generator current for several asymmetries of point operation.

Tab. 6. The frequency analysis of generator current for several asymmetries of point operation.

kth harmonic (1)	I_1 [mA]	I_2 [mA]	I_3 [mA]	I_4 [mA]
Asymmetry I = 0,50 I_N	312,0	42,0	67,0	19,0
Asymmetry I = 0,75 I_N	697,0	75,0	105,0	31,0
Asymmetry I = 0.00 I_N	1197,9	100,9	137,6	45,3

In figure 12 and in table 6 performed the frequency analysis of generator current for several load asymmetries. It can be observed that the asymmetry of load grow up, the magnitudes of characteristic frequencies increase. It shows the possibility to use the machine with permanent magnets to detection of exceeded acceptable level of vibration. Of course the generator must be scaled earlier.

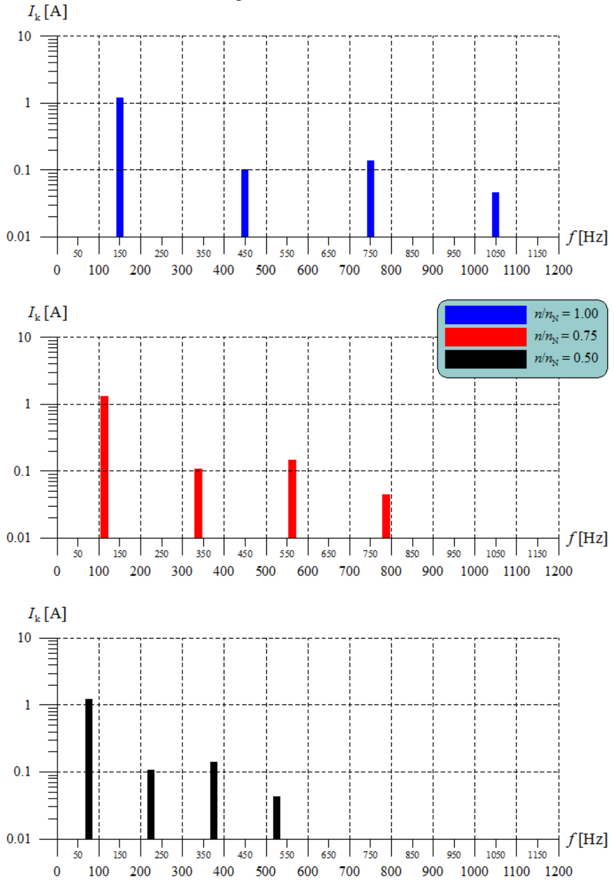

Fig. 13. The frequency analysis of generator current for asymmetry of point operation for several rotational speeds.

Tab. 7. The frequency analysis of generator current for asymmetry of point operation for several rotational speeds. – simulation results

kth harmonic frequency	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]
Asymmetry for: n = 0,50n_N	75,1	225,1	375,1	525,1
Asymmetry for: n = 0,75n_N	112,8	337,8	562,8	787,8
Asymmetry for: n = 1,00n_N	150,1	450,1	750,1	1050,1

Tab. 8. The frequency analysis of generator current for asymmetry of point operation for several rotational speeds. – calculation results (1)

kth harmonic frequency	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]
Asymmetry for: n = 0,50n_N	75,0	225,0	375,0	525,0
Asymmetry for: n = 0,75n_N	112,5	337,5	562,5	787,5
Asymmetry for: n = 1,00n_N	150,0	450,0	750,0	1050,0

The figure13 and tables 7-8 above present results of the frequency analysis of generator current for asymmetry of point operation for several rotational speeds. It can be observed the convergence with the calculations (1) results. This is proves of the correctness of the diagnostic method in the entire area of generator PM rotational speed.

SUMMARY

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 measuring sensors are used ones, for scaling the type of machine. The scaling is not required, if the intention is detect the disruption fact, not vibration level.

The Vibration measurements by this method can be performed on-line during the normal operation of the machine [3], [8].

The calculations, simulations and laboratory tests confirm the effectiveness of new vibration diagnostic method for generators excited by permanent magnets, where vibrations were created as a result of asymmetry of load. The analysis shows the possibility to use the machine with permanent magnets as a vibration sensor for itself.

The author never encountered such an application for PM generators, where the assessment of the intensity of the vibration a specific properties of the machine are used. This approach is innovative and custom. Presented diagnostic method greatly simplifies measure of vibration in PM machines, according to the author who makes researches of machines in the laboratory, as well as diagnostics of electrical machines operating in the industry [3], [5].

APPENDIX

Scientific work financed by state funds for science in 2013-2015, as a project No. 413/L-4/2012 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".

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PROBLEM ZWIĘKSZONEGO POZIOMU WIBRACJI, KTÓREGO PRZYCZYNĄ JEST ASYMETRYCZNE OBCIĄŻENIE GENERATORÓW WZBUDZANYCH MAGNESAMI TRWAŁYMI

Streszczenie

Praca przedstawia zastosowanie wibracyjnej metody diagnostycznej dla generatorów z magnesami trwałymi pracujących w stanach asymetrii obciążenia. Maszyny te są wykorzystywane w małych elektrowniach wiatrowych oraz wodnych. Opisywana metoda jest innowacyjna i unikalna. Wykorzystuje ona specyficzne właściwości konstrukcyjne maszyn z magnesami trwałymi, tj. indukowanie się SEM pod wpływem wibracji. W pracy przedstawiono min. podobieństwo maszyny z magnesami trwałymi do czujnika drgań, zawarto wyniki obliczeń, symulacji oraz badań laboratoryjnych. Metoda ta jest przedmiotem zgłoszenia patentowego [1]-[2].

Autor:
Marcin Baranski - Institute of Electrical Drives and Machines Komel, Laboratory of Electrical Machines, Research and Technical Expert, Katowice, 188 Rozdzienskiego Ave., Poland (email: m.baranski@komel.katowice.pl).