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MEASUREMENT AND QUANTITATIVE EVALUATION OF INVERTER-INDUCED BEARING CURRENTS

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Abstract: In this paper, new criterion for evaluation of endangerment of bearings due to bearing currents – the trend line of the Joule integral of bearing current - is proposed. Suggested is the measurement procedure for bearing currents with selection of appropriate sensor. An analysis, which is the basis for selection of current sensor for bearing current measurement, is presented. The shunt sensor as most appropriate sensor was implemented into measurement procedure and experimental measurements were performed on $1.6\,\mathrm{kW}$ brushless direct current (BLDC) motor.

Keywords: bearing currents, current sensor, Joule integral, level of endangerment of bearings.

1. INTRODUCTION

Modern electric motor drives are often composed of induction motor or permanent-magnet synchronous motor (PMSM) or BLDC motor and complex electronics with inverter as output stage. These drives provide good performances, high efficiencies and long life, but on the other hand there are parasitic effects, like electromagnetic interference (EMI) and bearing currents, present in these drives. Whereas EMI could disturb operation of nearby electronic devices, bearing currents could cause premature failure of bearings and consequently of whole drive.

The main causes for the parasitic effects are quick switching times of inverter‘s transistors, common mode voltage and stray capacitances and inductances in motor. Three phase power supply of induction or PMS or BLDC motor in modern drives is generated from direct current (DC) by inverter with pulse-width modulation (PWM) principle. While three phase electrical network commonly has balanced three phase voltages, this is not the case in three phase system, generated by inverter, which means that sum of three phase voltages is not 0 at every instant of time. The sum is called common mode voltage and has amplitude, proportional to DC link voltage in inverter and frequency, equal to carrier frequency of PWM, which is commonly between $1\,\mathrm{kHz}$ and $20\,\mathrm{kHz}$. Due to quick switching times of inverter’s transistors, rise and fall times of common mode voltage are short and therefore common mode voltage contains additional higher harmonic frequencies, also in megahertz range. Even though small, stray capacitances and inductances in motor provide low impedance paths to ground for current, driven by high frequency common mode voltage. This current is called common mode current. Common mode voltage and common mode current are sources of inverter-induced bearing currents [1], [2], which are classified into four groups, as it is shown in Fig. 1 [3]. Capacitive and electric discharge machining currents are caused by common mode voltage, whereas high frequency circulating currents and bearing currents due to rotor ground currents are consequence of common mode current. Electric currents, flowing through bearings, could cause small pits on bearing races and roller elements (Fig. 2) [4] and also degradation of bearing grease, which leads to long-term raise of vibrations and mechanical wear and consequently to premature failure of bearing.

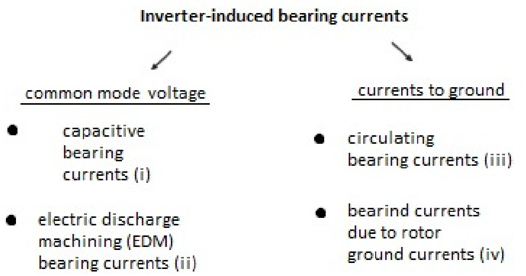

Figure 1. Classification of inverter-induced bearing currents.

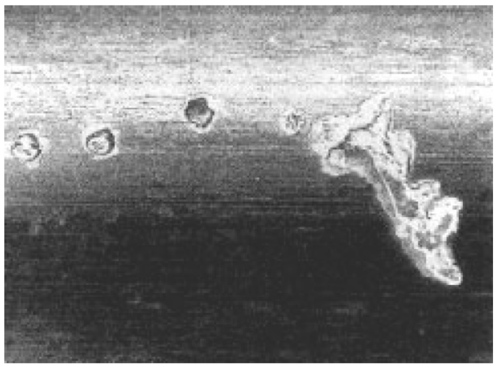

Figure 2. Small pits on bearing race

Measurement of bearing currents is complex task due to nature of these currents, which is high frequency and stochastic with short duration (few hundred nanoseconds). Additional complexity introduces installation of current sensor. It is impossible to measure current inside the bearing in the part, where bearing current actually occurs. It is also impossible to measure currents between shaft and inner bearing ring or frame and outer bearing ring [5]. The most widely used method to measure bearing currents is to put insulation sleeves between bearing outer ring and motor frame and to provide bypass of the insulation (short cooper wire), which could be disconnected, if needed. Preparation of motor, for bearing currents measurement is shown in Fig. 3. Bearing currents can be measured inside the bypass wire, but the measurement cannot give the information about distribution of the current inside the bearing. The distribution is commonly modeled and estimated [5]. It should be noted, that presence of measurement setup (insulating sleeves, bypass wire, measurement equipment) introduces additional measurement inaccuracies. Besides measurement of bearing currents, other related parameters are commonly investigated, namely bearing temperature, bearing (shaft-to-frame) voltage, voltage difference between shaft's ends, common mode current, stator ground current, rotor ground current and common mode voltage [3]. In this paper, we investigated only electric discharge machining (EDM) currents and capacitive bearing currents.

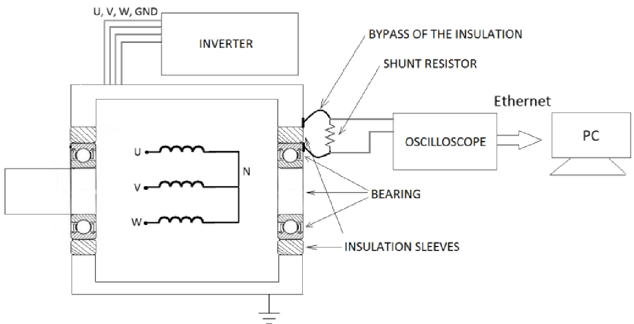

Figure 3. Installation of bearing into motor and measurement system with tested motor.

2. MECHANISM OF BEARING DAMAGE FORMATION

Thin film of bearing grease is formed between rolling element and bearing rings during operating speeds above few hundred rotations per minute (RPMs). This film prevents mechanical wear of rolling elements and bearing rings. Bearing grease is commonly dielectric. Therefore the grease film at sufficient speed prevents also electrical contact between rolling elements and bearing rings. Therefore bearing exhibits capacitive characteristic, as shown in Fig. 4.

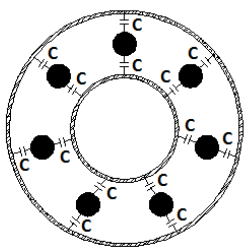

Figure 4. Main capacitances in bearing.

Due to existence of common mode voltage and stray capacitances in motor, there is also shaft voltage, with shape, that tracks the shape of common mode voltage. Shaft voltage is the same as bearing voltage. When the value of shaft voltage exceeds the value of threshold bearing voltage, discharge arc is formed in bearing grease. Shaft voltage discharges through this arc. Locally in the arc temperature significantly rises because of electric current passage through relatively small diameter. The surface of rolling element and bearing ring can be melted or even vaporized on the point, where current flows through, if the energy of the current is high enough. Small pits as shown in Fig. 2 are formed on the surfaces of rolling element and bearing ring in case of vaporisation of the material. The vaporised material is dropped in bearing grease. In long-term process of formation of pits, vibrations in bearing become significant. Therefore typical pattern, called fluting, is formed (Fig. 5). Furthermore, bearing grease is contaminated with metal particles and does not provide sufficient protection against mechanical wear. Bearing grease is also chemically changed due to passage of electric current.

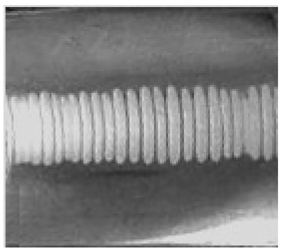

Figure 5. Fluting on bearing ring.

Bearing failure occurs soon after the formation of fluting. Bearing fails due to deformation of rolling elements or due to broken bearing cage, which keeps rolling element on proper distance to other rolling elements.

3. ANALYSIS OF CURRENT SENSORS

There are four common sensors for bearing currents measurement namely current probe, Rogowski coil, antenna, and shunt sensor. Current probes for oscilloscopes are commercially available at reasonable prices with bandwidths up to $120\,\mathrm{MHz}$, maximum peak current $30\,\mathrm{A}$ and $1\,\mathrm{mA}$ resolution, which is appropriate for bearing currents measurement.

Rogowski coils are cooper wire coils, wound on air core. They are especially designed to measure current in wire. Rogowski coil has to be clamped around the wire, where current has to be measured. Advantages are wide current range, quick response times, and linearity. They have frequency range with bandwidth up to $10\,\mathrm{MHz}$. While bearing currents have frequency content of several tens of megahertz, bandwidth introduces limitation of that sensor for bearing current measurement.

Antenna as a sensor for bearing currents measurement exploits the fact that bearing currents (at least some types of them) cause electric sparks in bearings and therefore emit electromagnetic waves. This type of measurement is problematic due to low energy radiated (rough approximation is made that only one-thousandth of energy released by discharge is radiated [5]), many sources of interference, and dependence of antenna position during measurement, etc. For these reasons, antenna has to be carefully designed, characteristics of interference sources have to be known and measured signal has to be filtered with carefully designed filters. Therefore this sensor is appropriate only for laboratory measurements and even in that case has limited accuracy.

Shunt sensors are available for measurements of wide range of currents and wide frequency range. The main problems, related to shunt sensors are their stray inductances (and capacitances). To suppress influence of stray inductance, the value of resistance has to be increased, but on the other hand increasing resistance increases influence on bearing currents' path. Selection of proper shunt is compromise between influence of resistance to current path and influence of stray inductance to overall impedance of shunt. Commercially available are shunts with bandwidth around $50\,\text{MHz}$.

Based on mentioned features of all four sensors, we decided to use current probe and shunt sensor and make additional tests of their response in frequency range, typical for bearing currents. Both, current probe and shunt sensors were used in combination with digital oscilloscope with $100\,\text{MHz}$ bandwidth and $1.25\,\text{GS/s}$. In combination with shunt sensor, voltage probe with $100\,\text{MHz}$ bandwidth was also used.

As current probe we used passive Hall-sensor probe, with analog bandwidth $50\,\text{MHz}$ (from $0\,\text{Hz}$ to $50\,\text{MHz}$), which allows maximum peak currents $15\,\text{A}$ and maximum continuous currents $10.6\,\text{A}$. Clamping current probe around wire introduces additional impedance in the circuit, what could have influence on measurement in some cases, but value of impedance is lower than $500\,\text{m}\Omega$ even at higher frequencies. Effective bandwidth B_{eff} of measurement system, composed of current probe with bandwidth $B_{\text{CP}} = 50\,\text{MHz}$ and oscilloscope with bandwidth $B_{\text{OSC}} = 100\,\text{MHz}$ is given by (1). The lower cutoff frequency is 0, so bandwidth denotes also upper cutoff frequency $B = f_{\text{upp,coff}} - f_{\text{low,coff}} \doteq f_{\text{upp,coff}}$. According to (1), bandwidth of measurement system would be $44.7\,\text{MHz}$.

$$B_{\text{eff}} = \frac{1}{\sqrt{(1/B_{\text{CP}})^2 + (1/B_{\text{OSC}})^2}} \qquad (1)$$

We made additional test of frequency response (only amplitude part) of current probe using function generator with upper cutoff frequency $50\,\text{MHz}$. Resistor with value of $6\,\Omega$ was supplied by constant voltage, so the current over the resistor was constant. Frequency was changed from $50\,\text{Hz}$ to $50\,\text{MHz}$. Test showed, that actual cutoff frequency of current probe is much lower, namely around $5\,\text{MHz}$, as could be seen in Fig. 6.

Results of the test show that tested current probe is not appropriate for bearing current measurements due to poor response at higher frequencies.

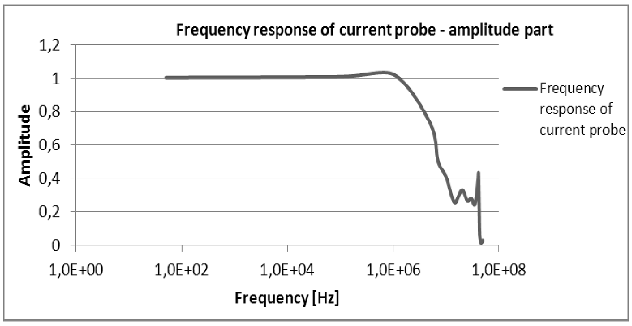

Figure 6. Frequency response of current probe – amplitude part.

As shunt sensor, we used current sensing resistors, of 1Ω resistance with low inductance and good frequency response $B = 50\,\text{MHz}$. Due to significant high-frequency noise, superimposed to the measured signal, we tested combinations with 1, 3, 5, 6 and 10 resistors connected serially. $3\,\Omega$ variant was found out as the best compromise, therefore, further investigations were made on that resistor. When shunt sensor is used, measurement system is composed of three elements, namely shunt sensor, voltage probe and oscilloscope. According to the (1), effective bandwidth of the system is $40.8\,\text{MHz}$. Considering known frequency response of the sensing element, it is possible to correct amplitudes of higher frequency components in bearing currents measurements, implementing correction algorithm, where every measured signal is transformed to frequency spectrum and multiplied by inverse function of function of frequency response of current probe.

4. NEW CRITERION FOR EVALUATION OF ENDANGERMENT OF BEARINGS

The most significant problem related to bearing currents is bearing failure due to increased vibrations and grease contamination, both caused by sparks of electric current in bearing. These sparks cause melting of surface of roller elements, contamination of bearing grease and chemical change of bearing grease, as it was described in chapter "Mechanism of bearing damage formation". Severity of consequences is strongly dependent on energy, released in bearing, during bearing current occurrence. Released energy W could be calculated with (2), where t_0 is the beginning of bearing current occurrence, and t_{end} is the time, when bearing current falls under the level, where it has no significant influence on the value of integral (e.g. $10\,\%$ of the maximum value) and does not exceed this level anymore, R is the local resistance in the area of bearing, and i_{b} is the instantaneous value of bearing current in time interval from t_0 to t_{end}, respectively.

$$W = \int_{t_0}^{t_{\text{end}}} R \cdot i_{\text{b}}^2 \,\text{d}t \qquad (2)$$

Resistance R in (2) is unknown parameter and hard to be precisely determined. For evaluation of the short circuits, the quantity of Joule integral is used as measure of thermal energy released during occurrence of short circuit [6]. The same physical principle is involved in melting process on bearing roller element, caused by bearing current. Therefore we chose this quantity as a measure of energy, released in bearing and consequently, measure of level of the endangerment of bearings, due to bearing currents. Joule integral J is described by (3), where t_0, t_{end} and i_{b} have the same meaning as in (2).

$$J = \int_{t_0}^{t_{\mathrm{end}}} i_{\mathrm{b}}^2 \, \mathrm{d}t \tag{3}$$

In close relationship with Joule integral, when concerning bearing currents, is maximum of absolute value of bearing current between times t_0 and t_{end}, $\max|i_{\mathrm{b}}|$. The value of $\max|i_{\mathrm{b}}|$ is commonly used in literature to characterize bearing currents, which could endanger bearings, whereas Joule integral is not used in a such way, even though that value is in close relationship with energy, which is responsible for damage of bearings.

Damage on the bearing, caused by bearing current, depends on released energy and the diameter of the arc, through which, current flows. The higher the energy is, more prominent the damage is and the lower the diameter of the arc is, more prominent the damage is. The energy can be estimated by calculation of joule integral of current. But the diameter of the arc cannot be estimated, calculated or measured. One approach to determine the average diameter of the arc is to disassemble the bearing before fluting is formed, measure diameters of pits and calculate average diameter. Another approach to take the diameter of the arc into consideration is to calculate apparent current density, described by some authors ([5]). The first approach is applicable only on disassembled bearing. The second approach is possible also in bearings that are still in operation, but gives only indirect information about diameter.

Without known diameter of arcs in bearings, one cannot determine the endangerment of bearing regarding known energy that is released. Therefore only energy or Joule integral itself are not useful as an absolute criterion for estimation of bearing endangerment. However, they are still useful as comparative criteria. Firstly the levels of bearing currents that endanger bearings have to be determined, using the first approach described in previous paragraph or more commonly with experimental approach (experiences from motor field tests). When these levels (of energy or Joule integral) are known, it is possible to use them as a comparative criterion for all the bearings of similar size. More bearings we have investigated regarding average diameter of pits or more experiences from filed tests for one dimension of bearing we have, more reliable criteria released energy and Joule integral are for that dimension of bearing.

Levels of bearing currents could change over time due to many parameters that affect on them. Therefor it is important to know typical motor operating parameters, namely bearing temperature, operational speed, radial and axial load, etc. Measurements of bearing currents have to be performed under typical values of parameters. Therefor measurement has to be done in longer time period, to allow parameters to reach steady state and to obtain trend line of bearing currents (of release energy or Joule integral). If the motor application requires frequent change of operation parameters (e.g. variable rotational speed), these conditions have to be simulated during bearing-currents measurement.

In this paper only free-run at nominal speed measurements are described and trend-line of one-hour test is shown.

5. EXPERIMENTAL TEST

The new criterion for evaluation of bearings' endangerment due to bearing currents were used in test of $1.6\,\mathrm{kW}$ BLDC motor, to determine levels and trend line of Joule integrals of bearing currents. Features of tested motor are: three-phase star winding connection, outer-runner rotor, $400\,\mathrm{V}$ nominal voltage, and $2250\,\mathrm{rpm}$ nominal speed. Motor was prepared for capacitive and EDM bearing currents measurement, which means that both bearings were electrically insulated to the motor frame and bypass of the insulation was established by one bearing (Fig. 3).

Measurement equipment was composed of four channel digital oscilloscope with $100\,\mathrm{MHZ}$ bandwidth and $1.25\,\mathrm{GS/s}$ maximum sampling rate, voltage probe with $100\,\mathrm{MHZ}$ bandwidth, and $3\,\Omega$ shunt resistor.

Objective of one-hour test, with measurement of bearing currents was to get trend line of bearing current occurrences and their energy level. Bearing currents with amplitude levels below $100\,\mathrm{mA}$ are commonly considered as not harmful to the bearings [3], therefore oscilloscope was set to edge triggering (rising edge) with level $300\,\mathrm{mV}$ (this represents $100\,\mathrm{mA}$ when $3\,\Omega$ shunt resistor is used). To determine the trend line of bearing currents occurrences, one does not need to detect every bearing current that occurs. It is also technically complicated to achieve that aim, due to time needed for data processing in oscilloscope and transfer to the PC. We set up the procedure, where oscilloscope goes to state of waiting to trigger event and when bearing current occurs, oscilloscope is triggered. There is a $100\,\mathrm{ms}$ time window, during which oscilloscope has time to process data and send it to the PC. After $100\,\mathrm{ms}$, oscilloscope goes again to the state of waiting for trigger event. Time window is sufficiently short, that one-hour trend line test has adequate number of measurements. During one-hour test on the computer run only program for saving data. All data processing and analysis were made afterwards. Data processing on PC included offset removal and extraction of time window of every measurement, where useful signal was present. After that, Joule integral of the signal was calculated according to (3). As numerical integration method Simpson's $3/8$ rule was used. With statistical analysis we analyzed distribution of frequency of occurrences during one-hour test, maximum levels of Joule integrals and distribution of different levels of Joule integrals during the test.

To the group of "capacitive currents" belong also currents, which occur when bearing is in conductive state, but cause of the occurrence is the same as for capacitive currents – change of one phase voltage and therefore of common mode voltage. These currents have common amplitude levels below 200 mA [3]. An example of that current is shown in Fig. 7.

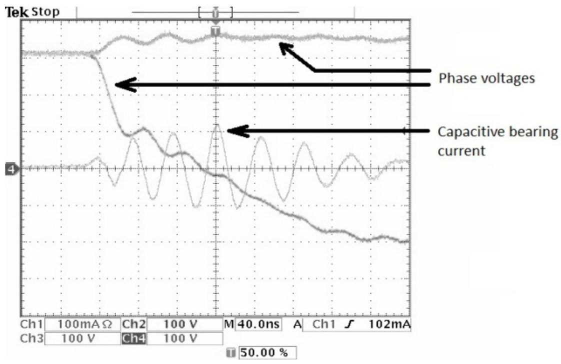

Figure 7. Example of »capacitive« bearing current

One hour test shows trend line of bearing current occurrences, where after motor startup prevail bearing currents with lower amplitudes and lower energies (lower Joule integrals), after 10 to 15 minutes frequency of currents with lower energies drops whereas frequency of currents with middle and higher energies rises (Fig. 8).

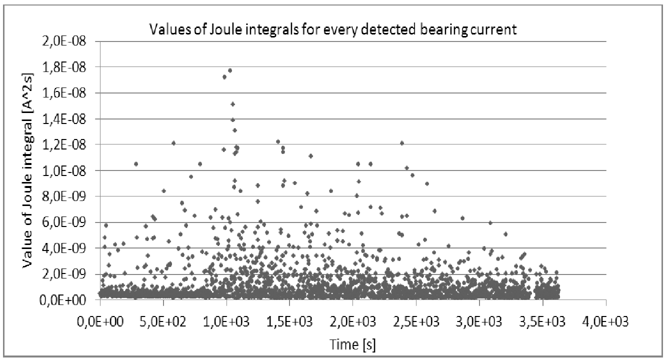

Figure 8. Values of Joule integral for every detected bearing current during one hour test.

After 30 minutes , frequency of currents with higher amplitudes gradually decreases, whereas frequency of currents with lower and middle energies remains approximately constant. It is assumed that after 30 minutes temperature in bearings reaches steady state and therefore trend line of bearing current occurrences remains constant, unless operating conditions of motor are drastically changed. Fig. 8 shows value of Joule integral of every detected bearing current during one-hour test. Majority of the values is low – under $1.0 \cdot 10^{-9}\ A^2 s$. Here trend line could be estimated. Fig. 9 provides better insight into happening during one-hour test and therefore is the best indicator of trend line.

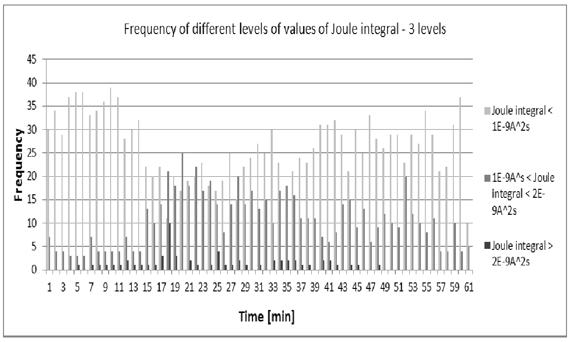

Figure 9. Frequency of different levels of values of Joule integral – 3 levels.

6. CONCLUSION

The paper presents the possibility to determine the level of bearings' endangerment based on fact, that one (or few) bearing current does not cause significant damage to the bearings. Important is how many bearing currents with significant levels of Joule integral occur in unit of time during normal operation of motor. Therefore we proposed a trend line of Joule integrals during one hour of normal motor operation as criterion of bearings' endangerment. However this criterion is not absolute. One could use it as comparative criterion, when motors with comparable dimensions and properties of bearings are tested.

7. REFERENCES

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