SELECTED CHARACTERISTICS AND DIAGNOSTICS OF MOTOR POWERED BY FREQUENCY CONVERTER

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DOI: 10.17973/MMSJ.2017_12_201790
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All of the technical devices that are powered by the frequency converter, apart from their great advantages, also bring considerable pitfalls and risks. When designing a machinery, it is necessary to consider the negative effects of characteristics of the frequency converter on the rotating parts, especially on the bearings of motors, gearboxes, gears, seals, etc. These devices and their parts are usually exposed to the effects of capacitive and shaft currents that have a considerable impact on the reliability of machines and equipment.

This article focuses on the reasons for the use of insulated bearing (or insulated coupling) for asynchronous motors and on the influence of the measures taken to eliminate the adverse effects on the rotating parts. The following is an example of the use of technical diagnostics to determine the condition of some parts of the machinery, the example is evaluated, conclusions are drawn and analysed.

KEYWORDS

frequency converter, parasitic current and voltage, shaft voltage, capacitive current, technical diagnostics, FFT spectrum of vibrations acceleration, vibro-diagnostics

1 INTRODUCTION

For proper "machine-motor-converter" operation, it is necessary to bear in mind whether the motor is properly connected to the converter, correctly grounded and interconnected, as well as to consider the technical measures taken on the machinery to prevent the shaft currents from passing through the rotating parts. It is always necessary to be aware of how the device works and what all the links related to the electrical power supply of the motor are, speed control, resonance of the machinery system and its design. A beneficial effect on the life of the device is provided by the equipment of frequency converter, such as various filters, impedance coils, etc.

2 SOURCES OF PARASITIC CURRENTS AND VOLTAGE

In the sets of a frequency converter and a motor we can in fact find three basic sources of parasitic currents.

2.1 Shaft voltage

Is generated by induction of voltage on the motor rotor due to the electromagnetic field and motor asymmetry (fig.1).

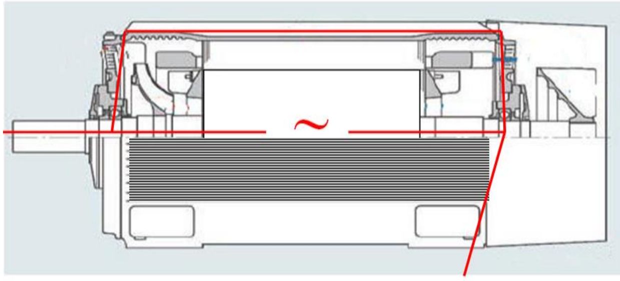

Figure 1. Closing of current circuit due to occurrence of shaft voltage

2.2 Capacitive currents

In the connection circuit of the asynchronous motor and the motor's own construction, the live parts of the conductors and windings are insulated. All circuit insulations behave as a capacitor with a certain capacity at higher frequencies (fig.2). The lower the impedance (resistance to alternating current) is the higher the current frequency and the insulation capacity $Z_L = 1/(2\pi fC)$ is. Additional capacities in the circuit of the motor are also formed by the air gap of the motor and the bearing insulation.

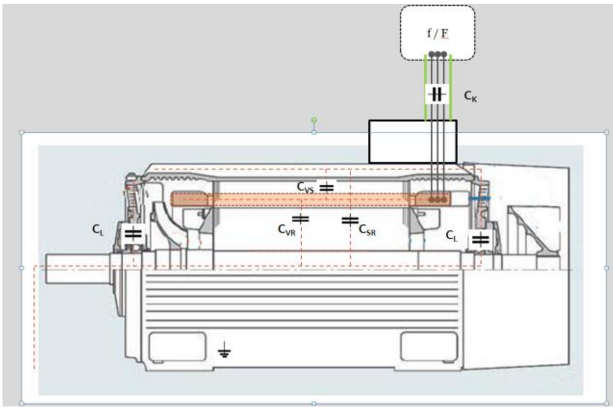

Figure 2. Generation of capacitive currents

C_{VS} – capacity between the winding and the stator packet
C_{VR} –capacity between the winding and the rotor packet
C_{SR} – capacity between the stator and rotor packet
C_L – bearing capacity
C_K – cable capacity

2.3 Other currents

Stray currents, static electricity, currents generated on other devices, or induced currents passing from static non-live parts to the rotor of the device (fig.3).

3 DESCRIPTION OF INDIVIDUAL SOURCES OF PARASITIC CURRENTS

3.1 *Shaft voltage and currents*

An asynchronous motor shaft induces the so-called shaft

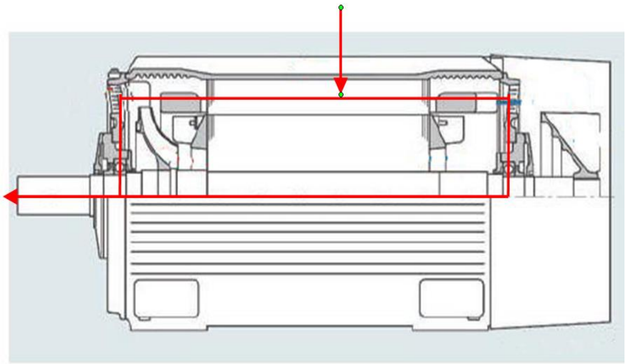

Figure 3. Currents flowing through non-live parts of the motor (stray currents)

voltage as a result of the magnetic field. Its size is influenced by many factors such as the electric motor design, geometrical asymmetry of motor, asymmetry of power supply voltage, etc. The voltage generated on the rotor is then closed through the bearings, the coupling or the gearing of the gearbox, etc. The frequency of these currents depends on the frequency of the power supply voltage, and the current flowing through the bearings depends on the size of shaft voltage and the lubricant resistance in the bearings. The usual value of shaft voltage, when it is necessary to prevent its passage through the bearings, is 0.3 V. In order to prevent damage to the motor bearings or related devices, an insulated bearing is used on motors at the opposite side from the coupling. This protection is usually sufficient to prevent the passage of the bearing currents.

If the motor has two free ends (two couplings), it is also necessary to use an insulated coupling on the insulated bearing side (fig.4). This is because if a non-insulated coupling is fitted on both sides of the motor, the shaft current would be closed through the connected device and this could damage both the motor and the two connected devices.

3.2 *Capacitive currents*

Principle of function of converter with pulse width modulation

To understand the effect of frequency converter on the device, it is necessary to be familiarized with how the converter works and how the power supply frequency of the motor is being changed. The frequency converter consists of four main parts: rectifier, DC link, converter, and control circuit (fig.5). A three-phase frequency converter is supplied with alternating current, typically at a frequency of 50 Hz; this current is rectified in the rectifier. A rectified DC is "wavy". In the DC link of the frequency converter, the rectified current is stabilized and smoothed using various filters, coils and capacitors. The converter occupies the last position in front of the motor, where the output voltage is adjusted to the requirements for powering the motor. The converter sets the output voltage important parameter of the frequency converter is pulse frequency.

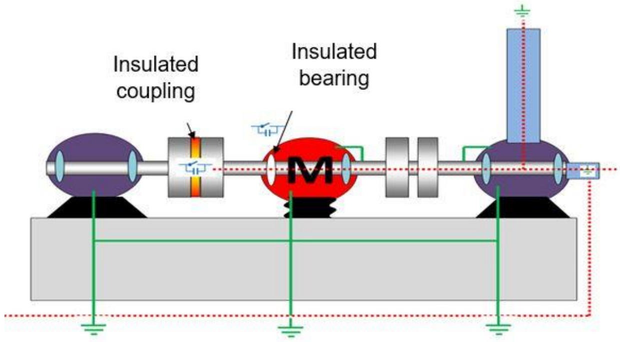

Figure 4. Machine unit with two insulated ends, insulated bearing and coupling

according to the load so that the motor meets the required operating conditions over the entire control range depending on the motor power supply frequency.

The modulated output voltage from the frequency converter has a rectangular character, and the current forms the required sinusoid of the respective frequency (fig.6). An important parameter of the frequency converter is the so-called pulse frequency. The size of this pulse frequency (in the order of kHz) affects the shape of the output voltage and current. The higher the frequency, the smoother the sinusoid of current is. The size of pulse frequency also affects the motor noise, motor losses and, last but not least, also the magnitude of capacitive currents. [Mathew et al. 2014].

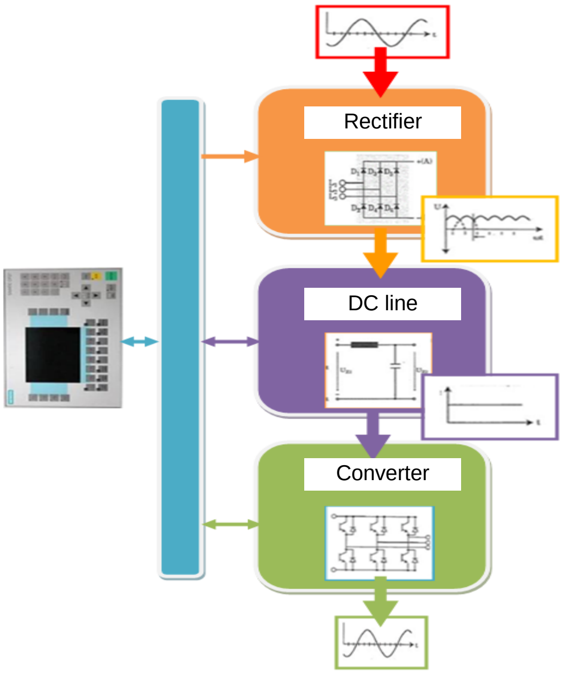

Figure 5. Diagram of frequency converter

Influence of pulse frequency on the service life of machinery

When powering the motor from the frequency converter, the RF pulse frequency (kHz) is also modulated on the power supply frequency (Hz). There are many insulations (capacities) in the circuit of the electric motor that behave like a capacitor in the circuit. Each of these capacities (capacity of conductors, capacity of winding insulation, rotor rods, air gap etc.) has its impedance (alternating current resistance) of $Z = 1/(2\pi fC)$. That means, the higher the pulse frequency, the smaller the impedance of the insulating material, and the greater the current flowing through the insulation. These currents are called capacitive currents.

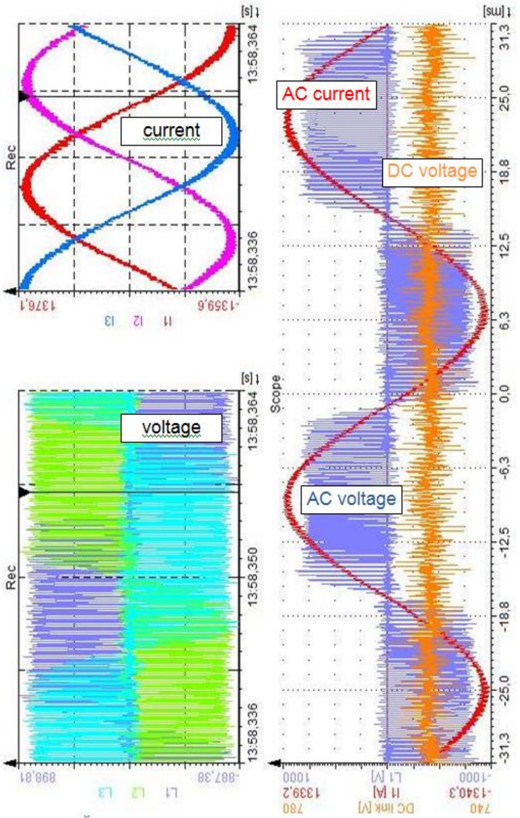

Figure 6. Time record of intermediate circuit voltage, output current and voltage from the frequency converter

If these currents are being closed through the motor bearings or through gear teeth, seals, etc., they reduce the service life of the machinery or its components.

Today, motor manufacturers produce motors that are ready to work with the frequency converter. The motor has an appropriate winding, reinforced insulation, and the front bearing (NDE) is mostly insulated. This bearing insulation works relatively well at lower frequency currents (e.g. power supply frequency of 60 Hz), but for currents with a frequency higher than 1 kHz, it works as a capacitor (fig.7).

To prevent damage to the motor bearings and other equipment, the manufacturer's recommendations to correctly connect the non-live parts of the entire device should be followed. On the shaft side it is also advisable to use grounding of the shaft by means of a brush, where the motor stator is conductively connected to the motor rotor. The connection of the stator part with the rotor is also recommended for the driven device to prevent damage to the bearing, or the gearing. It is also very important to have all the stator parts of all the devices grounded with protection provided by the connections.

The reason is that it is necessary to equalize the electrical potentials between the individual components of the device and also to ensure a reliable conduction path with the smallest

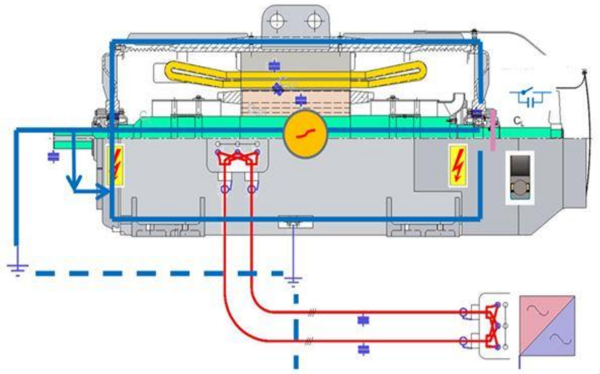

Figure 7. Overall diagram of motor connection to the frequency converter

possible impedance outside the rotating parts of the machinery.

Long-term experience shows that bearings are endangered when the effective value of shaft voltage exceeds 200-250 mV. At higher voltages, the plastic lubricant in the bearing may degrade and thereby lose its lubricating properties and damage the bearing path due to the passage of bearing currents.

When using converters, the peak voltage between the outer ring of the bearing and the rotor (bearing voltage) can also be dangerous for the bearing because it can reach several tens of volts, even if the effective value of the bearing voltage is relatively low.

To prevent damage to the rotating parts of the device due to capacitive currents, all measures must be taken to prevent the passage of capacitive currents through the motor bearings or the other parts connected to the motor rotor. Standard measures, apart from the correct grounding and connections of the equipment, include the motor connection using symmetrical shielded cables, where the cable shielding is conductively connected to the frequency converter housing, and on the motor, special EMC bushings are used to connect the cable shielding to the cable casing. Another measure is the use of different RF filters and ferrite cores on both the output and input of the frequency converter to suppress the pulse frequency and its harmonic components in the current spectrum. [Santosh et al. 2015].

3.3 Other currents

This category of parasitic currents includes currents which may not be related to the device itself, but can greatly affect the life of this device. For example, there may be stray currents in the vicinity of the railways, lightning currents, equipotential bonding, induced voltage on lines and cable bridges in asymmetrical or inappropriate locations of conductors, etc.

4 DIAGNOSTICS AND ANALYSIS OF CURRENT, VOLTAGE AND INFLUENCE ON VIBRATION OF MACHINERY

On the two-pole motor 3000 RPM / 50 Hz, 500 kW, diagnostics of frequency spectra and the effect of FM pulse frequency on the vibration spectrum in motor bearings were performed. Measurements were made when starting the device from zero to 1350 rpm. A vibration spectra analysis was performed at the measuring points of L1 and L2 bearings, and the analysis of current was performed on the phase conductors of the power supply line to the frequency converter and on the PEN conductors, and also on the phase conductors of the asynchronous motor connection, the PE conductor in the cable and the PE conductor of motor grounding. In addition, the current was measured on the shaft between the motor and the driven machine (Fig.8).

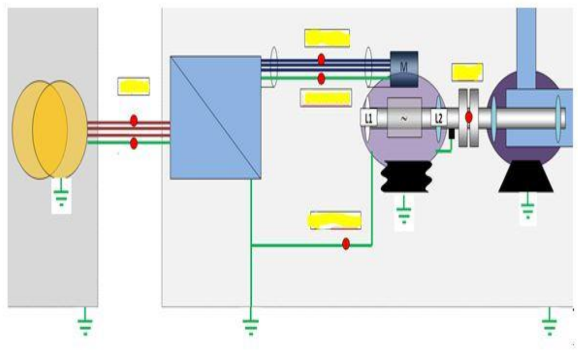

Figure 8. Measurement points on the test device

4.1 Dependence of vibrations on motor bearings

The vibration spectrum (Fig.9) was measured using accelerometers that were fitted on the measuring mounts in the site of the bearings located at an angle of 45 ° of the vertical axis. Measurement was performed using a vibration analyser manufactured by the ADASH company. In the spectrum of vibrations speed (fig.10), we can see the RPM frequency of vibrations speed (e.g. residual non-weight) and the frequency of the double of the motor power supply frequency. Due to the very near values of power supply and RPM frequency, the resolution of the origin of 2x harmonic multiple of these frequencies is considerably difficult. From the waveform of the 2x harmonic frequency and the small slip of the motor, it can be assumed that this is a 2x harmonic multiple of the motor power supply frequency.

4.2 FFT spectrum of vibrations acceleration on L1 and L2 bearings

A spectrum of vibrations acceleration (Fig.11) is evaluated in the band up to 10 kHz. In order to better analyse the effect of the pulse frequency on the vibrations acceleration, it is necessary to adjust the resolution of the acceleration spectrum so that the number of lines is sufficiently fine, and, on the contrary, the length of measurement of a single spectrum is as short as possible. By appropriate adjustment, we will provide a sufficient visual display of the spectrum cascade or the spectrograph for the acceleration display.

In the spectrum of vibrations acceleration (Fig.12), when starting the motor from zero to the operating speed, harmonic multiples of 1250 Hz pulse frequency of frequency converter are clearly visible. With increasing speeds, the sidebands are widened depending on the power supply.

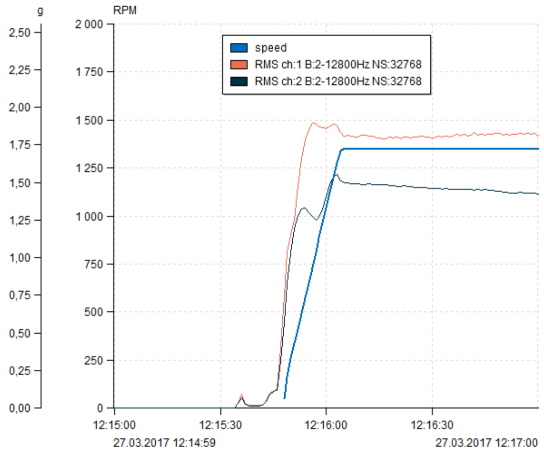

Figure 9. Speed of vibrations on motor bearings

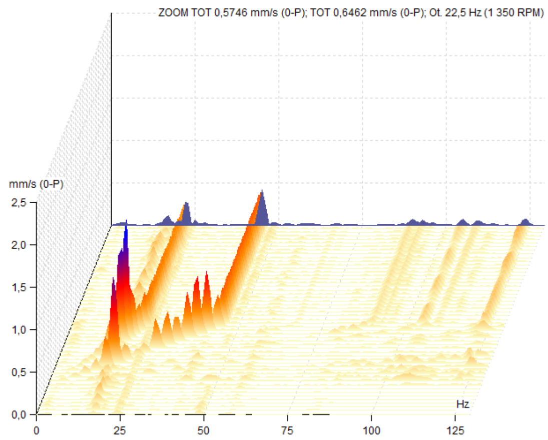

Figure 10. Cascade of frequency spectrum of vibrations speed on motor bearings

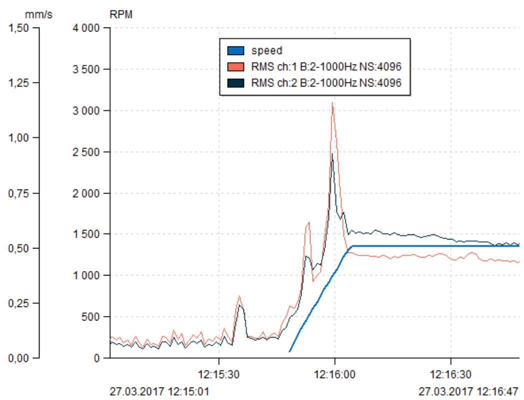

Figure 11. Acceleration of vibrations on the motor bearings

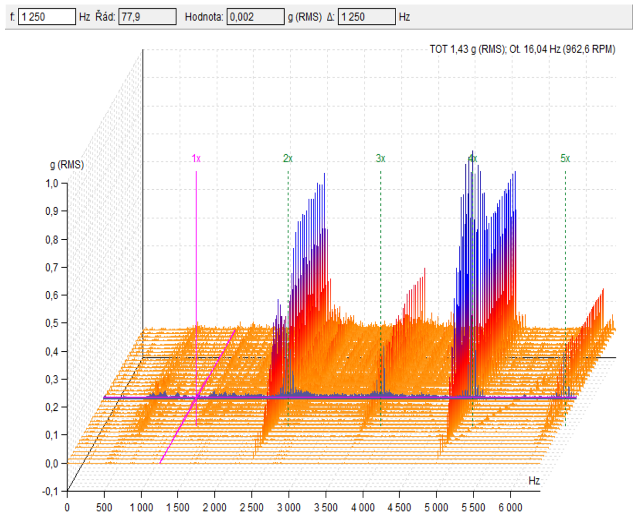

Figure 12. Cascade of frequency spectrum of vibrations acceleration on motor bearings

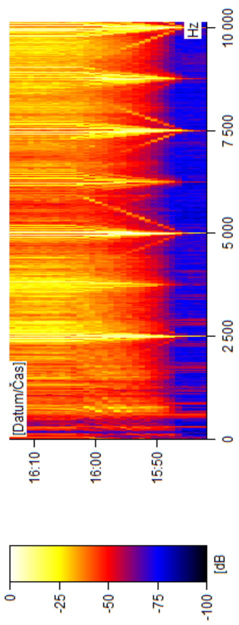

Figure 13. Spectrograph of frequency spectrum of vibrations acceleration on motor bearings

frequency of the motor (fig.13). The vibrations spectrum is analogous to the vibrations spectrum of the power supply current for the motor.

4.3 *Spectrum of power supply current for the frequency converter from the transformer station*

To analyse the current and voltage spectra, a Dewetron analyser was used along with the corresponding clamp converters of current, or Rogowski coils.

In the spectrum of the power supply current (Fig.14) for the frequency converter, we can see the network frequency of 50 Hz and the harmonic multiples which are caused by switching of power elements of the rectifier of the frequency converter.

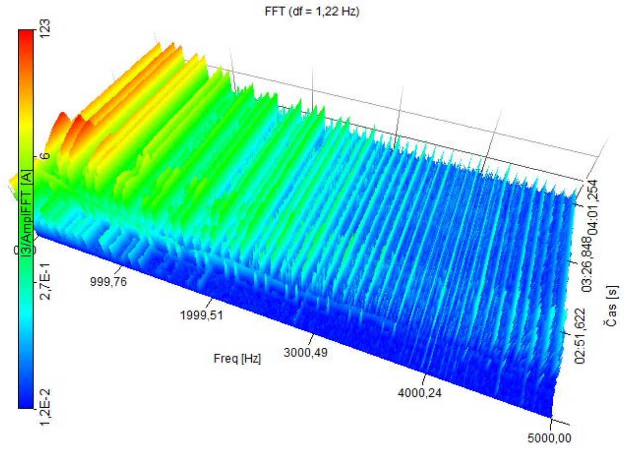

Figure 14. Cascade of spectrum of power supply current for frequency converter

4.4 *Spectra of voltage to supply the frequency converter from the transformer station*

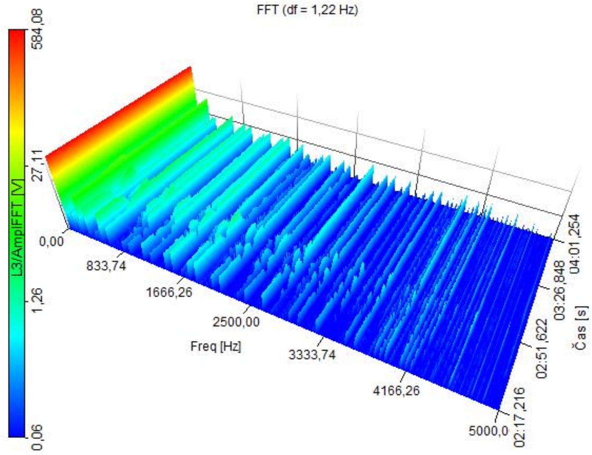

Figure 15. Cascade of spectrum of power supply voltage for frequency converter

There are no pulse frequencies and harmonic multiples with sidebands in the spectra of current (Fig.14) and voltage (Fig.15) of power supply for the frequency converter. This is due to the fact that the rectifier and the converter are separated from each other by the intermediate circuit, where the DC part is smoothed and filtered, separating thus the pulse frequency effect on the secondary side of the transformer.

4.5 *Spectrum of current in the PE conductor between the frequency inverter and the transformer station*

The current and voltage are measured on the supply cables of the frequency converter. If possible, the probes to measure the current are positioned at a sufficient distance from the frequency converter to eliminate the effect of the frequency converter on the probe conductors.

In the spectrum of current in the PEN conductor, we can see the power supply frequencies for 50 Hz frequency converter, the power supply frequencies for the motor start-up from 0-

22 Hz (fig. 17) and the pulse frequencies of 1250 Hz with sidebands and harmonic multiples (fig.16).

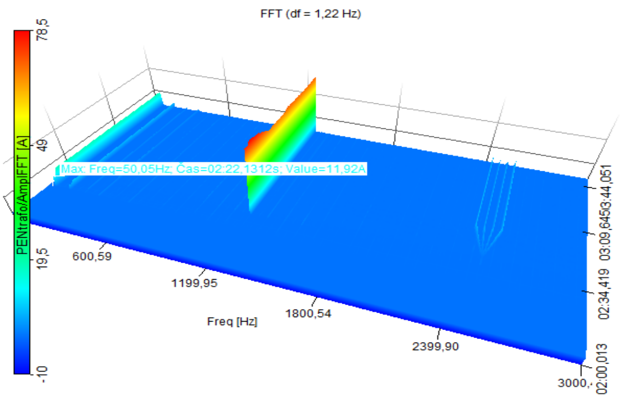

Figure 16. Cascade of spectrum of current up to 3 kHz in PE conductor between the transformer and the frequency converter

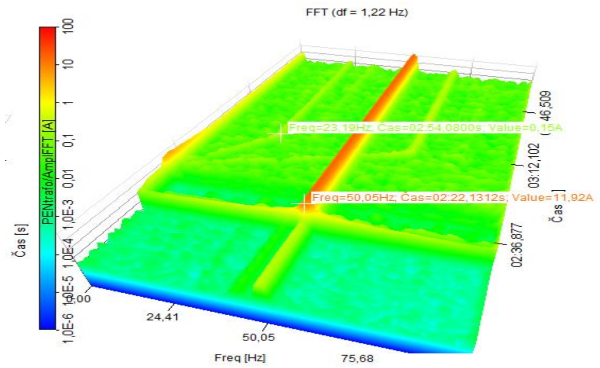

Figure 17. Detail of cascade of power supply current for frequency converter

4.6 Spectrum of power supply current for motor

Voltage measuring probes are connected to the input terminals of frequency converter. For voltage analysis, it is necessary to have a sufficiently voltage-rated voltage input for this measurement. In our case, the Dewetron instrument has an input measuring voltage up to 1200 V (0-P).

When starting the motor in the spectra of current, we can see the frequency of motor power supply and its harmonic multiples, and, at higher frequencies, also the pulse frequency with sidebands and its harmonic multiples (fig.18).

4.7 Spectrum of power supply voltage for the motor

In the spectrum of voltage for the power supply of motor through its start-up from 0 to 22 Hz (fig.19), high pulse frequencies of 1250 Hz with sidebands and harmonic multiples are shown at higher frequencies (fig.20). The spacing frequency of these sidebands corresponds to the power supply frequency of the motor. At this frequency, insulating materials behave like capacitors (condensers), and capacitive current, corresponding to these high frequencies, passes through these materials.

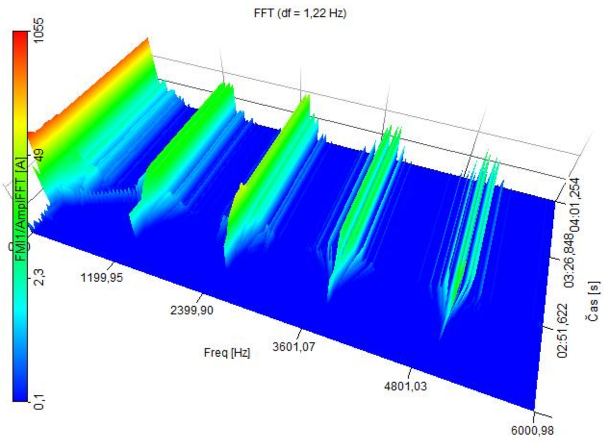

Figure 18. Cascade of spectrum of power supply current for the motor

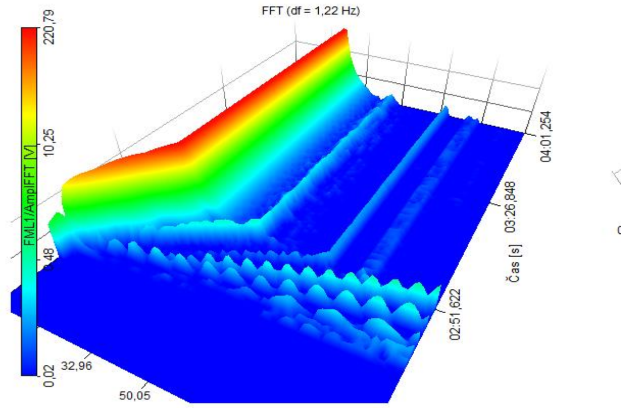

Figure 19. Detail of cascade of spectrum of power supply voltage for the motor

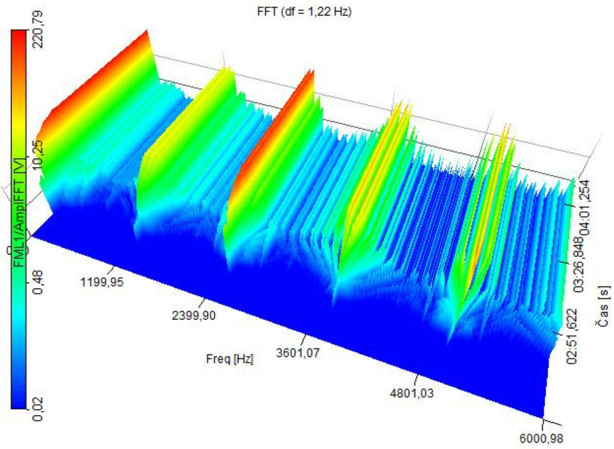

Figure 20. Cascade of spectrum of power supply voltage for the motor

From the graph of power supply current and voltage, it is evident that there is a dependence between the current and the voltage at the start-up of the motor. When starting the motor, the voltage increases gradually, depending on the motor speed, and with the motor acceleration, the power supply current decreases. An analogy with the vibrations spectrum should also be noted. In the vibrations spectrum, the dependence of acceleration amplitudes during the motor start-up is very similar to the spectrum of power supply current. Amplitudes of current and acceleration on pulse frequency components rise with a change in speed above the steady-state value set for steady motor speeds.

4.8 Spectrum of current in motor grounding

Further measurement of the spectra was performed on the PE conductor of motor external grounding. In the spectra of the grounding current there are components of the current from both the power supply of the frequency converter (50 Hz) and from the current of power supply of the frequency converter (the change of the spectrum at the start-up of the motor from 0 to 22 Hz) and the pulse frequency and its harmonic multiples with sidebands (1250 Hz) (fig.21).

4.9 Spectrum of current in the PE conductor of power supply cable of the motor

This measurement was carried out using a Rogowski coil, which was placed around all four parallel PE cable conductors connecting the motor to the frequency converter.

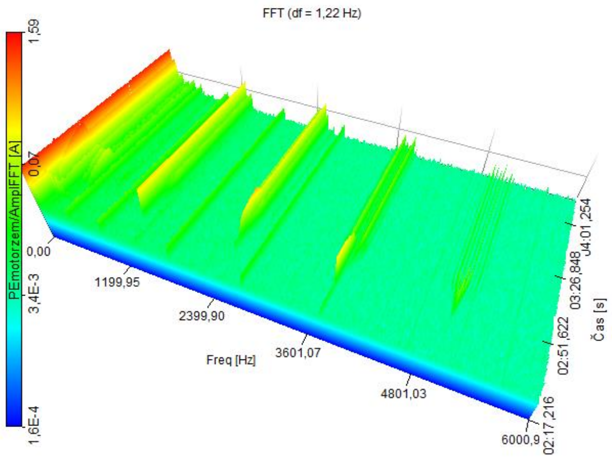

Figure 21. Spectrum of capacitive currents generated by the motor ground conductor up to 6 kHz

In the measured spectrum of the current in PE conductors, there are also harmonic multiples of the pulse frequency with the sidebands (fig.22). By comparing the magnitudes of these capacitive currents, it is clear that the magnitude of these currents is greater in the PE conductors in the cables than in the PE conductor of the motor grounding. The magnitude of these currents and their ratio also depends, among others, on the impedance of the individual ground loops that are being closed between the frequency converter and the motor.

4.10 Spectrum of current on the shaft (coupling) between the motor and the driven machine

Shaft currents were measured using a sufficiently long Rogowski coil, which was placed around the shaft behind the coupling, well away from the motor being measured.

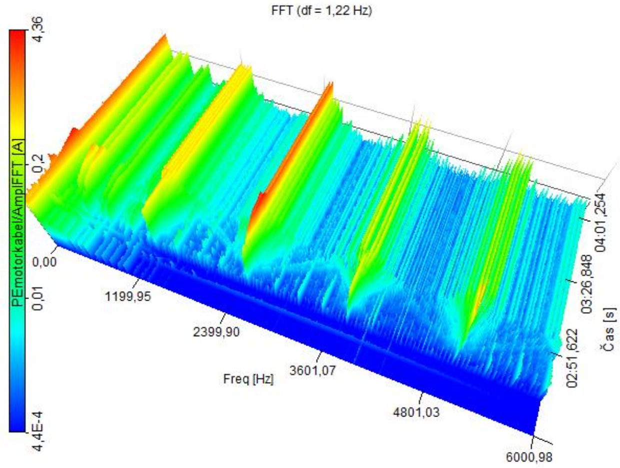

Figure 22. Spectrum of capacitive currents in the PE conductor of the motor connecting cable

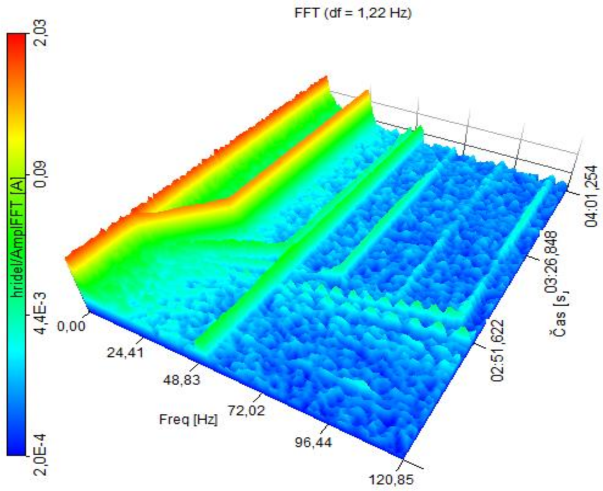

Figure 23. Spectrum of low frequency current flowing through the motor coupling

In the spectrum of the current measured on the coupling between the motor and the driven machine, all the frequencies of motor power supply and their harmonic multiples, as described above (see Figures 23), can be seen again.

4.11 Summary of performed measurement

A 500-kW centrifugal compressor device was analyzed in terms of vibrations measured on the motor bearings and also in terms of its dependence on the power supply frequencies of the motor and frequency converter. By comparing the individual components in the measured spectra, the influence of the individual causes and manifestations in the spectrum of the current measured on the shaft of the machinery was described.

The flow of currents from individual voltage sources which are closed through the static parts of the machinery, the conductive parts of the structures and the buildings are also closed through the rotating parts of the machines.
The sources of these currents can be found in the following influences:

- Low frequencies - currents caused by asymmetry of the magnetic field in the motor, power supply frequency of the frequency converter, induction of voltage on the cable bridges, etc. These frequencies correspond to the power supply frequency of the network, the power supply (varied) frequency of the motor and its harmonic multiples.
- High frequencies - capacitive currents due to pulse frequency of the frequency converter, their harmonic multiples with sidebands. These higher frequencies are caused by the passage of high frequency current through the insulation capacity of live parts. These are the so-called capacitive currents, which are closed from live parts (conductors), through insulation (capacity), and branching through the construction (non-live parts) of the device back to the frequency converter housing.

All these currents that are closed through the rotating parts of machinery reduce the life service of plastic lubricants, bearings, shaft seals, or gearing in couplings and gearboxes.

5 CONCLUSION

As described above, connecting the motor and frequency converter brings a number of advantages in machine control options, but it also brings many pitfalls based on the principles of changing the power supply frequency of the motor. For this reason, it is necessary, as already mentioned in the mechanical design of the device, to take into consideration the use of insulated bearings and couplings, and also both the grounding of the rotating parts of the motor itself and, in some cases, of the driven equipment. The aim of all these measures is to prevent the passage of any current through the rotating parts of the device, thereby degrading the lubricants and reducing the life service of bearings, seals, gears and other parts.
The basis for all measures to protect the machinery is to have the machinery properly grounded and all the parts where some currents may occur should be properly connected by a suitable jumper so that the impedance is as small as possible and the capacitive currents do not pass through the rotating parts of the device. Another measure that can be applied to suppress high frequencies in the current is the use of various filters and impedance coils at both the output and the input of the frequency converter, the use of shielded symmetrical cables where the shield is connected (grounded) on both sides of the cable by EMC bushings.
A suitable measure to suppress shaft currents is the use of insulation on bearings and couplings where, due to the induction of voltage on machinery, the flow of current through the rotating parts may be closed. An example of this is an insulated bearing or a shield charge on the motor, or an isolated coupling between the motor and the driven device.
It should be noted that on electric machines and in their vicinity, where the electromagnetic field is present, voltage can be induced, thus closing the current passing through the machine components, or, in certain cases, the current from a foreign source passing through the machinery.
Determining the cause of damage to machine parts due to the passage of the current is usually demanding and time-consuming. It is always better to take adequate measures to prevent the passage of all types of parasitic currents than to repair the equipment in increasingly very short intervals, and especially to replace the bearings.
The present article also highlights the use of technical diagnostics to solve the problems described above. This is especially the vibro-diagnostics which, in the case of machinery, is an indispensable method for assessing the condition of these devices.

ACKNOWLEDGEMENTS
This work has been supported by Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic (Grant No. FSI-S-17-4477).

REFERENCES
[Bacha et al. 2014] Bacha, S. and Munteanu, I. Power Electronic Converters Modeling and Control. Publisher Springer-Verlag London, 2014. ISBN 978-1-4471-5478-5
[Bausiere et al. 1993] Bausiere, R. and Labrique, F. Power Electronic Converters. Publisher Springer-Verlag Berlin Heidelberg, 1993. eBook ISBN 978-3-642-52454-7
[**Demetgul et al. 2017**] Demetgul, M. and Ünal, M. Fault Diagnosis and Detection. Publisher InTech, 2017. ISBN 978-953-51-3203-5
[Karmakar et al. 2016] Karmakar, S. and Chattopadhyay, S. Induction Motor Fault Diagnosis. Publisher Springer Singapore, 2016. eBook ISBN 978-981-10-0624-1
[Mathew et al. 2014] Mathew, R., Mohandas, P. A Bridgeless CUK Converter Based Induction Motor Drive For PFC Applications. In : International Journal of Electrical Engineering & Technology (IJEET), Volume 5, Issue 12. Ernakulam, India, 2014. ISSN 0976-6545.
[Santosh et al. 2015] Santosh, D., Gadekar and Bhole, A. A. A New Boost Regulator Based Induction Motor Drive In : International Journal of Electrical Engineering & Technology (IJEET), Volume 6, Issue 5. Aurangabat, India. 2015. ISSN 0976-6545.
[**Szcześniak 2013**] Szcześniak, P. Three-phase AC-AC Power Converters Based on Matrix Converter Topology. Publisher Springer-Verlag London, 2013. ISBN 978-1-4471-4896-8

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