Dependence of the spectral components of the stator current on damage in the electric motor

P N Charikov and A G Afanasenko
Ufa State Petroleum Technological University, Branch in Sterlitamak, Sterlitamak, Russian Federation

E-mail: charikovpn@gmail.com

Abstract. Safety and fail-safety of production processes largely depend on the technical condition of machine assemblies that play a key role in production. The main drive mechanism of machine assemblies is an asynchronous electric drive with a squirrel-cage rotor. Damage to any part of the electric motor reduces the performance and service life of the machine. Malfunctions resulting from normal wear and tear, errors in maintenance and design, harmful environmental influences and other factors must be identified and eliminated in a timely manner. In this regard, the analysis of the condition of the electric motor and the prediction of damage plays a major role in increasing the reliability and increasing the service life of the equipment. This article will consider the regularities of the spectral components of the stator current of an electric motor from the mode of failure.

1. Introduction
A three-phase stator winding of an asynchronous electric motor, connected to a three-phase AC current network, creates a magnetic field. The magnetic field generated in the stator winding can be circular or elliptical. In a circular magnetic field, the vector of spatial magnetic induction rotates uniformly and describes a circle, that is, the value of the vector does not depend on the spatial position and remains unchanged.

The circular rotating field created by the stator winding can be only if the vectors of the magnetic induction of each phase are symmetric. Compliance with this condition is achieved by the fact that all windings of an electric machine are made the same, and their axes are displaced in space by 120 electrical degrees relative to each other and included in the network of three-phase symmetrical sinusoidal voltage.

If the symmetry of the vectors of the magnetic induction of the phase windings is violated, the rotating field of the stator becomes elliptical. An elliptical rotating field contains a component (reverse rotating) that is greater or less than the fundamental. The reverse magnetic field of an electric machine degrades its operational properties, this is due to the creation of an opposing (braking) torque. In an asynchronous electric motor, an elliptical magnetic field will occur when the supply voltage is violated (asymmetry in the three-phase voltage network), asymmetry of the stator windings (unequal resistance of the windings, different number of turns), incorrect connection of the electric motor (the beginning and ends of the windings are confused), bearing failure, damage drive mechanism, misalignment of stator and rotor, rotor and drive mechanism.
As the result of the effects of an elliptical magnetic field in the air gap of an asynchronous machine, an infinite field spectrum is created, which can be decomposed into a number of harmonics. Harmonics of the stator magnetic field are induced in its current.

By analyzing the harmonics of the stator current, it is possible to draw a conclusion about the nature and development of the damage to the electric motor.

The investigated electrical signals of an asynchronous motor is a periodic process. The current signal of an inoperable engine containing harmonics can be represented as the sum of \( N \) sinusoidal components with different frequency \( \omega_n \) and phase shift \( \phi_n \) (1).

\[
i = I_{m0} + \sum_{n=1}^{N} I_n \sin(\omega_n t + \phi_n)
\]

where \( I_{m0} \) – the amplitude of the sinusoidal current (amplitude is the maximum instantaneous value of the current that it reaches).

The instantaneous value of the current is the value that it reaches at a certain point in time \( t \).

\( \omega \) – pulsation, \( \omega = 2\pi f = 2\pi/T \),

\( T \) – period of alternating current (time during which alternating periodic current makes a full cycle of its changes)

\( f \) – alternating current frequency,

\( \phi \) – initial phase of alternating sinusoidal current (phase of current at time \( t = 0 \)).

The angular frequency of each component is \( n \) times higher than the fundamental frequency of the first harmonic.

In the spectral analysis of periodic functions, the expansion by the Fourier integral is used. The spectrum obtained by decomposition is the main characteristic of the frequency domain. The spectrum allows you to determine the frequency domain in which the signal is located. Mathematically, spectral analysis represents the decomposition of the signal under investigation into trigonometric functions - sines and cosines. A set of harmonic oscillations forms the spectrum of the signal.

A visualisation of the signal can be seen from its spectral diagram, they are distinguished by amplitude figure 2, a (frequency - amplitude) and phase figure 2, b (frequency - phase). The signal spectrum is divided into amplitude (many harmonic amplitudes) and phase (many harmonic phases).

The value of the harmonics that appear in the electric motor depends not only on the damage that has occurred, but also on the parameters of the electric motor and the drive mechanism. For more accurate diagnostics, it is necessary to take into account the following parameters of the electric drive: rated voltage, rotation speed, electric motor power, bearing type and information about the drive mechanism (belt or gear type).
2. Possible defects

2.1. Damage to the rotor windings
Disturbance of the uniformity of the air gap between the stator and the rotor. The air gap divergence can be static or dynamic. In case of static disturbance of the air gap, the minimum radial position is fixed in space. When the air gap is dynamically disturbed, the minimum radial position rotates with the rotor. Possible causes: taper diameter of the rotor, bending of the rotor due to thermal or mechanical influences, destruction of bearings, imbalance of the load and the rotor.

2.2. Bearings
Bearing condition analysis is the most important task, as more than 40% of all motor failures are attributed to bearing failures. Bearing failures have a significant frequency range.
Rolling bearings consist of a stationary outer ring 2, which is located inside the machine body and is stationary; inner ring 1, which is adjacent to the shaft and rotates with it; a cage 3 holding the rolling elements and rolling elements 4, which are rollers providing rolling between the inner and outer rings.

By analyzing the harmonics of the current supplying the motor, the following frequencies can be distinguished from the damage and geometry of the bearing.

\[ f_{RE} = \frac{n}{2} f_r \left(1 - \frac{BD}{PD} \cdot \cos \beta \right), \]  
\[ f_{IR} = \frac{n}{2} f_r \left(1 + \frac{BD}{PD} \cdot \cos \beta \right), \]  
\[ f_{OR} = \frac{PD}{BD} f_r \left(1 - \left(\frac{BD}{PD} \cdot \cos \beta \right)^2 \right), \]  
\[ f_{CB} = \frac{1}{2} f_r \left(1 - \frac{BD}{PD} \cdot \cos \beta \right), \]

where \( f_{RE} \) – defect frequency caused by the destruction of rolling elements;
\( F_{IR} \) – characterizes the destruction of the inner ring;
\( F_{OR} \) – characterizes the destruction of the outer ring;
\( F_{CB} \) – cage breakage frequency;
\( PD \) – bearing pitch diameter;
\( BD \) – ball bearing diameter;
\( n \) – number of rolling elements;
\( f_r \) – rotational speed;
\( \beta \) – taper angle of inner ring bore.

The calculated frequency values are approximate and differ and are valid by 10 - 15%.

3. Characteristics of the drive mechanism defect

Electric motor drive defects related with actuator can be divided into two categories: load failure defects and transmission failure defects. All obtained conclusions were simulated in laboratory conditions, tested on industrial units.

3.1. Pulleys

The main problems with pulleys are related to the misalignment between the motor pulley and the drive pulley. The frequencies at which the defect appears depend on the rotational speed of the drive.
mechanism and on the diameter of the pulleys (7).

\[ f_p = \frac{D_D \cdot f_r}{D_L}, \]  

(7)

where \( f_p \) – pulley load frequency;
\( f_r \) – rotation frequency;
\( D_D \) – motor pulley diameter;
\( D_L \) – load pulley diameter.

The harmonic indicating a pulley defect is in the frequency range from \( f_1 \pm f_p \), where \( f_1 \) is the frequency of the motor supply.

3.2. Belt drives
To diagnose belt drives faults, it is necessary to calculate the frequency of manifestation of a belt defect. (8).

\[ f_B = \frac{D_M \cdot \pi \cdot f_r}{L_B}, \]  

(8)

where \( f_B \) – frequency characterizing the defect of the belt drive;
\( f_r \) – rotation frequency;
\( D_M \) – motor pulley diameter;
\( L_B \) – belt diameter.

The main defects associated with the belt drive are belt breakage, loosening of the belt tension, too strong tension. The harmonic, indicating belt drive problems is in the frequency range from \( f_1 \pm f_B \), where \( f_1 \) is the motor supply frequency. Also, at these frequencies, defects in the actuator of belt drives are displayed only with the highest amplitude.

3.3. Gearbox defects

![Figure 5. Schematic representation of a gearbox.](image)

Disturbances in the operation of the gearbox are observed in two frequency ranges. These frequencies are related to speed conversion. Harmonics indicating a defect in the gearbox are in the frequency ranges \( f_i \pm f_{R1} \) и \( f_i \pm f_{R2} \), where \( f_i \) is the frequency of the motor supply. The value \( f_{R1} \) is the speed before the speed conversion and \( f_{R2} \) is the speed after the speed conversion. These values characterize transmission damage (cog fracture). The second frequency range \( f_s \), indicating a violation in the gearbox, depends on the speed of the shaft and the number of the gear cogs (9).

\[ f_s = n \cdot f_{R1} = N \cdot f_{R2}. \]  

(9)
The amplitude values of the defect are sensitive to load changes. With a sharp change in load, amplitude jumps without a defect can occur, therefore, to analyze a malfunction, it is necessary to make measurements under the same conditions.

3.4. Centrifugal pump defects
The main frequency characteristics indicating a malfunction of centrifugal pumps are the pump speed $f_p$ and the transmission frequency of the blades $f_{bt}$ (10).

$$f_{bt} = n \cdot f_p,$$

(10)

where $n$ – number of pump blades.

The amplitude of the pump rotation frequency $f_p$ indicates a misalignment between the engine and the pump impeller (skew or imbalance). The $f_{bt}$ component indicates the wear of the pump impeller blades.

3.5. Fan damage
As well as in centrifugal pumps, the main frequency characteristics indicating a malfunction of the fans are the rotation frequency $f_r$ and the frequency of passage of the blades $f_{bt, r}$ (11).

$$f_{bt, r} = n \cdot f_r,$$

(11)

where $n$ – number of fan blades.

The fan speed amplitude $f_r$ indicates a misalignment between the motor and the fan (skew or imbalance). The $f_{bt, r}$ component indicates the wear of the blades.

4. Conclusion
Diagnostics of the state of the electric drive of heavy-duty mechanisms is an urgent task. Failure of the electric drive can lead to emergency situations, harm the health of personnel, and lead to significant material losses. The use of algorithms for predicting the failure of an electric drive allows you to more competently draw up preventive maintenance schedules and streamline the system for equipment procurement for reserve. The algorithms considered above show that the current harmonics can be used to judge not only the state of the electric motor, but also the drive mechanisms. The use of artificial intelligence systems makes it possible to create expert systems for monitoring the state of an electric drive.

References
[1] Katsman M M 2013 Electric Machines (Moscow: Publishing Center “Academy”) p 496
[2] Prakhov I V and Bashirov M G 2010 Influence of operating modes and typical damages of pumping and compressor equipment with an electric drive on the generation of higher harmonic components of currents and voltages Transport and storage of oil products and...
hydrocarbons 4 18-21

[3] Rathor T S 2004 Digital Measurements Methods and Circuitry (Moscow: Technosphere) p 376
[4] Solonina A, Ulakhovich D and Yakovlev L 2002 Algorithms and Processors for Digital Signal Processing (St. Petersburg: «BCHV-Petersburg») p 464
[5] Sergienko A B 2007 Digital Signal Processing (St. Petersburg: «BCHV-Petersburg») p 768
[6] Penrose H Practical Motor Current Signature Analysis Taking the Mystery Out of MCSA (Old Saybrook: ALL-TEST PRO A division of BJM Corp) p 25
[7] Borges da Silva L E, Lambert-Torres G, Santos D E, Bonaldi E L, de Oliveira L E L and Borges da Silva J G 2009 An Application of MSMA on Predictive Maintenance of TermoPE’s Induction Motors, Revista Ciências Exatas 15 100-8
[8] Amaral T, Pires V, Martins J, Pires A and Crisóstomo M 2009 Image Processing based Classifier for Detection and Diagnosis of Induction Motor Stator Fault 10.5772/7052
[9] Shahin Heydayti Kia, Humberto Henao and Gérard-André 2010 Torsional vibration assessment using induction machine electromagnetic torque estimation IEEE Transactions on Industrial Electronics 57 11
[10] Bonaldi E L, de Oliviera L E L, Lambert-Torres G and Borges da Silva L E 2007 Proposing a procedure for the application of motor current signature analysis on predictive maintenance of induction motors Proc. of the 20th International Congress & Exhibition on Condition Monitoring and Diagnosis Monitoring Management (Faro: COMADEM 2007) pp 1-15
[11] Poon H L 1990 Verbal time series reports generation in condition monitoring Computers in Industry 15 293-301
[12] Burr D J 1987 Experiments with a connectionist text reader Proc. of the First International on Neural Networks ed M Caudill and C Butler 4 (San Diego CA: SOS Printing) pp 717-24