Problems of diagnostics of asynchronous motor powered by an autonomous voltage inverter

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Abstract. The article considers the most modern and most informative methods for diagnosing faults in squirrel-cage induction motors with a short-circuited rotor. The methods are based on the evaluation of vibrations and electrical parameters, as well as coordinates during operation and are normalized when powered from a sinusoidal voltage with frequency of 50 Hz. The main advantages and disadvantages of these methods, as well as the main indicators characterizing the general technical condition of the electric motor, are described. The application of these methods when powered from a non-sinusoidal voltage is impossible due to the complex harmonic composition of current and voltage. The consequence of this composition are the ripple moment and additional power loss. The interaction of the harmonics of the inverter and subharmonics, caused by faults, leads to the occurrence of a resonance phenomenon, and therefore to a decrease in the stability of the electric drive.

1. Introduction
Modernization of electrical systems is associated with the introduction of a variable frequency drive based on an induction motor (IM) with a short-circuited winding. Their widespread use is due to technical, energy and economic criteria [1-3]. A high level of operational characteristics of IM is achieved through the use of frequency control algorithms [4, 5]. The use of frequency converters with different algorithms allows you to reduce the starting current and to smoothly control the speed of rotation of the motor. However, these results in additional losses from higher harmonics, a decrease in the permissible moment due to increased heating, moment pulsations appear, the interaction of magnetic fields causes additional noise, and the durability of the motor insulation decreases. Most of these shortcomings are resolved for systems of electric drives with high demands on the dynamics of large and extra-large power. At the same time, little attention is paid to electric drives of small and medium power of own needs and common industrial use, which leads to irrational costs of electricity from 5 to 15% [6, 7]. It also leads to accelerated wear, deterioration in the quality of regulation and further to an emergency stop, which is an additional cost to the enterprise.

Many studies are devoted to diagnostics of asynchronous motors, but their application provided power from a semiconductor frequency converter, and in particular an autonomous voltage inverter is impossible due to non-sinusoidal currents and voltages. The tasks of ensuring energy saving and steady operation of the electric drive of the presented objects, means of technical diagnostics and monitoring remain relevant.
2. Diagnostic methods
Currently it is known methods for the diagnosis of electric drives [8-11]:

1. Methods based on the analysis of vibrations of individual elements of the unit.
2. Methods based on measuring and analyzing the magnetic flux in the gap of the engine and the secondary electromagnetic fields of the machine.
3. Methods based on measuring and analyzing the temperature of individual elements of the machine.
4. Methods of diagnostics of mechanical assemblies (in particular bearings) based on the analysis of iron content in oil.
5. Methods of diagnosis of the state of isolation
6. Methods based on the analysis of electrical coordinates and machine parameters.

There are also other expert methods based on the control of one or several parameters, allowing to judge about one or several nodes of the machine.

Vibrodiagnostic methods are most widely used. The essence of the methods is to analyze the vibration parameters at various points of the electric motor. Vibration parameters include vibration displacement, vibration acceleration and vibration velocity, and their effective (root mean square) values and their peak factors are subject to registration. Also, methods of spectral analysis, in which the amplitude values of individual harmonic components of the vibration signal are used as diagnostic parameters, are also widely used. Limits of permissible vibrations are given in GOST 12379-93. The vibration parameters are controlled at several points, mainly in the bearing assemblies and in the attachment points of the foundation of the unit, and vibration parameters in the vertical, horizontal and axial directions are to be recorded. As primary transducers it can be used as contact sensors, and contactless - optical displacement sensors.

The disadvantages of vibration diagnostics methods include:

1. The necessity of direct access to the unit being diagnosed, which is not always possible in the conditions of mining production. In the case of installation of sensors in the production of the machine increases the cost.
2. The methods are well adapted for diagnosing primarily mechanical damage to both the engine and the mechanism associated with it. However, electrical damage (which accounts for no less than 85% of damage to drive motors) cannot always be detected due to changes in vibration parameters, which either leads to no damage detection or false triggering, depending on the threshold values adopted in the diagnostic model.

Methods based on an analysis of the electrical parameters of the operating equipment, namely currents, voltages and consumed power are in higher priority. Their use is possible without direct access to the machine being diagnosed, especially when using split current sensors such as current tongs. Currently, Hall-based sensors operating in a wide frequency range with constant sensitivity are used as current and voltage sensor, which makes it possible to record oscillations with frequencies from zero to several tens of kilohertz. In this case, the following parameters are used as diagnostic parameters: harmonic components of the stator current spectrum, harmonic components of the power consumption spectrum.

3. Analysis of the problem
Considering an asynchronous motor with a short-circuited rotor when powered from a sinusoidal voltage, described by the equations in the operator form [2, 12, 13], it is possible to estimate the state by several criteria:

1. mechanical characteristics;
2. power consumption;
3. frequency composition of the current spectrum.

Evaluation of mechanical characteristics allows you to visually see the starting moment, start time, nominal speed, and moment ripple factor, at the type and degree of the defect, determined by equation (1).
where $M_{(n)}$ is amplitude value of the $n^{th}$ harmonic component, $M_{av}$ is average value of the electromagnetic moment, Nm;

$$K_{ERM} = \sqrt{\frac{\sum_{n=2}^{n} M_{(n)}}{M_{av}}}$$

(1)

The most common IM defect is a short circuit in the stator winding of a different type, equivalent in magnitude to the maximum current protection.

For example, AD V08B06U87 with technical characteristics of Table 1 remains operable with an equivalent short circuit up to 30%, but the mechanical characteristics have the following deviations of Table 2.

**Table 1.** Technical characteristics of IM series V08B06U87

| Parameter   | Power, kW | Power factor, $\cos \phi$ | $R_s$, Ohm | $R_r$, Ohm | $L_s$, H | $L_r$, H | $L_{ms}$, H | $p$ | $S_n$ | $S_k$ | $J_{\Sigma}$, Nm |
|-------------|-----------|---------------------------|------------|------------|---------|---------|----------|-----|-------|-------|--------------|
| Value       | 7         | 0.92                      | 0.871      | 0.5        | 0.124   | 0.125   | 0.122    | 1   | 0.03  | 0.32  | 0.88         |
Table 2. Parameters of the mechanical part of IM in the single-phase short-circuit stator

| Short-circuit degree In phase A, % | Starting torque, $M_{\text{start}}, \text{Nm}$ | Acceleration time $T_s, \text{s}$ | Ripple factor, $K_{\text{ERM}}$ % |
|-----------------------------------|---------------------------------|-----------------|------------------|
| 0                                 | 175.89                          | 0.440           | 2.2              |
| 5                                 | 241.21                          | 0.340           | 2.3              |
| 10                                | 242.42                          | 0.371           | 3.0              |
| 15                                | 242.82                          | 0.375           | 7.1              |
| 20                                | 243.09                          | 0.392           | 8.3              |
| 25                                | 243.09                          | 0.398           | 12.3             |
| 30                                | 245.97                          | 0.402           | 15.7             |

The occurrence of a 20% fault in phase A does not instantly lead to a complete malfunction, but increases power loss and as a result leads to additional heating and degradation of adjacent nodes.

Analysis of the frequency components of the current spectrum consumed by the motor obtained by the fast Fourier transform (FFT) allows us to identify the frequencies characterizing the defect of a particular node and its degree relative to the main harmonic of the power supply network Figure 2.

![Figure 2](image_url)

Figure 2. a – The current spectrum of IM in normal condition, b - current spectrum of IM at 20% short circuit in the stator winding phase, when powered from sinusoidal voltage

When using a frequency converter for asynchronous motors of low and medium power, a two-element structure is most often used with an unmanaged rectifier and an independent voltage inverter Figure 3a. Therefore, the IM supply is carried out from the voltage and non-sinusoidal current and is described by equations (2).

$$
\begin{align*}
  u_m(t) &= u_m \sin(\omega_1 t + \varphi) + \sum_{m=1}^{\infty} u_{mM} \sin(m\omega_n t) + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} u_{mM} \sin(m\omega_n \pm n\omega_1) t, \\
  i_m(t) &= i_m \sin(\omega_1 t + \varphi) + \sum_{m=1}^{\infty} i_{mM} \sin(m\omega_n t) + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} i_{mM} \sin(m\omega_n \pm n\omega_1) t, 
\end{align*}
$$

(2)

where $i_m, u_m$ – amplitude values of the current and voltage of the stator (A); $i_{mM}, u_{mM}$ – current and voltage harmonic amplitudes of the stator (A), multiples of carrier frequency; $i_{mM}, u_{mM}$ – amplitudes of the harmonics of the current and voltage stator (A); $\omega_1 = 2\pi f_1$ – rotation frequency of the main harmonic of current and voltage (rps); $\omega_n = 2\pi f_n$ – otational frequency of the harmonic carrier current and stator voltage (rps); $m = 1, 2, 3...$ and $n = 1, 2, 4, 5, 7...$ – multiplicity of carrier $\omega_n$ and fundamental rotational speed $\omega_1$; $f_1, f_n$ – main and carrier frequencies.
The presence of a defect in IM causes a subharmonic component of the form, which interacts with higher harmonics of the autonomous voltage inverter, forming a combination harmonics Figure 3b.

![Figure 3a](image1.png) ![Figure 3b](image2.png)

**Figure 3.** a – Current spectrum when powered by autonomous voltage inverter in good condition; b - current current spectrum at 20% short-circuit in the phase of the stator winding when powered by autonomous voltage inverter.

With such a number of harmonic and subharmonic components in the current spectrum, it is difficult to identify and determine the characteristic frequencies of what they are due to.

The corresponding higher and main harmonics form with the flux linkage the main and pulsating components of the electromagnetic moment. Subharmonics caused by a malfunction will also generate additional pulsating moments. And in case of coincidence of harmonics - frequency resonance, pulsating moments can become comparable with a constant electromagnetic moment, which will cause additional vibrations, rooted destruction or overturning of the electric drive. Figure 4.

![Figure 4a](image3.png) ![Figure 4b](image4.png)

**Figure 4.** Electromagnetic moment and its spectrum: a - in working condition; b - the current spectrum of IM at 20% short-circuit in the phase of the stator winding, powered by autonomous voltage inverter.
Table 3. Pulsations of the electromagnetic moment from the harmonic composition of current and voltage

| Short-circuit degree in phase, A, % | Current nonsinusoidality ratio, \( K_I \) | Voltage nonsinusoidality ratio, \( K_U \) | Ripple ration, \( K_{ST} \) |
|-----------------------------------|--------------------------------|--------------------------------|-----------------|
| 0                                 | 2.27                          | 4.51                          | 4.4             |
| 5                                 | 4.50                          | 4.51                          | 7.9             |
| 10                                | 4.92                          | 4.51                          | 8.5             |
| 15                                | 5.20                          | 4.52                          | 11.6            |
| 20                                | 7.31                          | 4.53                          | 18.9            |
| 25                                | 11.83                         | 4.53                          | 22.4            |
| 30                                | 13.18                         | 4.53                          | 26.2            |

Analyzing the data, the resulting data can be concluded that defects in IM when powered by an autonomous voltage inverter appear only as subharmonic components of the current consumed by the motor. Consequently, the harmonic composition due to the work of the autonomous voltage inverter is identical in the spectrum of voltage and current.

4. Conclusion

According to the results of these studies, the frequency regulation of IM with a power semiconductor frequency converter to determine the state of the electrical machine, on which the quality of control regulation depends, is difficult for the following reasons:

1. The complex harmonic composition of the current and voltage caused by the operation of an autonomous voltage inverter makes it difficult to isolate the frequencies characterizing faults in the motor. The use of filters of various designs leads to data loss and does not allow to accurately determine the state of IM;

2. Pulsations of the electromagnetic moment cause additional vibrations in the engine, which will not allow to isolate values caused by a defect using vibration analysis;

3. The increase in the fault level corresponds to an increase in power losses, and in the case of resonance of the harmonics of the inverter current and harmonics of the defect current.

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