Diagnostics of an asynchronous motor powered from a self-commutated voltage inverter

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Abstract. The presented research is focused on two issues. The first one is finding additional parameters that characterize the technical condition of an electric machine according to the current consumption. The second one is increasing of the informativeness of diagnostic methods in conditions of limited access to equipment and incomplete information. The paper discusses a method for diagnosing low and medium power asynchronous electric motors by electrical parameters. It is shown that asynchronous electric motors powered from a self-commutated voltage inverter have contained higher harmonic components in addition to the main harmonic. The non-sinusoidal voltage leads to the emerging of the highest current components in the stator winding of the motor. This is the reason for occurring of a pulsating component of the torque on the motor shaft. Therefore, there are two types of ripple: the one caused by the power supply from the self-commutated inverter and the one caused by defects. The moments’ coincidence of these ripples leads to increasing in the amplitude of oscillations. However, significant noise due to the presence of an autonomous inverter does not allow using the current spectrum to diagnose damage. Analysis of the hodographs of the Park’s vector of the stator current and voltage allows one to exclude harmonic components that were formed by the carrier frequency (and multiple of it). At the same time, analyzing the modulus of the Park’s vector and its spectrum, one can note pulsations of the amplitude values of the vector modulus corresponding to certain damage.

1. Introduction

No modern production can do without electric motors. According to modern trends, asynchronous motors (AM) with a squirrel-cage rotor are occupying leading positions [1, 2]. Electric motors (as all mechanisms) are subjected to wear. During their operation, there are defects for various reasons (build quality, an operation reason, an external reason, etc.) [3, 4]. This leads to an emergency stop, further degradation or work with parameters different from nominal values. All this leads to additional costs of enterprises [5].

At the same time, the existing methods for diagnosing of AM [6], based on the analysis of the electrical and vibration parameters, provide qualitative identification of a degree and a type of defects. However, with the wide use of frequency converters, the efficiency of these methods is sharply reduced. The causes are the electromagnetic and electromechanical incompatibility of a static frequency converter with AM [7, 8] and the appearance of a large number of current harmonic components, consumed by the motor. The mass introduction of frequency converters is justified by the significant increase in the energy efficiency of the electric drive for a class of high-power electric machines (100 kW – 1 MW) and the construction of high-dynamic systems with various control algorithms on their basis. An
asynchronous electric drive achieves optimal energy efficiency parameters by means of scalar and vector control algorithms [9, 10]. Deviation of the parameters of AM associated with aging and degradation leads to a decrease in the quality of regulation and an increase in losses [11, 12]. The power of losses of AM of low and medium power is comparable to the cost of the equipment. Therefore, they need to be diagnosed by actual condition in order to prevent further degradation of the coupled equipment and dynamic growth of losses [13-15]. This increases the number of difficulties and problems.

2. Simulation of an operation of the asynchronous motor with an autonomous inverter supply.

When an asynchronous motor is powered from a self-commutated voltage inverter, the output voltage contains higher harmonic components in addition to the main harmonic. These harmonic components form the appropriate currents in the stator, which are described by the following equations:

\[ u_i(t) = u_m \sin(\omega_i t + \varphi) + \sum_{m=1}^{\infty} u_{mM} \sin(m \omega_M t) + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} u_{nM} \sin(m \omega_M t + n \omega_i) \]

(1)

\[ i_s(t) = i_m \sin(\omega_i t + \varphi) + \sum_{m=1}^{\infty} i_{mM} \sin(m \omega_M t) + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} i_{nM} \sin(m \omega_M t + n \omega_i) \]

(2)

where \( i_m, u_m \) — amplitude values of the current and the voltage of the stator (A); \( i_{mM}, u_{mM} \) — amplitudes of harmonics of the current and the voltage of the stator (A); \( i_{nM}, u_{nM} \) — amplitudes of mix harmonics of the current and the voltage of the stator (A); \( \omega_i = 2 \pi f_i \) — the frequency of the rotation of the main harmonic of the current and the voltage (rad/s); \( \omega_M = 2 \pi f_M \) — the frequency of the rotation of the carrier harmonic of the current and the voltage of the stator (rad/s); \( f_i \) — mains frequency; \( f_r \) — carrier frequency of the converter; \( m = 1, 2, 3... \) and \( n = 1, 2, 4, 5, 7... \) — are the multiplicities of the carrier \( \omega_s \) and the main \( \omega_i \) frequencies of rotation.

Under the influence of the non-sinusoidal voltage, according to equation (1), the current flows in the stator winding of the asynchronous motor. It, in addition to the main harmonic, also contains the highest harmonic components (2). Under the influence of the highest harmonic components, moving magnetic fields arise in the motor air gap. Their speeds and directions are determined by the numbers of these harmonics. As a result, magnetic fields are generated in the motor rotor which also rotates at appropriate angular speeds. During the interaction of the magnetic fields of the stator and the rotor in the air gap of the motor, electromagnetic moments of two types appear: constant and pulsating ones, defined by the equations:

\[ M_e = M_n + M_{ip} + M_{ik} \]

\[ M_n = I_n \cdot \psi_n \sin(\theta_n) \]

\[ M_{ip} = I_i \cdot \psi_p \sin(\theta_{ip}) \]

\[ M_{ik} = I_i \cdot \psi_k \sin(\theta_{ik}) \]

(3)

where \( M_e \) — a resulting motor electromagnetic torque; \( M_n \) — a constant moment caused by the main harmonic of the current and flux of the same order (n); \( M_{ip} \) — pulsating moments created by combinations of an \( i \)-harmonic of a stator current and a \( p \)-harmonic of a flux linkage; \( M_{ik} \) — pulsating moments caused by subharmonic components of defects.

As a result of the coincidence of the frequencies of the harmonic components of the electromagnetic moments, the amplitude of such oscillations is comparable to the constant electromagnetic moment (figure 1). These electromagnetic moments are generated by the harmonics of the current and flux linkages of different orders and moments caused by the subharmonic components of the current caused by various kinds of defects in the AM. At the same time, pulsations of the electromagnetic moment with such an amplitude will lead to an increase in noise and vibration, significantly reducing the lifetime of the asynchronous motor. Therefore, analysis of vibrations with such a number of components becomes difficult [16, 17].
Figure 1. Pulsation of electromagnetic moments with a stator defect with $t = 6$ s (short circuit of phase A) when (a) an asynchronous motor is powered from a sinusoidal voltage and (b) from a non-sinusoidal voltage (voltage inverter).
With so many components of the current harmonics (figure 2b), it is impossible to isolate those that are caused by various defects in contrast to the current spectrum of an asynchronous motor with a sinusoidal voltage supply (figure 2a). The analysis of the current spectrum of the stator does not allow for a quantitative assessment of the level of the defect during its further development. However, it is possible to determine the occurrence of the defect in both electrical and mechanical parts at an early stage, in the form of peaks at characteristic frequencies [19, 20].

![Figure 2. Current spectrum when an asynchronous motor is powered from a sinusoidal voltage (a) and from a non-sinusoidal voltage (voltage inverter) (b) with a stator defect (short circuit of phase A).](image)

3. Application of the method of the Park’s vector to analyze the occurrence of damage.

In the Park’s method, the $i_d$ and the $i_q$ components of the stator current are used depending on $i_d = f(i_q)$, which are a hodograph (Lissajous figure) and which are calculated using transformations in the stator coordinate system [5]:

\[
\begin{align*}
    i_d(t) &= (\sqrt{2/3})i_A(t) - (\sqrt{6})i_B(t) - (\sqrt{6})i_C(t) \\
    i_q(t) &= (\sqrt{2})i_B(t) - (\sqrt{2})i_C(t)
\end{align*}
\]

where $i_A$, $i_B$, $i_C$ – active values of phase currents.

Under the ideal conditions with symmetry and sinusoidal currents, corresponding to the work of an asynchronous motor without defects, the field in an electric machine is circular in shape, and the Park’s vector components [6] are expressed as:

\[
\begin{align*}
    i_d &= (\sqrt{3}/2)i_A \sin(\omega t) \\
    i_q &= (\sqrt{3}/2)i_A \sin(\omega t - \pi/2)
\end{align*}
\]

When an asynchronous motor is powered from a self-commutated voltage inverter, and there are defects in the electrical, electromagnetic or mechanical parts of an AC electrical machine, there are changes in its magnetic field, which corresponds to the change in the hodograph shape of the stator current vector [20]. The equations (5) are not applicable due to non-sinusoidal currents and stress, but
they allow one to define the reference form of the hodograph. Since the diameter of the hodograph curve is proportional to the amplitude of the current, its shape becomes thicker when the motor load increases. Depending on the degree of the defect, the magnitude of the load and distortions in the current and voltage of the network, the hodograph changes from a circle to a complex elliptical shape, as well as its width and angle of rotation of the major semi axis relative to the real axis in the complex plane (figure 3).

![Figure 3](image)

Figure 3. Deviation of the hodograph of the Park’s vector of the stator current of the AM (series “AHP 132 M4”): a – the hodograph of the current of a properly functioning motor; b – the hodograph of the current with a defect in a stator winding (short-circuit of several turns of the phase A); $I_{st.n}$ – the standard stator current (A); $I_{st.d}$ – the actual stator current at the defect (A).

According to [1], diagnostic features characterizing the technical condition should be highlighted. These are the features such as a change in the minor and major semi axes of the hodograph degenerated into an ellipse, the angle of rotation relative to the d-axis of the complex plane and the width of the hodograph. These parameters make it possible to detect a defect at the level of a unit of an electrical machine (stator, rotor or mechanical part). However, they do not provide for the selection of the type of a defect (insulation failure, interturn, short circuit, phase-to-phase, phase failure). The hodograph width is defined as the modulation depth $I=f(t)$ of the modulus of the current of the Park’s vector, defined by the equation:

$$I_m(t) = \sqrt{i_d^2(t) + i_q^2(t)}$$  \hspace{1cm} (6)

Performing similar transformations (5, 6, 7) for the voltage, supplying the asynchronous motor from the voltage inverter, one gets:

$$U_m(t) = \sqrt{u_d^2(t) + u_q^2(t)}$$  \hspace{1cm} (7)

When analyzing the hodographs of the current vectors $I_m(t)$ and the voltage $U_m(t)$ obtained by equations (6, 7), representing a harmonic series, it is found that any simulated characteristic frequency is counted only once.

The further spectral analysis of the modules of the vectors reveals that when supplying an asynchronous motor from an autonomous voltage inverter, the hodograph of the voltage vector has a complex harmonic composition corresponding to the harmonics in the hodograph spectrum of the current vector at the same frequencies. In the event of a defect, harmonic components are present only in the hodograph spectrum of the current vector, and their amplitude characterizes the degree of a defect (table 1). As well as the proposed method eliminates the harmonic components formed and multiples of the carrier frequency, which simplifies the analysis of the spectrum.
Table 1. Harmonic composition of the hodographs of the current and voltage vectors at various degrees of a defect.

| Frequency | Amplitude of harmonics of a properly functioning motor | Amplitude of harmonic during the short circuit 10% | Amplitude of harmonic during the short circuit 30% |
|-----------|------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
|           | \( I_{m(0)} \), dB | \( U_{m(0)} \), dB | \( I_{m(0)} \), dB | \( U_{m(0)} \), dB | \( I_{m(0)} \), dB | \( U_{m(0)} \), dB |
| 54.38     | -53.63 | -133.70 | -41.97 | -133.70 | -37.41 | -133.70 |
| 100.00    | -11.13 | -9.90  | -11.13 | -9.90   | -11.13 | -9.90   |
| 154.80    | -75.94 | -135.50| -52.04 | -135.50 | -48.32 | -135.50 |
| 200.00    | -30.10 | -26.25 | -30.10 | -26.25  | -30.10 | -26.25  |
| 245.40    | -80.44 | -149.00| -57.86 | -149.00 | -56.56 | -149.00 |
| 300.00    | -35.85 | -36.34 | -35.85 | -36.34  | -35.85 | -36.34  |
| 345.80    | -89.62 | -148.90| -63.91 | -148.90 | -63.09 | -148.90 |
| 400.00    | -43.60 | -43.61 | -43.60 | -43.61  | -43.60 | -43.61  |
| 445.40    | -89.04 | -160.90| -69.06 | -160.90 | -67.21 | -160.90 |
| 500.00    | -57.56 | -51.39 | -57.56 | -51.39  | -57.56 | -51.39  |
| 545.80    | -94.78 | -158.30| -73.56 | -158.30 | -69.85 | -158.30 |
| 600.00    | -61.02 | 57.75  | -61.02 | 57.75   | -61.02 | 57.75   |
| 646.60    | -98.07 | -174.10| -78.02 | -174.10 | -72.51 | -174.10 |
| 700.00    | -63.44 | -63.69 | -63.44 | -63.69  | -63.44 | -63.69  |
| 746.60    | -105.70| -166.00| -81.99 | -166.00 | -73.97 | -166.00 |
| 800.00    | -70.66 | -69.33 | -70.66 | -69.33  | -70.66 | -69.33  |
| 847.30    | -102.70| -194.30| -85.47 | -194.30 | -76.18 | -194.30 |
| 900.00    | -80.93 | -74.73 | -80.93 | -74.73  | -80.93 | -74.73  |
| 947.40    | -106.18| -172.00| -88.04 | -172.00 | -77.01 | -172.00 |
| 1000.00   | -81.26 | -79.96 | -81.26 | -79.96  | -81.26 | -79.96  |

4. Conclusion
The use of combined diagnostic methods allows one to improve the quality of the estimation of the technical condition of the controlled object. It is reflected in the reduction of various kinds of damage with the timely organization of repair. Since the asynchronous motor is an electromechanical and electromagnetic system, the reflection of defects is observed in electrical, electromagnetic and mechanical processes. The method proposed in this research will allow for the construction of informative diagnostic systems for electrical parameters in the conditions of power supply of an electric machine from an autonomous inverter.

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