Asynchronous motor drive operability field with two-link structure of frequency converter

Y L Zhukovskiy¹, N. Korolev², I. Filatova³

¹,²,³ St. Petersburg Mining University, 2, 21 Line of Vasilyevsky Island, St. Petersburg, 199106, The Russian Federation

E-mail: Zhukovskiy_yul@pers.spmi.ru

Abstract. The article presents an approach to determining the electric drive’s operability based on an asynchronous motor with a short-circuited rotor and a two-link frequency converter. Mathematical description of the frequency-controlled electric drive is performed, in particular, selection of criteria taking into account an electric and mechanical part. The harmonic current distortion coefficient as a component of the power coefficient is used for the determination of the energy criterion. The mechanical criterion is the coefficient of the electromagnetic moment pulsation, on the value of which the conjugated equipment depends. The operability field is represented as a function of three variables: (a) rotor speed, (b) current harmonic distortion coefficient, and (c) electromagnetic moment pulsation coefficient. The obtained surface makes it possible to determine the actual state of the electric drive and to estimate the reserve of operability, which allows reducing the operating costs in terms of repair and maintenance.

1. Introduction

One of the main processing units at any oil and mining plant, processing plants and other raw materials sector facilities are electromechanical equipment. Ensuring energy efficiency and working capacity of these facilities consists of control, management, and quality of engine installation. Unexpected complete or partial failures lead to the following negative consequences [1, 2, 3]:

- Shortage of products (loss of potential profits);
- Electricity consumption increasing;
- Increasing components warehouse costs, turnover costs and costs for consumable materials;
- Collateral damage because of the electromechanical equipment’s emergency stoppings.

These problems occur during the transition from repair so-called ‘Run to Break or Run-to-Failure’ to repair according to the ‘actual condition’ [4]. They can be partially solved, but at the same time, it leads to a complication of protection and redundancy system that requires additional high-qualified staff and services, and additional electricity and self-diagnostic systems [5, 6].

The next stage is implanting proactive management according to the predicted values of the electromechanical equipment’s technical condition [7, 8]. It allows managing energy efficiency and operability of individual technological units [9, 10].

There are several experimental approaches to implementing such systems based on big databases, neural networks, and artificial brains, digital twins, and machine learning [11, 12]. The last one is less expensive and easier to implement since it is based on algorithms of diagnosis [13, 14, 15].
2. Approach and methods

The first aim is to classify the diagnostic object. The integrated object is the electric drive system of the workshop. The classification was carried out according to the following criteria:

1. Power category (low-power – up to 0.4 kW, average 0.4-200 kW, multi-watt – up to 2 MW, super multi-watt – more than 2 MW);
2. Static and dynamic characteristics of a controlled electric drive;
3. The degree of the electric drive response (permissible downtime without economic damage: 1-10 days; 1-5 hours; less than 1 hour; 10-30 minutes, 10-60 seconds).

The second aim is the generation of electric drives groups according to these criteria. A diagnostic technique is defined for each of the groups. The main group of most enterprises is an average and low-power electric drive with low dynamics and downtime requirements of less than 1 hour [16, 17, 18]. According to researches, the method based on the analysis of electrical parameters and coordinates prevails among the electromechanical equipment’s diagnostic methods particularly applicable to low and average power drives [19, 20]. Two sets of Hall effect current and voltage sensors are needed as primary transducers with the minimum sampling rate required [21]. Secondary and subsequent conversions can be performed on a microcontroller, personal computer, or cloud space according to Figure 1.

![Figure 1. Schematic structure of the analyzed electric drive.](image)

The operability determination approach is based on the method of current spectral analysis through fast discrete Fourier transformation (FFT). Harmonic distortion coefficient of current supplied to the engine was selected as energy criterion, - \( K_I \), taken into account at determining the power factor at non-sinusoidal currents and voltages, according to formula (1).

\[
K_I = \frac{P}{S} = 3I_{lip}U_{ip} \cos \varphi / 3I \cdot U = \left( I_{lip} / I \right) \left( U_{ip} / U \right) \cos \varphi = K_I \cdot K_U \cos \varphi, \tag{1}
\]

where \( I_{lip}, U_{ip} \) – amplitude of main harmonics of current and voltage in phase (V, A); \( I, U \) – effective current and voltage (V, A); \( P, S \) – useful and total power (W, VA); \( \varphi \) – shift angle between main harmonic of phase current and voltage (rad).

When the electric motor is powered from the autonomous voltage inverter, the current \( I \) will be determined by the stator current \( I_{st} \) according to formula (2).

\[
I = I_{st}(t) = I_s \sin(\omega_1 t + \varphi) + \sum_{n=1}^{\infty} I_{m} \sin(m\omega_1 t) + \sum_{n=1}^{\infty} I_{nm} \sin(m\omega_n \pm n\omega_1 t), \tag{2}
\]

where \( I_n \) – amplitudes of stator current harmonics, divisible by basic harmonics (A); \( I_m \) – amplitudes of current harmonics (A), divisible by carrier frequency; \( I_{nm} \) – amplitudes of combination harmonics of stator current (A); \( \omega_1 = 2\pi f_1 \) – current main harmonic speed (rad/s); \( \omega_n = 2\pi f_n \) – the speed of stator current carrier harmonic (rad/s); \( m = 1, 2, 3, ... \) and \( n = 1, 5, 7, ... \) – the multiplicity of carrier \( \omega_n \) and main \( \omega_1 \) rotation speeds; \( f_1, f_n \) – main and carrier frequencies (Hz).

Main types of defects are detected, in terms of bearing wear, air gap eccentricity, turn-to-turn short
circuits and rotor rods break [1, 2, 11, 12], described by harmonic components of current (3). These conclusions are based on the results of statistical data analysis on the failure of electric drive operability due to failures of the asynchronous motor.

\[ i_{d1}(t) = I_s \sin(\omega_r (1 \pm 2ks)t), \quad i_{d2}(t) = I_{d,sc} \sin(\omega_1 \frac{n}{p} (1 - s) \pm k \theta), \]

\[ i_{d3}(t) = I_s \sin \omega_1 t, \quad i_{d4}(t) = I_{d,sc} \sin(\omega_1 r \frac{1 - s}{p} \pm n \theta) \pm \omega_1 \frac{1 - s}{p}, \]

where \( i_r, I_{d,sc}, I_{sc} \) – amplitudes of stator current modulated at defects of the rotor, stator, bearings, and air gap eccentricity; \( \omega_r = 2\pi f_r \) – rotor speed (rad/s); \( s \) – sliding off the asynchronous engine; \( k = 1, 3, ..., \) odd integer; \( p \) – number of pairs of poles; \( r_s \) – number of rotor bars.

Taking into account (3), the stator current, \( I_{st} \), if there are any faults in the asynchronous engine, will be determined according to formula (4).

\[ I_{st}(t) = I_s \sin(\omega_0 t + \varphi) + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} I_{nm} \sin(m \omega_0 t) + \sum_{n=1}^{\infty} I_{num} \sin(m \omega_0 t \pm n \theta) + \sum_{di} I_{di} \sin(\omega_{di} t), \]

where \( I_{di} \) – amplitudes of stator current (A), corresponding to defect; \( \omega_{di} = 2\pi f_{di} \) – the speed of stator current’s harmonic component caused by a defect (rad/s); \( f_{di} \) – defect frequency.

Taking into account (1), (3) and (4) the current harmonic distortion coefficient is represented as two components (5).

\[ K_f = \frac{I_{yp}}{I} = K_{f(o)} + K_p, \]

where \( K_{f(o)} \) – current harmonic distortion coefficient, determined by the type and structure of the power converter; \( K_p \) – current harmonic distortion coefficient, determined by electric drive defects.

Distortion of stator current curve leads not only to non-sinusoidal of current and to power factor decrease, but also it is the motor-forming value of asynchronous motor electromagnetic moment (6).

\[ M_e = \frac{3}{2} z_p \frac{L_m}{L_s} I_{st} \psi_r \sin(\theta), \]

where \( z_p \) – number of asynchronous engine’s pairs of poles; \( L_m \) – magnetizing inductance; \( L_s \) – armature circuit inductance; \( \psi_r \) – armature flux linkage; \( \theta \) – the angle between stator current vectors \( I_s \) and armature flux linkage \( \psi_r \).

Therefore, a constant air gap torque is generated by the interaction of the stator current harmonics and the armature flux linkage the same order, multiple of the main frequency. Interference of different orders harmonics leads to the formation of pulsating components of air gap torque. Pulsating air gap torque is possible to divide into moments formed by combinations of stator current’s higher harmonics and harmonic components caused by defects of asynchronous motor’s electrical or mechanical parts. Consequently, resulting air gap torque can be presented as a formula (7).

\[ M_e = M_{(n)} + M_{(qp)} + M_{(di)} = \sum_{n=1}^{\infty} I_{st(n)} \psi_{r(n)} \sin(\theta) + \sum_{q=1}^{\infty} \sum_{p=1}^{\infty} I_{st(q,p)} \psi_{r(p)}(\theta_q) + \sum_{i=1}^{\infty} I_{st(i)} \psi_{r(i)}(\theta_i), \]

where \( M_{(n)}, M_{(qp)}, M_{(di)} \) – air gap torque components (Nm), generated as a result of the interaction of \( n \) stator current harmonics and the armature flux linkage, \( di \) stator current harmonics and the armature flux linkage, \( q \) stator current harmonics and \( p \) the armature flux linkage harmonics; \( I_{st(n)}, I_{st(q,p)}, I_{st(i)} \) – components of stator current and the armature flux linkage (A, Wb); \( \theta_q, \theta_p, \theta_i \) – the angle between \( q \) the stator current harmonics and \( p \) the armature flux linkage harmonics, \( \theta_{(di)} \) – the angle between \( di \) the stator current harmonics and the armature flux linkage (rad).

Air gap torque ripple ratio defined as (8), is divided into components taking into account (6), (7) in the form of following formula (9).

\[ K_p = \sqrt{\sum_{n=2}^{\infty} M_{n}^2} \]

\[ \sum K_p = \sqrt{\sum_{n=2}^{\infty} M_{n}^2 + \sum_{q=2}^{\infty} \sum_{p=2}^{\infty} M_{q}^2} \]

\[ K_{av} = K_{p(o)} + K_p^* \]
where: $M_{av}$ – the average of asynchronous motor's air gap torque (Nm); $K_{p(n)}$ – air gap torque ripple ratio determined by type and structure of power frequency converter; $K_{p^*}$ – air gap torque ripple ratio determined by the type and level defect of electric drive's engine and mechanical part.

3. Study of electric drive operability field

According to the electric drive structure Figure 1 and mathematical tools (1-9) model of electric drive with asynchronous motor and two-link frequency converter were developed. We used such tools as MATLAB Simulink Figure 2a, which allows studying the electric drive operability field.

We simulated faults as an equivalent phase-to-phase short circuit in phase A-B at the moment $t = 1.4$ s in steady-state mode (time interval $0 < t < 1.2$ s) in the electric drive. As a result of this experiment, there is a change in the shape and amplitude of the current consumed by the asynchronous motor and an increase in the frequency and amplitude of pulsation Figure 2b, which corresponds to an increase in the harmonic distortion coefficient $K_I$ and air gap torque ripple ratio $\Sigma K_p$ (Fig. 3). Power and mechanical parameters of electric drive operability decrease in case of such faults.

![Figure 2. a – electric drive model with asynchronous motor and two-link frequency converter; b – oscillogram of the electric motor output coordinates.](image-url)
Figure 3. Change in harmonic distortion coefficient $K_I$ and air gap torque ripple ratio $\Sigma K_p$ of asynchronous motor: a – under normal conditions; b – with phase-to-phase fault stator winding at the moment $t=1.4 \, \text{c}$.

Figure 4. Operability fields of the electric drive: a – settlement maximum permissible; b – under normal conditions; c – with stator winding defect.

Thus, the operability field is specified by the manufacturer’s requirements for harmonic distortion coefficient level $K_I (>5\%)$ and air gap torque ripple ratio $\Sigma K_p (>20\%)$ with frequency control, as a function of three variables $f(\omega_r, K_I, \Sigma K_p)$ Figure 3. Coordinates outside the field correspond to partial or complete electric drive inoperability.

4. Conclusion
Because of mathematical analysis and simulation, the obtained operability field will allow providing:
1. Monitoring the actual technical condition of frequency-controlled electric drive with high speed and accuracy relative to existing diagnostic methods.
2. Obtaining forecast values of actual state as state vector and coordinates of electric drive working point.
3. Organization optimal maintenance and repair periods; research and synthesis control algorithms to extend lifetime.

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