Journal of Physics: Conference Series

**PAPER** • **OPEN ACCESS**

# Diagnostics and evaluation of the residual life of an induction motor according to energy parameters

To cite this article: Y Zhukovskiy and N Koteleva 2018 *J. Phys.: Conf. Ser.* **1050** 012106

# Diagnostics and evaluation of the residual life of an induction motor according to energy parameters

**Y Zhukovskiy, N Koteleva**

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

Email: zhukovskiy_yul@pers.spmi.ru; Koteleva_NI@ pers.spmi.ru

**Abstract**. The various devices based on vibration, thermal, electromagnetic and other methods are used to diagnose an asynchronous motor today. The use of vibration diagnostics is common for large machines. The emergency stop of the large machines leads to significant downtime and non-produced products meaning that the enterprise incurs significant material losses. However, for low-power engines, vibration diagnostics are used only as a periodic assessment of the state without accumulation of data and their subsequent analysis. It should also be noted that the vibration signals measured from the rolling bearing are affected by varying operating conditions and noise that distort the signal and complicate the faults identification for further evaluation of the residual life. In a number of cases, such as submersible pumps, nuclear power plant safety aggregates, mining equipment, it is practically impossible to use vibration, thermal and other methods for diagnosing asynchronous motors. Therefore, the actual task of this research is the development of a method for diagnosing and estimating the residual life in conditions of the systems without any maintenance, based on the electric motor energy parameters.

## 1. Introduction

Electric motors, like all electromechanical equipment, are subject to wear and tear, and their operation often causes malfunctions, breakdowns or operation with parameters that differ from the nominal values. Since electric power is converted into mechanical energy in the electric motor, it is obvious that the malfunctions of electric motors can be caused both by malfunctions in electric and electromagnetic systems, and by defects in mechanisms[1,2]. In the manufacture and operation of asynchronous motors, there are deviations in the engine parameters from the nominal values [3]. These deviations can be caused both by technological errors in the manufacture of the engine, by incorrect operating conditions, and by wear during operation.

One of the most common defects are those associated with the electric motor bearings, the rotor cage, and also with the change of the amount of looseness between the rotor and the stator. Defects of rolling bearing are one of the main causes of the engine disintegration of electrical machines, so diagnostics and early detection of designing defects are necessary. It makes possible to prevent more catastrophic consequences of a failure. Operation of the electric motor with defects of the rolling bearing does not lead to its immediate failure, but reduces reliability of an operation, a durability and other technical and economic indicators. The magnetic field in the air gap distorts, the efficiency is reduces by 1–2% [7], additional ultra-harmonics of the consumed current appear, the starting torque reduces by 10-12% [3, 4], the heat loss by 4–5% [6].

## 2. The essence of the diagnostic method

The essence of the proposed method is that the basis for the application of electrical equipment and associated devices is the transform of electrical energy [1]. At the same time, a part of the energy is lost in the electrical equipment and associated devices, so any thier damage, one way or another, leads to increased losses and lower coefficient of efficiency. For technically sound electrical equipment, the dependence of losses (a coefficient of efficiency) from load is known, and in the event of a malfunction this dependence changes. The method provides registration and accumulation of values of electrical quantities (currents, voltage and power) of the controlled object and creation of a pattern set of calibration values corresponding to the resource of the testing equipment. If there is the sufficient statistical data, it is possible to predict the dynamics of these changes in the future, i.e. estimate the residual resource. More detailed information on the causes of the loss is carried by oscillography charts of instantaneous power and by power constructed for individual frequency components, after the Fourier transform.

An integral assessment of the state of the equipment is formed as a set of estimates of all nodes and subsystems, therefore for an asynchronous motor as a whole, the state estimation will be formed on the basis of parallel chains of diagnostic parameters for each detected defect. The resulting residual resource will be determined by the most rapidly developing and the least manageable defect [2]. Owning full information about the detected defects and the possible influence of each of them on the residual life of the product, it is possible to solve the task of determining the amount of services work necessary to bring the life of the product to the required level. Knowing the causes of each defect and the factors that affect its development, it is possible, by influencing the causes and factors, to suspend or slow down the development of the most critical defects, thus saving the performance capabilities. For this, the use of IoT technology is proposed. This technology allows an accumulating, aggregating and analyzing large amounts of data "Big Data" to identify the causes of defects using artificial neural networks and machine learning.

## 3. The electrical parameters analyzing

The system receives electric power from the industrial network with power $P_0$ , an electric transducer transforms the electrical energy parameters, giving out at the output energy with power $P_1$ , In the process of transformation, part of the energy is lost as a loss $\Delta P_1 = P_0 - P_1$ . Similarly, the energy receives on the input of electromechanical transducer $P_1$ , part of which $\Delta P_2 = P_1 - P_2$ is lost during the transform process, on the output remains $P_2$ . For mechanical transducer, accordingly, on the input is received $P_2$ , in the transform process is lost $\Delta P_3 = P_2 - P_3$ , on the output remains $P_3$ .

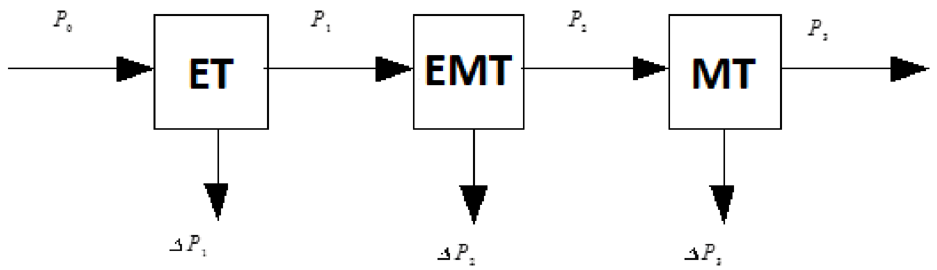


**Figure 1.** Structural circuit of energy transform in the electric motor

In the static mode, the conversion factor of each of the sides of the circuit is characterized by a constant transmission factor, the coefficient of efficiency. Accordingly, for the power on the output of the i-th transducer, expression

$$P_{i-1} = \eta_i \cdot P_i \,,$$

where $P_{i-1}$ – the power on the output of the transducer, W.; $P_i$ - the power on the input of the block, $\eta_i$ - the coefficient of efficiency of the transducer, it equals

$$\eta_i = \frac{P_{i-1}}{P_i} = \frac{P_i - \varDelta P_i}{P_i} = 1 - \frac{\varDelta P_i}{P_i} \,,$$

where $\varDelta P_i$ – value of losses in the transducer, W.

It should be noted that the summand $\frac{\varDelta P_i}{P_i}$ in essence represents the amount of losses in the transducer, referred to the consumed power of the transducer. So, the new designation for this summand have to be introduced

$$\rho_i = \frac{\varDelta P_i}{P_i} \,. \tag{1}$$

With different loads of the transducer, that is, with different values of the output power $P_{i-1}$, the efficiency is different. The dependence $\eta_i = \eta_i(P_{i-1})$ is usually given in the technical data of the corresponding transducer, or can be obtained experimentally, for a technically sound transducer. It should be taken into account that this dependence, as a rule, is nonlinear. If this relationship is known, then it is possible to determine the dependence of the parameter $\rho_i$ on the output power $P_i$.

$$\rho_i = 1 - \eta_i(P_i) = \rho_i(P_i) \,. \tag{2}$$

The electric motor contains three transducers connected in series, therefore, one can write

$$P_3 = \eta_3 \cdot \eta_2 \cdot \eta_1 \cdot P_0 \,,$$

or,

$$P_3 = [1 - \rho_1(P_1)] \cdot [1 - \rho_2(P_2)] \cdot [1 - \rho_3(P_3)] \cdot P_0 \,. \tag{3}$$

During operation of the electric motor, the transducers accumulate damage that leads to a deterioration in their energy characteristics. The consumption power is increasing with present the constant output power, and for various types of damage, the additional component of loss will depend on the output power in different ways.

We denote additional losses in the i-th transducer $\xi_i(P_i)$, then

$$P_3 = [1 - \rho_1(P_1) - \xi_i(P_i)] \cdot [1 - \rho_2(P_2) - \xi_i(P_i)] \cdot [1 - \rho_3(P_3) - \xi_i(P_i)] \cdot P_0 \,. \tag{4}$$

Losses in each transducer using the function of the consumed power can be determined for state of unit in a technically sound and for the state of unit in the real time. Comparison of these dependencies allows us to estimate the value of additional losses caused by the development of damage, which is used as an assessment of the technical condition of the electric motor (Fig. 2).

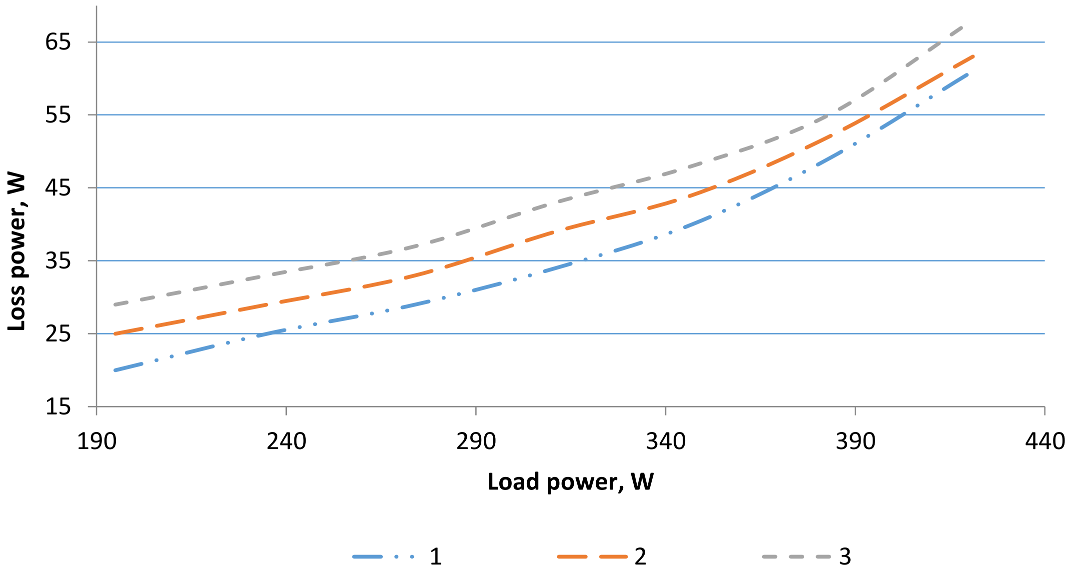


**Figure 2.** Energy losses for various faults and loads: 1 – technically sound, 2 – damaged 2 rotor winding rods, 3 – damaged 6 rods and defects in foundation installation

As the electric motor generates a resource, the amount of power loss in the electric motor at the same load increases. In this case, the coefficient of change in losses equal to the difference of the relative power consumed by the electric motor at a given load value can serve as an indicator of its technical condition.

$$\Delta\rho(P_2) = \frac{(P_{1b} - P_{1m})}{P_{1b}}, \quad (5)$$

where – $P_{1b}$ initial value of power consumption of the electric motor under load $P_2$ , measured on a technically sound motor in the initial period of its operation, kW; $P_{1m}$ – the current value of the motors power consumption under load $P_2$ , measured during its operation, kW.

In this article the method for determining the energy losses in the electric drive of mining machines is proposed. At the beginning of operation, on a known serviceable motor, during the shift, the power consumption $P_{1i}$ of the electric motor is measured $N$ times in the time interval

$$\Delta t_i = \frac{T_{sh}}{N}, \quad (6)$$

Where $T_{sh}$ – the time of a shift, hr.

The shorter the time interval $\Delta t_i$ , the higher the reliability of the measurements

Further, the average value of the power consumption $\overline{P_1}$ of the electric motor is determined and its standard deviation $S_{\overline{P_1}}$ according to the formulas:

$$\overline{P_1} = \sum_{i=1}^{N} \frac{P_{1i}}{N}, \quad (7)$$

$$S_{\overline{P_1}} = \sqrt{\sum_{i=1}^{N} \frac{(\overline{P_1} - P_{1i})^2}{N-1}}. \quad (8)$$

According to the "Three sigma rule" with a probability of not less than 99.7%, the value of the consumed power should fall within the interval

$$P_1 \in (P_{1\max}, P_{1min}), \tag{9}$$

where

$$P_{1\min} = \overline{P_1} - 3 \cdot S_{\overline{P_i}}, \tag{10}$$

$$P_{1\max} = \overline{P_1} + 3 \cdot S_{\overline{P_i}}. \tag{11}$$

Further, at intervals of time $T_{diag}$, the value of which should be determined on the basis of statistical data on motor failures, the power consumption is measured and the average $\overline{P_1}'$, minimum $P'_{1min}$, maximum values $P'_{1max}$ of the power consumption during the shift are determined. Next, the average value of the coefficient of loss variation is determinates

$$\Delta\rho_{av} = \frac{\overline{P_1}' - \overline{P_1}}{P_{1b}}, \tag{12}$$

Then, the value of the coefficient of loss variation at the minimum and maximum load

$$\Delta\rho_{min} = \frac{P'_{1min} - P_{1min}}{P_{2nom}}, \tag{13}$$

$$\Delta\rho_{max} = \frac{P'_{1max} - P_{1max}}{P_{2nom}}. \tag{14}$$

where $P_{2nom}$ – nominal value of mechanical power of electric motor, kW.

The results of calculation of losses according to formulas (12) - (14) characterize the technical state of the motor, if these values exceed the permissible limits, the value of which should be determined on the basis of statistical data on the failures of electric drives of this type, it should be concluded that a malfunction is likely.

**The residual life evaluation**

The technical resource $T_p$ is usually expressed in units of time and characterizes the time interval during which, with a given probability, the diagnosed object does not go over to the limit state. It should be noted that the reasons for the failure of these or other parts of the electric drive are the energy losses in them, in particular, the life of the insulation of the windings of the electric machine is determined by its heating and is proportional to the square of the current consumed and, accordingly, to the losses of power consumption.

The concept of an energy resource $Q$ is added. It equals to the reduced value of losses in a motor during the time before its transition to the limit state

$$Q = \rho T_p. \tag{15}$$

The nominal energy resource can be defined as

$$Q_{nom} = \rho_{nom} T_{p.\text{nom}}. \tag{16}$$

The theoretical and experimental dependences of the energy losses and the efficiency of the drives of mining machines as functions of the consumed electric power, current, as well as parameters characterizing the operating modes of the mining machine, in particular, on the feed rate, are presented in [2, 6, 7]. These dependences are non-linear, especially with high loads. To account for energy losses during overloads above nominal, it is proposed to introduce an overload coefficient $K_{ov}$ characterizing

the increment of losses in the motor during overload and determined by the performance characteristics of this motor.
Thus, by monitoring the power consumption at certain intervals, it is possible to estimate the amount of spent energy resource from expression

$$Q_0 = \sum_{i=1}^{N} K_{ovi} \cdot \rho_i \Delta t_i \ , \tag{17}$$

where $K_{ovi}$ – coefficient of overload in *i*-th measurement; $\rho_i$ – reduced losses during the *i*-th measurement, determined by the performance characteristics: $\Delta t_i$ – duration of the time interval between measurements, during which the load is assumed unchanged, h;
Using the concept of the resource, expressed by the formula (17), the expected residual resource can be determined:

$$T_{p.ex} = \left(1 - \frac{Q_0}{Q_{nom}}\right) T_{nom} \ . \tag{18}$$

With a polyharmonic composition of the consumed power:

$$\rho_i = \sum_{k=1}^{M} \rho_{ik} (\omega_k) \ , \tag{19}$$

where $\rho_{ik}(\omega_k)$ – *k*-th harmonic component in the loss spectrum, $M$ – is the number of harmonics of the spectrum analyzed.

It is suggested in the expression to take into account that individual components of the spectrum have a greater impact on energy resources, introduction of weighting factors

$$\rho_i = \sum_{k=1}^{M} K_{hhk} \rho_{ik} (\omega_k) , \tag{20}$$

where $K_{hhk}$ – weight coefficients that take into account the significance of the *k*-th harmonic of the spectrum.

Taking into account the above, for the expected residual resource the expression (17) takes the form:

$$Q = \sum_{i=1}^{N} K_{ovi} \left[ \sum_{k=1}^{M} K_{hh.\kappa} (\omega_k) \rho(\omega_k) \right] \Delta t_i \ . \tag{21}$$

Substituting expression (20) in (18), we obtain for the remaining resource:

$$T_{p.ex} = \left(1 - \frac{Q_0}{Q_{nom}}\right) T_{p.nom} \sum_{i=1}^{N} K_{ovi} \left[ \sum_{k=1}^{M} K_{hh.k} (\omega_k) \rho(\omega_k) \right] \Delta t_i \ .$$

## 4. Conclusions

To solve the problems of diagnostics of electric motors located in unattended, hard-to-reach technological zones, information-measuring methods are needed that allow estimating the remaining resource by electrical parameters. The proposed methodology is based on the collection, the aggregation, the classification and the analyzation of statistical data of electrical quantities and control of the consumed electric power in order to determine the remaining life of the electric motor. Comparison of load loss diagrams allows you to obtain knowledge about the current state of the machine and can be used to predict the residual resource. If it is necessary to determine the type of damage, oscillography charts of the power transformed in a Fourier series can be used. Monitoring of the power change of losses at characteristic frequencies will determine the type and level of the defect. For the practical application of this method, a large array of statistical data is needed that will allow us to extract knowledge of the changes in the frequency components of power and to fix a diagnostic picture of the initial and critical state

## 5. Acknowledgments

The presented results were obtained as a part of scientific researches according to the contract № 13.3746.2017/8.9 within the scope of the State task “The designing on the base of systematic and logic probability evaluations of rational and economically proved structure of centralized, autonomous and combined power supply systems with high reliability and stability level with usage of alternative and renewable power sources for uninterrupted power supply of enterprises with continuous technological cycle”

## References

[1] Korolev N A and Solovev S V 2017 *IOP Conference Series: Materials Science and Engineering* **177(1)** 012007
[2] Zhukovskiy Yu L, Korolev N A, Babanova I S and Boikov A V 2017 *IOP Conf. Series: Earth and Environmental Science* **87** 032055
[3] Haidong Shao, Hongkai Jiang, Xun Zhang and Maogui Niu Published 2015 *IOP Publishing Ltd Measurement Science and Technology* **26(**11)
[4] Zhukovskiy Y and Koteleva N (2017) *IOP Conference Series: Materials Science and Engineering* **177(1)** 012014
[5] Belsky A, Skamyin A and Iakovleva E 2016 *International Journal of Applied Engineering Research* **11(1)** pp 233–238
[6] Kozyaruk A 2011 *Notes of the Mining Institute* **192** pp 100–104
[7] Leonidovich Z Y, Urievich V B 2015 *International Journal of Applied Engineering Research* **10 (20)** 41150–41155
[8] Pashkov E N, Martyushev N V, Ponomarev A V 2014 *IOP Conference Series: Materials Science and Engineering* **66 (1)** 012014
[9] Pashkov E N, Martyushev N V, Masson I A 2014 *IOP Conference Series: Materials Science and Engineering* **66 (1)** 012011
[10] Shevchuk V A, Muravlev O P, Stolyarova O O, & Shevchuk V P (2016) *MATEC Web of Conferences* **91** 01033