The calculation of asynchronous motors characteristics based on the T-shaped equivalent circuit according to catalogued data

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Abstract. The paper focuses on the issue of calculating the operational characteristics of low-power asynchronous motors used in the agro-industrial complex. The substantiation of the relevance related to reducing the error while calculating the operating characteristics for the estimation and selection of a rational electric drive is given. The literature analysis presented considers the various methods of calculating the main characteristics of asynchronous motors. The equations have been compiled and solved; they help to calculate the operational characteristics without direct reference to the resistance values in the T-shaped equivalent circuit of the motor. The results of calculating the characteristics of one asynchronous motor and their comparison with the known characteristics given in the theory of electrical machines are presented. A method of engineering calculation for educational and work tasks to improve the efficiency of using electric drives is proposed. The field of further research in terms of clarifying the empirical coefficients and revising the complexity of tasks related to determining the resistance of a T-shaped equivalent circuit considering the capabilities of modern computing environments has been determined.

1. Introduction

An electric drive based on asynchronous motors is a widespread mechanism for converting electrical energy into mechanical useful work within a wide variety of technological processes for various units.

Asynchronous electric motors of various capacities are used in engineering practice. In this regard the calculation of engine characteristics is performed on the basis of G and M-shaped substitution schemes, which is quite enough for medium and high-power engines, but introduces a significant error for low-power engines that are widely used in the agro-industrial complex.

Modern computing environments make it possible to use more accurate methods with the minimal time costs; for this reason, it is advisable to return to the analysis of the T-shaped asynchronous motor equivalent circuit and the application of its consequences to calculate the characteristics of the electric drive.

The following main characteristics are distinguished in electric drives for motors:
1) the mechanical characteristic showing the relationship between the developed force (torque) and the speed of the drive unit (rotor);
2) the electromechanical characteristic showing the current value of the main motor winding (stator winding for asynchronous motors) depending on the speed of the drive unit (rotor).
Besides for solving some system engineering tasks it is necessary to know the characteristics that represent the efficiency of using the engine:

1) the characteristic of the power factor, which makes it possible to determine the load rationality of the conductor cross-sectional area in the supply wires (cables);
2) the characteristic of the efficiency factor, which makes it possible to determine the electric motor efficiency and is used for the analysis of thermal processes.

Currently, the scientists are following the two different ways of doing research in this sphere:

1) the study of determining the G and M -shaped equivalent schemes parameters empirically through constructive data, through catalogue data or by combining these methods [1-8];
2) the study of selecting the necessary characteristics close to the real ones and suitable for the purposes of engineering calculation [9, 10].

Diverse approaches to studying asynchronous motors, their characteristics and the ways to improve their reliability are investigated by a variety of criteria. Some authors consider the problem from the point of view of minimizing engine losses [11], others investigate the torque of the load and carry out high-performance speed control, for which they use an accurate linearization method with nonlinear feedback based on the theory of differential geometry [12]. Recently, new strategies for controlling field attenuation with variable reference voltage for asynchronous motors have been proposed [13], [14]. Scientific studies devoted to the reliability of asynchronous motors and the systems in which they are used are relevant as they help to solve the problem of reducing costs and excessive time spent on maintenance and troubleshooting [15, 16].

It should be noted that the joint task of determining a holistic methodology for calculating the asynchronous motors characteristics, taking into account the resistances of the equivalent circuit, is not properly studied. In engineering practice, well-known ratios from the theory of electric machines are used, as well as the formulas with empirical coefficients. It should be noted here that for most of these empirical coefficients, the ratios were determined on the basis of examining the early series engines, while modern industry continues to improve the designs of asynchronous motors. In general, this inevitably leads to the fact that the empirical coefficients will differ more and more from the real values, which means that the calculation error will also be greater. This trend is especially strong for asynchronous motors of low power (less than 2.2 kW), which are widely used in the agro-industrial complex.

Based on the analysis performed, it can be concluded that it is necessary to refine the existing engineering calculation methods to reduce the impact of accumulated errors.

2. Methods and materials

A T-shaped asynchronous motor equivalent circuit based on standard assumptions within the framework of electric machines theory is used to improve the accuracy of determining the characteristics parameters. We assume that there is such a T-shaped circuit with six linear resistances; and for this scheme it is possible to calculate the characteristics corresponding to the desired asynchronous motor.

![Figure 1. Calculated T-shaped equivalent circuit of asynchronous motor.](image)
The traditional transition to the G or M-shaped scheme is not performed. Determination of the total circuit resistance is carried out in two stages:
1) the determination of the equivalent resistance from parallel connection of magnetizing and rotor circuits;
2) the summation of the stator circuit resistance and the equivalent resistance of the magnetizing and rotor circuits.

Omitting the equivalent transformations, we obtain it in an integrated form at the first stage:

$$z_{2m}(S) = r_m \frac{1+A_1 S + A_2 S^2}{1+B_1 S + B_2 S^2} + i x_m \frac{1+A_3 S^2}{1+B_1 S + B_2 S^2},$$  \hspace{1cm} (1)$$

where $A_1, A_2, A_3, B_1, B_2$ are the dimensionless coefficients determined by constant resistances in circuits:

$$A_1 = \frac{r_m^2 + x_m^2}{2}, \hspace{1cm} A_2 = \frac{x_m^2 + x_2 r_m (r_m^2 + x_m^2)}{x_m r_m}, \hspace{1cm} B_1 = \frac{2r_m}{r_2}, \hspace{1cm} B_2 = \frac{r_m^2 + (x_m + x_2)^2}{r_2^2}. \hspace{1cm} (2)$$

It should be noted that the sliding coefficients in the first degree are inversely proportional to the active resistance of the rotor circuit also in the first degree; a similar situation with the second degree is observed for the sliding coefficients with the second degree.

Being at the second stage and omitting the equivalent transformations, the total resistance in an integrated form can be determined by the formula

$$z_S(S) = r_0 \frac{1+Cr_1 S + Cr_2 S^2}{1+B_1 S + B_2 S^2} + i x_0 \frac{1+Cx_1 S + Cx_2 S^2}{1+B_1 S + B_2 S^2},$$  \hspace{1cm} (3)$$

where $r_0 = r_1 + r_m$ is an active resistance of idling, Om; $x_0 = x_1 + x_m$ is the reactance of idling, Om; $C_1, C_2, C_1, C_2$ are the dimensionless coefficients determined by constant resistances in circuits:

$$Cr_1 = \frac{1}{r_2} \cdot \frac{2x_1 r_m + x_m^2}{r_0}, \hspace{1cm} Cr_2 = \frac{1}{r_2} \cdot \frac{r_1 r_m^2 + (x_m + x_2)^2 + r_m x_m^2}{r_0}, \hspace{1cm} (4)$$

$$Cx_1 = \frac{1}{r_2} \cdot \frac{2x_1 r_m}{x_0}, \hspace{1cm} Cx_2 = \frac{1}{r_2} \cdot \frac{x_1 (r_m + x_2)^2 + x_m^2 x_2 + x_2 (r_m + x_m)}{x_0}.$$  \hspace{1cm} (5)$$

From formula (3) we determine the module function of the total resistance in a circuit

$$|z_S(S)| = z_0 \frac{(1+Dz_1 S + Dz_2 S^2 + Dz_3 S^3 + Dz_4 S^4)^{1/2}}{1+4B_1 S + 4B_2 S^2} \hspace{1cm},$$

$$|z_S(S)| = z_0 \frac{(1+Dz_1 S + Dz_2 S^2 + Dz_3 S^3 + Dz_4 S^4)^{1/2}}{1+4B_1 S + 4B_2 S^2}.$$  \hspace{1cm} (6)$$

Any polynomial of the fourth degree can be expressed through the square of the polynomial of the second degree considering the remainder. Then expression (5) can be transformed into:

$$|z_S(S)| = z_0 \frac{1 + Fz_1 S + Fz_2 S^2 + Fz_3 S^3 + Fz_4 S^4}{1+4B_1 S + 4B_2 S^2} \hspace{1cm},$$

$$|z_S(S)| = z_0 \frac{1 + Fz_1 S + Fz_2 S^2 + Fz_3 S^3 + Fz_4 S^4}{1+4B_1 S + 4B_2 S^2}.$$  \hspace{1cm} (7)$$

where $Fz_1, Fz_2, Ez_2, Ez_3$ are the dimensionless coefficients:

$$Fz_1 = \frac{Dz_1}{2}, \hspace{1cm} Fz_2 = \sqrt{Dz_4}, \hspace{1cm} Ez_2 = Dz_2 - (Dz_1^2)^{1/2} - 2 \sqrt{Dz_4}, \hspace{1cm} Ez_3 = Dz_3 - Dz_1 \cdot \sqrt{Dz_4}.$$  \hspace{1cm} (8)$$

Taking as an assumption that the subduplicate expression (7) in the area of small slips (on the working part of characteristics) differs slightly from one, the function of the total resistance can be written in a simplified form:
\[ |z_2(S)| = z_0 \cdot \frac{1 + Fz_1 S + Fz_2 S^2}{1 + Bz_1 S + Bz_2 S^2}. \]  

(9)

From expressions (3) and (9) it is possible to determine the power factor functions in the circuit:

\[ \cos \varphi(S) = \frac{r_0}{z_0} \cdot \frac{1 + Cr_1 S + Cr_2 S^2}{1 + Fz_1 S + Fz_2 S^2} = \cos \varphi_0 \cdot \frac{1 + Cr_1 S + Cr_2 S^2}{1 + Fz_1 S + Fz_2 S^2}, \]  

(10)

where \( \cos \varphi_0 \) is an idle power factor.

Assuming that the circuit is powered by a sinusoidal voltage with a constant frequency, expression (9) can be used to find the function of the electromechanical characteristics of an asynchronous motor:

\[ I(S) = \frac{U}{|z_2(S)|} = I_0 \cdot \frac{1 + Bz_1 S + Bz_2 S^2}{1 + Fz_1 S + Fz_2 S^2}, \]  

(11)

where \( U \) is the net phase voltage, V; \( I_0 = U/z_0 \) is the engine idling current, A.

From expressions (10) and (11) the following conclusions can be drawn:

1) the no-load current directly depends on the voltage value and does not depend on the active resistance of the rotor circuit;
2) the no-load power factor does not depend on the net voltage and on the active resistance of the rotor circuit;
3) in asynchronous motors with a phase rotor the dimensionless coefficients will change inversely proportional to the value of the total additional resistance \( r_d \) to the appropriate degree when active additional resistances are introduced into the rotor circuit:

\[ Bz_1, Fz_1 \propto \frac{r_2}{r_2 + r_d}, \quad Bz_2, Fz_2 \propto \left( \frac{r_2}{r_2 + r_d} \right)^2; \]  

(12)

4) in expression (11) we can find the slip coefficients without determining the circuit resistances using the data of the no-load test and four points with identified currents, power factors and speeds.

3. Results and discussion

The verification of the obtained expressions was carried out on the basis of numerical calculations using the example of a randomly selected asynchronous motor of a conventional design to compare the calculated characteristics known from the theory of electrical machines.

The AIR80B2 engine was chosen for the research, the cataloguedata were taken according to the data of the JSC "Mogilev Plant "Elektrodvigatel": 2.2 kW; 2810 rpm; efficiency is 79.7%; \( \cos \varphi_n = 0.87; \) \( m_p = 2.1; \) \( m_0 = 2.6; \) \( m_{\text{min}} = 1.8; \) \( i_p = 6.4. \) Thus, we can determine the nominal slip \( S_n = 6. (3) \% \), rated current in the phase conductor \( I_n = 4.807 \) A, rated motor torque \( M_n = 7.476 \) N∙m, synchronous speed \( \omega_0 = 314.159 \) rad/s.

The additional data established experimentally are required to calculate the characteristics (10) and (11). In those cases when it is impossible to conduct an experiment, it is recommended to take values close to real ones by the specific points of characteristics determined through empirical ratios:

1) the experiment data carried out in idle mode can be evaluated as follows:

\[ I_0 = I_N \cdot \left( \sin \varphi_N - \frac{\cos \varphi_N}{m_C + (m_C^2 + 1)^{1/2}} \right). \]  

(13)

\[ \cos \varphi_0 = 0.15 \ldots 0.20. \]  

(14)

2) at the critical speed (at the maximum torque) the current and slip can be evaluated as follows:

\[ S_C = S_N \cdot \frac{m_C + (m_C^2 + 2m_N(m_C - 1))^{1/2}}{1 - 2m_N(m_C - 1)}, \]  

(15)

\[ I_C = (0.75 \ldots 0.85)I_N; \]  

(16)

3) starting current with slip equal to one (at zero speed):
The third additional point can be taken at half the nominal slip

\[ I_{hs} = (0.41 \ldots 0.47) \cdot (I_0 + I_N), \]  

\[ \cos \varphi_{hs} = (0.68 \ldots 0.78) \cdot \left( \cos \varphi_0 + \cos \varphi_N \right). \]

Further the following parameters values are determined:
\[ \cos \varphi_0 = 0.15, \quad I_0 = 2.76 \text{ A}, \quad S_c = 40.048\%, \quad I_C = 42.632 \text{ A}, \quad I_S = 53.2 \text{ A}, \quad I_{hs} = 4.989 \text{ A}, \quad \cos \varphi_{hs} = 0.765. \]

From these data it is possible to solve a system of four linear equations with four unknown coefficients using expression (11); it is not difficult when using computing environments. Then we transfer the coefficients \( Fz_1 \) and \( Fz_2 \) to equation (10) and find unknown coefficients.

**Table 1.** Results of determining the coefficients of engine characteristics.

| Engine  | \( Fz_1 \) | \( Fz_2 \) | \( Bz_1 \) | \( Bz_2 \) | \( Cr_1 \) | \( Cr_2 \) |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|
| AIR80B2 | 0.49      | 13.899    | 18.384    | 277.691   | 251.738   | 516.089   |

The calculation of the mechanical characteristic can be performed according to the Kloss formula (without simplifications for high-power engines):

\[ M(S) = \frac{2m_C \cdot M_N (1 + e \cdot S_c)}{S/S_c + S_c/S + 2e \cdot S_c}, \]  

where \( e = 1 \) is the coefficient determined from the ratio of the equivalent circuit resistances. In the practice of an electric drive application, this coefficient is determined under the condition when the nominal torque is reached at the nominal slip:

\[ e = \frac{S_N / S_c + S_c / S_N - 2m_C}{2S_c (m_C - 1)}. \]

Based on the known characteristics it is possible to determine the motor efficiency function on arbitrary slip:

\[ \eta(S) = \frac{M(S) \cdot \omega_0 (1 - S)}{3U \cdot I(S) \cdot \cos \varphi(S)}, \]

\[ \eta(S) = \frac{2m_C \cdot \omega_0 (1 + e \cdot S_c)}{3U \cdot I_0 \cdot \cos \varphi_0 \cdot S_c}, \quad \frac{S (1 - S)}{1 + 2eS + S^2} \cdot \frac{(1 + Fz_1 S + Fz_2 S^2)^2}{(1 + Bz_1 S + Bz_2 S^2) (1 + Cr_1 S + Cr_2 S^2)}. \]

It should be noted that expression (22) is visually simpler than (23) and it will be expedient to use it when performing numerical calculations.

The results of calculations based on the estimated data using AIR80B2 engine are shown in the figures below as an example.
Figure 2. Natural mechanical (---) and electromechanical (···) characteristics of AIR80B2 asynchronous motor.

Figure 3. Natural performance characteristics of AIR80B2 asynchronous motor in the slip range from 0 to $S_N$.

--- stator current characteristic in r.u.
- -efficiency characteristic
··· power factor characteristic

It should be noted that if we assume that the AIR80B2 motor has a phase rotor (but not squirrel-cage) and an additional active resistance is introduced into its circuit, when using the coefficients from Table 1 and when recalculating through relations (12), similar artificial characteristics can be obtained.

Figure 4. Electromechanical characteristics of AIR80B2 asynchronous motor

--- natural characteristic
- - artificial characteristic at $r_d = 0.5 \, r_2$
··· artificial characteristic at $r_d = r_2$
4. Conclusion

The use of computing environments for engineering design tasks in the educational and detailed design of electric drives is an important task. At the same time, a number of problems, the solution of which was previously roughened in order to reduce the complexity of calculations, can be solved by automating calculations.

The method of engineering calculation presented in this paper helps to evaluate the main characteristics of electric motors with a minimum amount of experimental data.

In further studies, it is necessary to clarify the empirical coefficients used when trying to estimate the values of current and power factor at different rotor speeds, and to find all six resistances of the T-shaped asynchronous motor equivalent circuit; this will improve the accuracy of calculating the artificial characteristics when the frequency of the supply network current changes.

References

[1] Myaskovskiy V A 2020 Study of methods for calculating parameters of the asynchronous motor equivalent circuit according to the manufacturer's catalogue *Young scientist* 20 (310) 127-33

[2] Timinskaya E I, Afanasyev M A 2017 Method of calculating the main parameter of the asynchronous motor equivalent circuit (Moscow: Abstracts of the Twenty-third International Scientific and Technical Conference of Students and Postgraduates "Radioelectronics, Electrical engineering and Power engineering") p 31

[3] Sivokobylenko V F 2016 Hybrid replacement scheme for asynchronous motors with a deep-groove or two-cell rotor *Electricity* 4 34-40

[4] Gridin V M 2012 Calculation of parameters of the asynchronous motor equivalent circuit according to catalogue data *Electricity* 5 40-4

[5] Popovich A N, Golovan I V 2012 Determination of parameters of the asynchronous motor equivalent circuit and their nonlinear dependencies based on the results of field analysis *The Institute of Electrodynamics, the National Academy of Sciences in Ukraine* 31 38-48

[6] Druzhinin A V, Druzhinina E A, Poluzadov V N 2013 Determination of parameters of a T-shaped asynchronous motor equivalent circuit when calculating the control systems for a frequency-controlled electric drive *Izvestia of higher educational institutions. Mining Magazine* 3 98-105
[7] Beshta A S, Semin A A 2012 The feature of using a T-shaped asynchronous motor equivalent circuit for parameter identification tasks *Electromechanical and energy-saving systems* **3**(19) 553-5

[8] Makeev M S, Kuvshinov A A 2013 Algorithm for calculating the parameters of the asynchronous motor equivalent circuit according to catalogue data *Vector of Science of Tolyatti State University* **1**(23) 108-12

[9] Zinnatullina G S, Vavilov V E 2019 Research of an asynchronous motor with a short-circuited rotor by means of computer modeling *Youth Bulletin of the Ufa State Aviation Technical University* **1**(20) 67-71

[10] Grachev G M 2013 Substantiation of a rational variant of an electric drive operating in a repeated-short-term mode (Chelyabinsk: Materials of the LII International Scientific and Technical Conference "Achievements of Science are for agro-industrial production") pp 243-6

[11] Gomez J C, Morcos M M, Reineri C A and Campetelli G N 2002 Behavior of induction motor due to voltage sags and short interruptions. *IEEE Trans Power Deliv.* **17**(2) 434-40

[12] Zhong B and Ma L 2021 Active disturbance rejection control and energy consumption of three-phase asynchronous motor based on dynamic system’s decoupling *Sustainable Energy Technologies and Assessments* **47** 101338

[13] Hong Z, Bo W and Wuqiao L 2013 A Novel Field Weakening Control Strategy with Variable Reference Voltage for Asynchronous Motor *IFAC Proceedings Volumes* **46**(20) 80-5

[14] Essam E and Mahmoud A 2018 Matrix converters and three-phase inverters fed linear induction motor drives - Performance compare *Ain Shams Engineering Journal* **9**(3) 329-40

[15] Halina T, Stalnaya M, Eremochkin S and Ivanov I 2016 Modeling electromechanical characteristics of three-phase motors with inverters vector - algorithmic type in Matlab Simulink environment *Procedia Engineering* **165** 995-1005

[16] Szolc T and Pochanke A 2012 Analytical-computational approach to dynamic investigation of the electro-mechanical coupling effects in the rotating systems driven by asynchronous motors *Institution of Mechanical Engineers - 10th International Conference on Vibrations in Rotating Machinery* 753-63