Automation of determining the parameters of the asynchronous motor short-circuit mode

A A Shevchenko, Z S Temlyakova, M E Vilberger, A A Temlyakov

Novosibirsk State Technical University, 20, Karl Marx ave., Novosibirsk, 630073, Russia

E-mail: comrade.zed92@gmail.com

Abstract. The research subjects are asynchronous motors of the type ATM4 in the power range from 400 to 8000 kW produced by NPO “ELSIB” PAO. The article proposes a method for optimizing the calculation of heating parts of the active volume of large asynchronous motors in the short-circuit mode of the engine. The calculation method is based on the fundamental provisions of the theory of electric machines. The purpose of the study is to automate the calculation of heating different parts of the active volume of the motor. The calculation of heating is determined by the need to preserve the operability of the motor in the event of emergency situations in production. The originality of the study lies in the fact that the algorithm for calculating the time to achieve critical heating of various parts of the active volume of the asynchronous motor is modified based on known positions. This provides the correct protection against the effects of thermal overheating. The results of the study are presented on a specific example of the motor.

1. Introduction

Many scientific schools are engaged in the research of thermal conditions of electrical equipment. The problems concerning thermal overheating of various parts of electrical equipment have been relevant for decades. This is confirmed by modern scientific publications of famous Russian and foreign scientific schools (universities of St. Petersburg, Krasnoyarsk, Novosibirsk) [1–4], (University of Padova, Italy) [5].

Heat sources have been known in the field of electrical machine research for quite some time. However, modern research tools (such as numerical modeling, new software products, and modified mathematical models) can reduce labor costs and improve the accuracy of the results. In the works of the authors [6–7], such transient modes of operation of asynchronous electric motors, such as engine self-starting, as well as engine starting using a soft start device, were previously considered. A special case of any starting mode is the short circuit mode of the electric motor.

When starting asynchronous squirrel-cage motors there is a starting current that exceeds the rated current 4-8 times. Inrush currents cause a decrease in the mains voltage. This voltage drop is small when starting small motors, but when starting asynchronous short-circuiting high-power motors, it can be significant. With a significant decrease in the mains voltage, the starting and critical moments of the motors, being proportional to the square of the voltage, decrease sharply. Electric motors operating at this time with an overload may stop, thereby switching to the short circuit mode [8].
2. Problem definition

It is necessary to set the automatics to shut off at a given temperature in order to avoid overheating of the active parts of the motors in the short circuit mode. Using a time relay is one of the cheap and reliable protection options. When the rotor is seized after starting (or for any other reason for stopping it), a current will flow in the stator winding, rods and short-circuiting rings. This current is equal to the starting current. This will lead to rapid heating of the active parts of the machine. In addition, when a soft starter or frequency converter is connected to the motor, high starting currents can damage these devices. Therefore, at known permissible values of heating of the engine parts in the short circuit mode, it is necessary to set the relay time setting, after which the machine will be disconnected from the network, if it does not reach the nominal operation mode.

The current task is reduced to:

1. Algorithm modification for calculating the time to reach the critical heating of the large asynchronous motor active parts based on the known formulas;
2. Automating value array calculation of the machine active part heating and finding the time to reach critical heating in order to reduce the calculation time and complexity.

3. The short circuit mode of the motor

Leaving the rotor stationary after energizing the stator winding, the asynchronous motor short-circuit will occur. This is similar to a transformer short circuit from the electrical engineering viewpoint. The mode is at the first moment of the motor start when the rotor has not yet come into rotation. As stated above, the stator currents are high in this state of the motor. Therefore, the motor cannot be left for a long time during a short circuit under full voltage in order to avoid creating an emergency situation due to excessive heating and damage caused to the insulation of the windings. This is also evidenced by the practice of conducting a short circuit experiment when a reduced voltage is supplied to the stator winding with the stationary rotor to get the required characteristics. The voltage is reduced; so far the stator current is nominal (or slightly higher) in order to avoid the winding overheating [9].

The distribution of the magnetic fields of the motor in a short circuit is shown in figure 1.

![Figure 1. The magnetic field distribution in the stalled asynchronous motor (the short circuit mode).](image)

Here $\Phi_0$ is the major magnetic flux;
$\Phi_{pc1}$ is the stator winding magnetic flux leakage;
$\Phi_{pc2}$ is the rotor winding magnetic flux leakage;
n$_1$ is the stator field rotation speed;
n$_2$ is the rotor field rotation speed which is zero.

The major magnetic flux is created in this mode by the joint action of the stator $F_1$ and rotor $F_2$ of MMF:

$$F_1 = m_1 \cdot \frac{0.45 \cdot w_1 \cdot k_{w1}}{p} \cdot I_1, \quad F_2 = m_2 \cdot \frac{0.45 \cdot w_2 \cdot k_{w2}}{p} \cdot I_2,$$

that is
Equality is fulfilled where $m_1$ and $m_2$ are the stator and rotor winding phase number; $w_1$ and $w_2$ are the stator and rotor number of turns; $k_{\text{win}1}$ and $k_{\text{win}2}$ are the stator and rotor winding factors; $p$ is the number of pole pairs.

This equality can be converted to:

$$\mathbf{T}_1 - \mathbf{T}_0 = -\mathbf{T}_2 \cdot \frac{m_2 \cdot w_2 \cdot k_{\text{win}2}}{m_1 \cdot w_1 \cdot k_{\text{win}1}}.$$

This equation is called a current equilibrium equation. It is true for any asynchronous motor operation mode.

If the rotor current rate is neglected, then the equation takes the form:

$$\mathbf{T}_1 = -\mathbf{T}_2 \cdot \frac{m_2 \cdot w_2 \cdot k_{\text{win}2}}{m_1 \cdot w_1 \cdot k_{\text{win}1}}.$$

Thereby we obtain the ratio of currents:

$$k = \frac{I_1}{I_2} = \frac{m_2 \cdot w_2 \cdot k_{\text{win}1}}{m_1 \cdot w_1 \cdot k_{\text{win}2}}.$$

Rotor magnetic flux leakage $\Phi_{pc2}$ creates the EMF leakage in rotor winding $E_{pc2}$, which value is determined by the equality:

$$E_{pc2} = -\mathbf{T}_2 \cdot x_2,$$

where $x_2$ is the rotor winding leakage inductive reactance.

Voltage drop across the rotor winding active resistance:

$$U_2 = I_2 \cdot r_2.$$

EMF equilibrium equations for the stator and rotor windings have the next form:

$$\begin{align*}
\mathbf{U}_1 &= -\mathbf{E}_1 + I_1 \cdot r_1 + \mathbf{T}_1 \cdot x_1; \\
\mathbf{E}_2 &= \mathbf{T}_2 \cdot r_2 + \mathbf{T}_2 \cdot x_2.
\end{align*}$$

The secondary equivalent circuit when the rotor is stalled is shown in Figure 2.

![Figure 2](image)

**Figure 2.** The secondary equivalent circuit when the rotor is stalled.

The rotor current is determined from the expression:

$$I_2 = \frac{E_{pc2}}{\sqrt{r_2^2 + x_2^2}}.$$

If the load resistance is included in the rotor winding circuit in an asynchronous motor with a fixed rotor, then it can be used as a transformer.
4. Short circuit mode parameter definition

The following machine parameters are needed to find the heating values in the short circuit mode and the time during which they occur:

- $U_{rat}$ is the rated stator voltage, V;
- $U_{low}$ is the stator undervoltage value, V;
- $I^*$ is the stator starting current ratio, r.u.
- $j_1$ is the stator winding current density, A/mm$^2$;
- $Q_b$ is the rotor bar losses, W;
- $c_b$ is the rotor bar specific heat capacity value, kJ/(kg·°C);
- $G_b$ is the rotor bar weight, kg;
- $Q_r$ is the rotor short-circuiting ring losses, W;
- $c_r$ is the rotor short-circuiting ring specific heat capacity value, kJ/(kg·°C);
- $G_r$ is the rotor short-circuiting ring weight, kg.

The metal specific heat values, used for the design of asynchronous motor rotor conductive parts, are given in table 1 [6].

| Material name | Specific heat capacity value, kJ/kg·°C |
|---------------|---------------------------------------|
| copper        | 0.390                                 |
| aluminum      | 0.896                                 |
| brass         | 0.377                                 |

In addition to the motor parameters, it is necessary to set the short circuit mode duration $\tau_{max}$, s, maximum permissible temperature value of the motor parts $\theta_{max}$, °C, as well as the time discreteness $\Delta\tau$, s. In addition, the user is invited to independently set the number of decimal places by entering an integer value, thereby ensuring the necessary accuracy.

Further calculation is automated and implemented as a software product written in the programming language JavaScript [7].

At the beginning of the calculation, the heat capacities of the rotor parts $C$, kJ/°C are determined, after which according to the known formulas the temperature rise rates of the machine parts $v$ are calculated [10]:

$$
C_{kits} = G_{kits} \cdot c_{kits};
$$

$$
v_i = \frac{0.85 \cdot I_i^2 \cdot j_i^2}{160};
$$

$$
v_{kits} = \frac{Q_{kits}}{C_{kits}}.
$$

The further calculation algorithm involves calculating the heating of the machine active parts $\theta$ for each time period $\Delta\tau$ during the entire period $\tau_{max}$:

$$
\theta_{kits} = \alpha^2 \cdot v_{kits} \cdot \Delta\tau,
$$

where

$$
\alpha = \frac{U_{low}}{U_{rat}};
$$

$\Delta\tau_i$ is the time elapsed since the start of the short circuit mode, increasing with each iteration by a $\Delta\tau$ value.

Next, a data array is formed into a table. In addition, a machine part heating auxiliary table for the rated voltage is compiled.
According to the calculation results, the program processes the resulting dataset to find the heating values of motor parts exceeding a specified value. If such the value is found, the program informs the user at what point in time which motor part will overheat.

If none of the machine parts within the specified time reaches the critical temperature, the program will also report this. In this case, it is recommended to increase the $\tau_{\text{max}}$ amount and re-calculate the problem.

5. **Mathematical simulation results**

Mathematical simulation of the short circuit mode is carried out in terms of the 5AZMV-3150/6000N2,5 asynchronous motor produced by NPO “ELSIB” PAO. A quantitative characteristic of the stator winding and the rotor bars and short-circuiting rings heating values for different points in time are given in Table 2.

| $\tau$, s | $\theta_1$, °C | $\theta_\varphi$, °C | $\theta_\text{k}$, °C |
|-----------|----------------|-----------------|----------------|
| 0.0       | 0.0            | 0.0             | 0.0            |
| 10        | 3.5            | 31              | 1.5            |
| 20        | 7.0            | 62              | 3.0            |
| 30        | 11             | 92              | 4.6            |
| 40        | 14             | 120             | 6.1            |
| 50        | 18             | 150             | 7.6            |
| 60        | 21             | 190             | 9.1            |
| 70        | 25             | 220             | 11             |
| 80        | 28             | 250             | 12             |
| 90        | 32             | 280             | 14             |
| 100       | 35             | 310             | 15             |
| 110       | 39             | 340             | 17             |
| 120       | 42             | 370             | 18             |
| 130       | 46             | 400             | 20             |
| 140       | 49             | 430             | 21             |
| 150       | 52             | 460             | 23             |

With voltage $U = 1800$ V the rotor bar heating will exceed the value 130 °C in the short circuit mode after 43 s. Therefore, with the permissible amount of heating of the motor parts in the short circuit mode equal to 130 °C, the relay time setting must be set to 43 seconds.

6. **Conclusion**

On the basis of the developed modification of a mathematical model implemented as a software product in the JavaScript programming language, asynchronous motors of the ATM4 type produced by NPO ELSIB PAO in the power range from 400 to 8000 kW are investigated. The processing results of the received data array are demonstrated by the example of the 5AZMV-3150/6000N2,5 asynchronous motor. Automation of the calculation provided a reduction of its time and labor costs. The results obtained in the form of electrical machine different part overheating allowed one to properly configure the motor time relay protection. Analysis of the results of overheating allows us to estimate the guaranteed lifetime of the insulation of the stator winding of an electric motor.

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