Heating calculation features at self-start of large asynchronous motor

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Abstract. The article proposes a method for optimizing the incremental heating calculation in the active volume of a large asynchronous motor for certain kinds of load characteristics. The incremental heating calculation is conditioned by the need to determine the aging level of the insulation and to predict a decrease in the electric machine service life. The method for optimizing the incremental heating calculation of asynchronous motor active volume is based on the automation of calculating the heating when simulating the self-starting process of the motor after eliminating an AC drop.

1. Introduction
An integral requirement of the supplying of automated production processes is the automatic recovery mode asynchronous motor requirement after a brief power failure, followed by the running-out of the rotor. The running-out means that the rotor is out of the mode of operation at the rated slip in case of drop or voltage outage. In short, the physical picture is described as follows: at a temporary reduction of the applied voltage within inadmissible limits, the asynchronous motors of the responsible mechanisms are not switched off, and at the same time with the restoration of the electricity supply voltage busbar installations are started up automatically, without the participation of the staff [1-4].

Short circuits in the networks causing the disappearance or reduction of voltage, as a rule, are short-lived. Due to their specific features, the rotors of asynchronous motors do not have time to stop, which ensures the continuation of the production technological process. However, as the slip increases, the rotor decelerates, which is accompanied by a current increase in the conductors of the stator and rotor windings, which in turn can lead to unacceptable overheating and, as a result, faster insulation aging.

The purpose of the work is to determine the algorithm for calculating the incremental heating of current-carrying parts of the active volume of an asynchronous motor when simulating the process of its self-starting in case of network accidentally lower voltage restoration and then assessing the possibility of automatically restoring the electric machine operating mode depending on the its load characteristic type.

Technologically, the numerical determination of the incremental heating of asynchronous motor current-carrying parts is based on the results of mathematical modeling of a physical process in a computer environment using [5, 6, 9, 10] the JavaScript programming language. The choice of the language is justified in [7].
2. Self-starting time calculation

The mathematical modeling procedure is branched and consists of several blocks and sub-blocks. Before calculating the heating of motor current-carrying parts (stator winding, bars and end rings of rotor), it is necessary to calculate the self-starting time. The following input data are necessary to do this:

\[ P_{\text{rat}} \text{ is the rated power, kW; } \]
\[ n_{\text{syn}} \text{ is the synchronous stator field speed, rpm; } \]
\[ J_{\text{mot}} \text{ is the dynamic moment of inertia, kg\cdot m}^2; \]
\[ J_{\text{mech}} \text{ is the dynamic moment of inertia of the mechanism, kg\cdot m}^2; \]
\[ s \text{ is the slip (13 values), r.u.; } \]
\[ T^* \text{ is the relative torques corresponding to slips (13 values), r.u.} \]

When implementing mathematical modeling, the following combination is chosen as the slip values, r.u.:
\[ 1; 0.9; 0.8; 0.7; 0.6; 0.5; 0.4; 0.3; 0.2; 0.15; 0.1; 0.05; s_{\text{bd}}, \]
where \( s_{\text{bd}} \) is the break-down slip value.

In addition, it is necessary to input a static dependence of the mechanism resistance torque depending on slip \( T_{\text{load}}(s) \) as well as the minimum value of the excess torque and the voltage recovery time discreteness. Details of the above parameters assignment are given in [1].

From the indicated initial data, it is necessary to emphasize the following values:

- initial \( (\alpha_1) \) and final \( (\alpha_2) \) value of the relative reduction of voltage,
\[ \alpha = \frac{U_{\text{low}}}{U_{\text{rat}}}, \]
where \( U_{\text{low}} \) is the value of the undervoltage, \( U_{\text{rat}} \) is the value of the rated voltage;

- \( T_e \) – excess torque value.

The self-starting time calculation consists of two main sub-blocks. The meaning of the first one is to determine all the quantities required for the self-starting time calculation; the second one is to analyze of the satisfaction of the self-starting condition requirements.

The voltage recovery time discreteness \( (\Delta t, \text{sec}) \) predetermines the accuracy of the self-starting time calculation. In the calculation it is assumed that segments \( \alpha_1: \alpha_2 \) and \( 0: \tau_{\text{recov}} \) vary linearly, according to the law \( y = x \). By linear interpolation range \( \alpha_1: \alpha_2 \) is divided by the number of parts corresponding to the predetermined discrete nature, with each interval of time corresponding to the value of \( \alpha_i \). By transformation of the differential equation of the torque change, the following dependence of the running-out time variation depending on slip is received:

\[ \tau(s) = 2 \cdot \pi \cdot n_{\text{syn}} \left( J_{\text{mot}} + J_{\text{mech}} \right) \frac{1}{30} \int_{0}^{1} ds \int_{0}^{\tau_{\text{recov}}(s)} \]

From this dependence the running-out slip \( s_{\text{ro}} \) is received.

Further, considering a quadratic dependence between the voltage and the time the program finds points for each value of the slip with all available on the results of division into segments value \( \alpha \), after which the results tabulates (the structure describes by Table 1). Also the authors calculated minimum value \( \alpha_{\text{min}} \), where the start/restart is physically possible.

Further, according to
\[ \tau = k \cdot T \cdot \frac{1}{\int_{0}^{1} ds \int_{0}^{\tau_{\text{recov}}(s)}} \]
the value of the starting time for each value of \( \alpha \) is calculated, assuming that this relative decrease in voltage is constant for the entire period of the motor operating time. This formula contains the parameters \( k \) (aggregate time constant coefficient) and \( T \) (motor time constant, sec), which are defined as follows:
\[ k = 1 + \frac{GD_{\text{mech}}^2}{GD_{\text{mot}}^2} = 1 + \frac{J_{\text{mech}}}{J_{\text{mot}}}; \]
Table 1. Structure of summary table.

| s | $\alpha_1$ | $\alpha_2$ | ... | $\alpha_n$ |
|---|---|---|---|---|
| $t_1$ | $t_2$ | ... | $t_n$ |

$s_1$ $T_{e1.1}$ $T_{e2.1}$ ... $T_{en.1}$

... ...

$s_{13}$ $T_{e1.13}$ $T_{e2.13}$ ... $T_{en.13}$

$$T = \frac{GD_{mot}^2 \cdot n_{rme}^2 \cdot 10^{-3}}{365 \cdot P_{uid}}.$$  

where

$$J = \frac{GD^2}{4};$$

$GD^2$ – amplitude torque, kg·m².

A more detailed description of the algorithm for calculating the self-starting time is given in [7].

3. Heating calculation at the self-start

Calculation of the heating at start-up is carried out after the determination of all the time intervals and is similar to the procedure for determining the time of self-start. The following data are used for the calculation:

- $T_{br}$ is the basic heating of the bars/rings, °C;
- $v_1$ is the stator winding temperature increase rate, °C/s;
- $p_{br}$ is the relative loss at the bars/rings, corresponding to the above set of slip values, r.u.

The incremental heating of the stator winding is determined by analogy with the starting time calculation:

$$\Theta_1 = \alpha^2 \cdot v_1 \cdot k \cdot T \cdot \frac{1}{0} \frac{ds}{T_{eav}(s)}.$$  

The incremental heating of the bars/rings of rotor:

$$\Theta_{br} = \alpha^2 \cdot k \cdot T_{br} \cdot \frac{1}{0} \frac{p_{brav}(s) \cdot ds}{T_{eav}(s)}.$$  

When calculating the heating during self-start, there is a difficulty in determining the values of the stator winding heating, bars and end rings of rotor when the rotor “hangs” in the asynchronous motor. It is known that the minimum value of the excess torque $T_{e, min}$, r.u. – this is the minimum difference between the values of the motor torque $T^r$ and the time $T_{load}$ resistance, at which there will be a guaranteed start / restart. In the mathematical model adopted assumption that with a smaller positive value of the excess torque to happen “hangs” of the rotor, that is, rotation at a constant angular velocity occurs until the stator winding voltage is increased to a value providing the necessary excess torque, and as a result, the continuation of the acceleration of the rotor. The actual physical picture – acceleration – will continue at lower angular acceleration. With excess negative torque, respectively, the angular acceleration takes a negative value. As an example, Fig. 1 gives a graphical interpretation of the dependence of the excess torque in the slip function $T_{load}(s)$. The area of excess torque $T_e$ is obtained as a function of the difference in the torque of the induction motor and the moment of load resistance.

The consequence of the "rotor hanging" is a significant increase in the temperatures of current-carrying parts due to a relatively long slip time, which corresponds to a high current value of the stator winding. In this case:
Here $t_{hang}$ is the time of “hang”, sec;
$j_1$ is the current density in the stator winding, A/mm$^2$;
$C_{br/r}$ is the specific heat capacity of the bars/rings material, kJ/kg·ºC;
$G_{br/r}$ is the weight of the bars/rings, kg;
$I_*$ is the relative starting currents corresponding to slips (13 values), r.u.;
$U_{\alpha,av}$ is the average value of voltage drop, V;
$k_t$ is the temperature coefficient, r.u.,

The average value of voltage drop and the temperature coefficient:

$U_{\alpha,av} = U_{nat} \cdot \frac{\alpha_1 + \alpha_2}{2}$,

$k_t = 1 + 0.004 \cdot (t_s - 15^\circ)$.

The values of the specific heat capacity of metals used for manufacturing the conductive parts of asynchronous motors are given in Table 2.

| Name of material | Specific heat capacity value, kJ/kg·ºC |
|------------------|--------------------------------------|
| copper           | 0.390                                |
| aluminium        | 0.896                                |
| brass            | 0.377                                |

The incremental heating from the value of critical slip to the nominal value is assumed to be 0.1 ºC.

4. Verification of the obtained method

The incremental heating calculation during self-starting of 4ARMAk-400/6000 UKhL4 type asynchronous motor (the rated power is 400 kW, the rated voltage is 6000 V, the synchronous stator field speed is 3000 rpm) produced by SPA “ELSiB” Inc. showed the operability, usability and accuracy of the obtained method. The received results do not different from the solution achieved by
standard methods for calculating the heating of motor current-carrying parts.

Basic calculation parameters:
- De-energization time: 2 sec;
- Voltage recovery time: 4 sec; [7,8]
- Voltage recovery time discreteness: 1 sec;
- Minimum value of the excess torque: 0.07 r.u.; [7,8]
- \( \alpha_1 / \alpha_2 = 0.6 \div 0.8 \) r.u.;
- \( J_{mot} + J_{mech} = 2 \div 3 \) kg·m².

The remaining parameters and the results are shown in Table 3.

| Slips, r.u. | 1.00 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 | 0.15 | 0.10 | 0.05 | 0.04 |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Relative torque curve (\( T_{rat} = 800 \) N·m), r.u. | 0.65 | 0.69 | 0.73 | 0.78 | 0.83 | 0.90 | 1.00 | 1.10 | 1.30 | 1.50 | 1.80 | 2.20 | 2.30 |
| Load mechanism curve, N·m | 90 | 53 | 32 | 72 | 130 | 200 | 290 | 390 | 510 | 580 | 650 | 720 | 740 |
| Self-starting time, sec | 2.51 | | | | | | | | | | | |
| Stator winding incremental heating, °C | 3.14 | | | | | | | | | | | |
| Bars incremental heating, °C | 5.87 | | | | | | | | | | | |
| Rings incremental heating, °C | 2.59 | | | | | | | | | | | |

5. Conclusion

Unprofessional selection of a pair of elements of the electrical installation “asynchronous motor” – “load” with certain types of load characteristics can lead to unacceptable overheating of current-carrying parts. The article proposes a method for automated calculation of asynchronous motor current-carrying parts incremental heating, the calculation results of which allow us to determine the machine insulation aging level.

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