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RESEARCH INTO INFLUENCE OF A CAPACITOR CONNECTED IN SERIES TO AN ASYNCHRONOUS MOTOR ON THE MOTOR OPERATION

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Abstract: Transmission of electrical energy to the place of consumption is accompanied by its loss, defined by the magnitude of currents that flow through thetransmission line. As the main load is inductive in nature, the currents in the line have reactive components, which provide additional energy losses in the line. For their reduction, a capacitor set is connected in parallel or in series to the consumer. The paper proposes a method and an algorithm of the research into the influence of capacitance value of the series capacitor set on the basic parameters and characteristics of asynchronous motors (AM). Unlike the classical equivalent circuits, the developed algorithm uses a mathematical model of AM in form of nonlinear equations system, which takes into account nonlinear dependences of flux linkage on currents and current displacement in squirrel-cage rotor bars. This allows the highly accurate determination of the electromagnetic parameters of the motor and varying (due to skin effect) resistances of the rotor winding, which significantly affect the occurrence of resonance.

Key words: asynchronous motors, reactive power, series capacitive compensation, static starting performance, saturation, skin effect.

1. Introduction

One of main consumers of reactive power is AM, sensitive to the change of supply voltage. In case of transverse compensation, the capacitor set is connected to the stator winding in parallel, and, therefore, it does not affect the working regime of AM. Meanwhile, the voltage of the motor can rise or fall when the capacitor set is connected in series to AM. This affects the motor's characteristics. So, with some values of capacitance of the series capacitor, AM may not develop the required starting torque or reach the required speed. Another feature of the motor's work with a series capacitor is the possibility of resonance phenomena, accompanied by a number of negative phenomena [2, 3, 5]. In particular, in starting modes of AM, there may occur self-excitation and subharmonic oscillation, which one may explore only through a dynamic mathematical model of the motor in phase coordinates [1]. However, there rises a problem of determining the capacitance value of the series capacitor set enabling AM start at a given motor load, and studying its effect on other indicators. Such tasks can be solved in transformed coordinate system, which significantly simplifies the calculation algorithm and increases its efficiency without loss of calculation accuracy.

The article aims at developing a method and an algorithm of solving the task of research into the influence of a series capacitor on operation of AM and on its characteristics.

2. The mathematical model

As the system of supply voltage is symmetric, it is possible to do research into the effect of capacity value of the series capacitor on the characteristics of AM, without losing accuracy, in the axes *x, y* by considering the supply of the motor via a series capacitor and calculating the static characteristics. The important factors that affect the flow of processes in AM are the magnetic circuit saturation and the phenomenon of current displacement in squirrel-cage rotor bars.

The current displacement in the rotor loops significantly affects the value of the starting electromagnetic torque of AM. To take it into account, the squirrel-cage rotor winding is represented by *n* windings formed by splitting the real bars into *n* elementary bars [4, 6]. The electromagnetic processes in steady mode of AM, which is supplied from a source through the series capacitor of *C* capacitance, are described by the nonlinear system of algebraic equations of the following form in the axes *x, y:*

$$\begin{gathered}
\omega_0 \psi_{sy} - r_s i_{sx} - x_c i_{sy} = -u_{sx}; \\
-\omega_0 \psi_{sx} - r_s i_{sy} + x_c i_{sx} = -u_{sy}; \\
s\omega_0 \psi_{1y} - r_1 i_{1x} = 0; \\
-s\omega_0 \psi_{1x} - r_1 i_{1y} = 0; \qquad (1) \\
\vdots \\
s\omega_0 \psi_{ny} - r_n i_{nx} = 0;
\end{gathered}$$

$$-sw_0 y_{nx} - r_n i_{ny} = 0\,,$$

where $y_k,\ i_k,\ r_k\ (k = sx, sy, jx, jy)\quad (j = 1,\ldots,n)$ are the flux linkages, currents and resistances of the loops; $s = (w_0 - w)/w_0$; w_0, w are the angular frequency of the supply voltage and angular velocity of the rotor; u_{sx}, u_{sy} are the supply voltage components [6]; $x_c = 1/(w_0 C)$.

The electromagnetic torque of AM in the axes *x*, *y* is determined by the formula

$$M_e = 1{,}5 p_0 (y_x i_y - y_y i_x)\,, \tag{2}$$

where p_0 is the number of the pole pairs of AM.

3. The algorithm for analysis of the steady mode

As a result of the nonlinear dependence of the loops flux linkage on the currents, resulting from the magnetic circuit saturation of AM, the system (1) is nonlinear and its solution requires the development of an appropriate algorithm. For its description, we shall represent the system in the form of vector

$$\vec{z}(\vec{y}, \vec{i}, s) = \vec{u}\,, \tag{3}$$

where $\vec{u}$, $\vec{y}$, $\vec{i}$ are the vectors of supply voltage, flux linkage and loops' currents. If the axis *x* coincides with the supply voltage phasor, then $u_{sx} = U_m$, $u_{sy} = 0$, and $\vec{u} = (U_m, 0, 0, \ldots, 0)^*$, where U_m is the amplitude value of the phase voltage (the mark * indicates transposition).

For a given value of the motor slip s, the solution to the system (3) is the current vector $\vec{i}$ that can be determined by the parameter continuation method [6] based on gradual increase of the exciting force from zero to a specified value. For this purpose, we multiply the vector $\vec{u}$ by a scalar parameter e $(0 \le e \le 1)$ and replace the equation (3) by

$$\vec{z}(\vec{y}, \vec{i}, s) = e\vec{u}\,. \tag{4}$$

As a result of differentiation of (4) with respect to *e*, the differential equation (DE) is obtained

$$A\frac{d\vec{i}}{de} = \vec{u} \tag{5}$$

where

$$A = \begin{array}{|c|c|}\hline A_{11} & A_{12} \\ \hline A_{21} & A_{22} \\ \hline\end{array}$$

$$A_{11} = \begin{array}{|c|c|c|c|}\hline x_{sysx} - r_s & x_{sysy} - x_c & x_{sy1x} & x_{sy1y} \\ \hline -x_{sxsx} + x_c & -x_{sysy} - r_s & -x_{sx1x} & -x_{sx1y} \\ \hline sx_{1ysx} & sx_{1ysy} & sx_{1y1x} - r_1 & sx_{1y1y} \\ \hline -sx_{1xsx} & -sx_{1xsy} & -sx_{1x1x} & -sx_{1x1y} - r_1 \\ \hline\end{array}$$

$$A_{12} = \begin{array}{|c|c|c|}\hline \ldots & x_{synx} & x_{syny} \\ \hline \ldots & -x_{sxnx} & -x_{sxny} \\ \hline \ldots & sx_{1ynx} & sx_{1yny} \\ \hline \ldots & -sx_{1xnx} & -sx_{1xny} \\ \hline\end{array}$$

$$A_{21} = \begin{array}{|c|c|c|c|}\hline \vdots & \vdots & \vdots & \vdots \\ \hline sx_{nysx} & sx_{nysy} & sx_{ny1x} & sx_{ny1y} \\ \hline -sx_{nxsx} & -sx_{nxsy} & -sx_{nxsy} & -sx_{nx1y} \\ \hline\end{array}$$

$$A_{22} = \begin{array}{|c|c|c|}\hline \vdots & \vdots & \vdots \\ \hline \ldots & sx_{nynx} - r_n & sx_{nyny} \\ \hline \ldots & -sx_{nxnx} & -sx_{nxny} - r_n \\ \hline\end{array}$$

When integrating the DE system (5) with respect to ε, we obtain (when ε = 1) the value of the current vector $\vec{i}$, that corresponds to the voltage *U* and is refined by the Newton's method. The differential inductive resistances $x = \partial(w_0 y)/\partial i$ are the elements of matrix *A* for corresponding values of AM currents. These resistances are determined by the characteristics of magnetization of the motor magnetic circuit, i.e. by the dependencies $y = y(i)$ of the modules of flux linkage phasors on the current phasors $y = y(i)$ according to [6]. The loops' flux linkages and the electromagnetic torque are determined according to (2) by the known value of the current vector $\vec{i}$ at the given motor slip.

4. The algorithm for characteristics' calculation

By specifying a number of slip values *s*, it is possible to obtain a multi-dimensional static characteristic as a dependence of current vector $\vec{i} = \vec{i}(s)$ on the motor slip that allows us to determine the dependences of other quantities on the motor slip for a given capacitor's capacitance. However, it is not an optimal way, because each time we need start from zero values of coordinates. The differential method for calculating the static characteristics [6] is more effective. For its implementation, the system of algebraic equations

(1) is differentiated with respect to the slip as an independent argument. The result is a DE system of the argument *s*,

$$A'\frac{d\vec{i}}{ds}=\vec{v},$$

where

$$\vec{v}=\left(0,\ldots,0,-\omega_0\psi_{ry},\omega_0\psi_{rx}\right)^*,$$

and the matrix A' differs from the matrix A of equation (5) only by the block A_{11}, which has no x_c elements.

The algorithm for calculating the static characteristics as a slip function consists of two stages. At the first stage, according to Paragraph 3, we determine the values of coordinates when the slip is $s=1$. At the second one, taking the voltages vector as constant, we change the slip from one to the nominal value that makes it possible to ensure the convergence of the iterative process, because the values of the coordinates obtained at the previous stage are usually in the neighbourhood of iterative process convergence point.

To calculate the coordinates' dependences on the capacitor's capacitance, we differentiate system (3) with respect to x_c as an independent argument, assuming the voltage and the slip as constant. The result is

$$A\frac{d\vec{i}}{dx_c}=\vec{c},$$

where $\vec{c}=\left(i_{sy},-i_{sx},0,\ldots,0\right)^*$.

As an example, in Fig. 1 for AM (P = 15 kW, U = 220 V, I = 29.8 A, $\cos\varphi=0{,}87$), which is supplied through a series capacitor from a 220 V source, we present the results of calculating the dependences of the capacitor voltage (1), the motor voltage (2) and the current (3) on the value of the capacitor's capacitance when *s* =1, and in Fig. 3 / when *s =0.021*. As shown in Fig. 2, when the motor slip is *s =1,* we attain the equality of the capacitor voltage and the motor voltage as well as the maximum current of AM at the capacitance close to 2,000 µF, and when the slip is *s =0.021* (Fig. 2), this maximum is reached at *C* = 500 µF.

The curves in Fig. 3 show that the maximum of the AM's electromagnetic torque corresponds to zero value of reactive power in the point of the capacitor's connection.

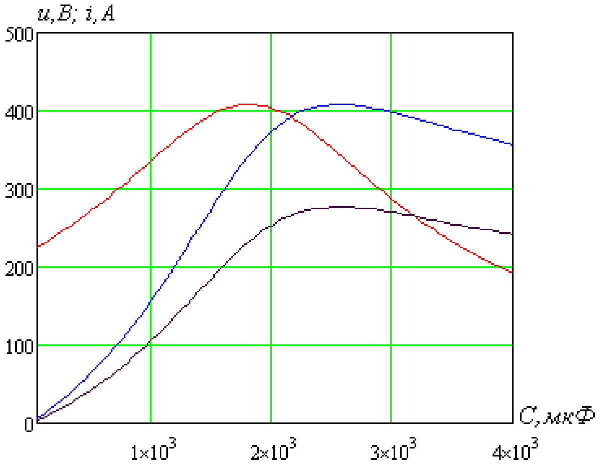

Fig. 1. Dependences of the capacitor voltage (red), the motor voltage (blue), and the current (brown) on the value of the capacitor's capacitance when the slip is s =1.0.

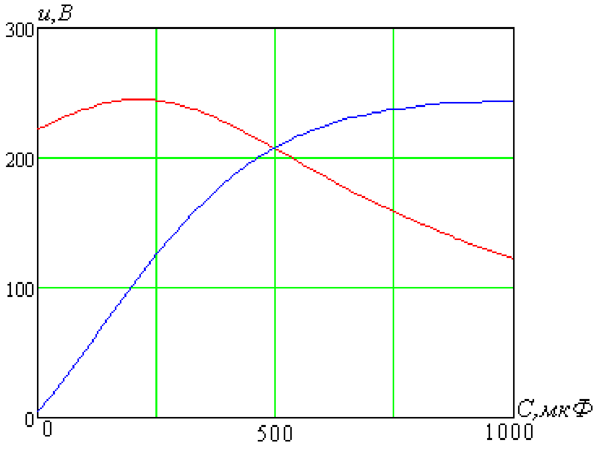

Fig. 2. Dependences of the capacitor voltage (red) and the motor (blue) voltage on the value of the capacitor's capacitance when the slip is s =0.021.

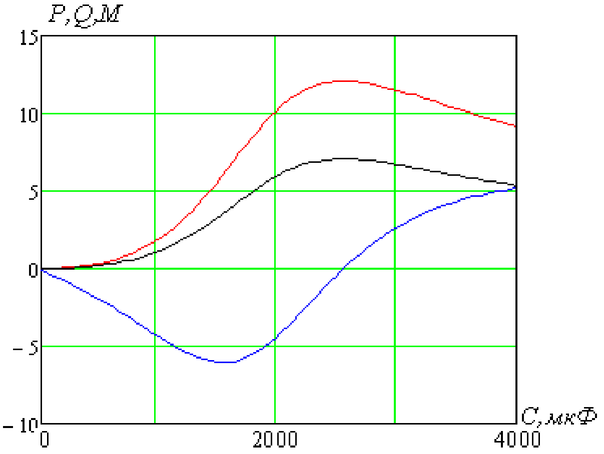

Fig. 3. Dependences of active power (red), reactive power (blue) at the device's input, and the electromagnetic torque (brown) on the value of capacitor's capacitance when the slip is s =1.0.

5. Conclusions

The presented algorithm gives the possibility to calculate steady modes and static characteristics of AM with series capacitive compensation of reactive power. The problem is solved in the orthogonal coordinate axes x, y what provides for simplicity of the algorithm and the minimum possible amount of computations. In the motor's mathematical model the magnetic circuit saturation and current displacement in the rotor bars, which significantly affect its characteristics, are taken into account. The software developed for the above algorithm can be used to estimate the operation options of an AM supplied from an electric network with appropriate reactances and make a reasonable choice of capacitor's capacitance for the series compensation of reactive power in given operation conditions.

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ДОСЛІДЖЕННЯ ВПЛИВУ ПОСЛІДОВНО УВІМКНЕНИХ КОНДЕНСАТОРІВ НА РОБОТУ АСИНХРОННИХ ДВИГУНІВ

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Пересилання електричної енергії до місця споживання супроводжується її втратами, які визначаються величиною струмів, що протікають по лініії. Оскільки основне навантаження має індуктивний характер, то струми в лінії мають реактивну складову, яка створює додаткові втрати електроенергії в лінії. Для їх зменшення використовують конденсаторні установки, які вмикають паралельно або послідовно зі споживачем. У роботі пропонується метод і алгоритм дослідження впливу значення ємності послідовно увімкнених конденсаторів на основні показники та характеристики асинхронних двигунів (АД). На відміну від класичних заступних схем, у розробленому алгоритмі використовується математична модель АД у вигляді нелінійної системи рівнянь, у якій враховуються нелінійні залежності потокозчеплень від струмів та витіснення струму в стержнях короткозамкненого ротора, що дає змогу з високою достовірністю визначати електромагнітні параметри двигуна та змінні внаслідок скін-ефекту активні опори обмотки ротора, які істотно впливають на появу резонансу.

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