Algorithm of the automatic synchronizer operation

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Abstract. When connecting powerful synchronous electric machines (SM) to the power system uses automatic synchronizers with constant lead time. It is necessary to improve their accuracy and performance for the success of synchronization on the technological requirements of production. METHODS. For SM change the angle of the rotor is determined in the three phases of the synchronized voltages. This allows to increase the number of measurements per unit of time. The least-squares method is used for extrapolating the function values at the interval forecast. REZULTS. The proposed algorithm for automatic synchronizer uses to predict the set of values of the functions change the angle of the rotor. This distinguishes it from the known algorithms, where the forecast is based on the three rotor angle values determined over the same time interval. This property improves the accuracy, reduces the time interval determine the forecast considers possible change of the acceleration slip angle of the rotor. Using the least-squares method allows to abandon the traditional derivative calculation of the angle of the rotor, which is associated with increased interference. In addition, this method characteristic filter properties. CONCLUSIONS. The developed algorithm allows to quickly define the time of synchronization and improves the conditions of the SM by keeping dynamic stability.

Keywords: automatic synchronizer, exact synchronization method, least squares method, synchronous motor.

1. Introduction
When powerful SM and power systems are switched on in parallel, it is often critically important to increase the speed and accuracy of the automatic synchronizers (SA) to determine the switching angle [1]. This is especially true when the backup power supply of SM is switched on by the method of precise synchronization in industries with a continuous technological process [2]. Here, an interruption in the work of the SM leads to large economic and environmental losses (metallurgy, petrochemistry, transit of hydrocarbons, treatment facilities, etc.). The current-free pause, admissible under the condition of maintaining the dynamic stability, namely, the rotation of the SM rotor at an angle of 360 degrees, can be 450 - 550 ms and depends on the operating parameters and characteristics of the motors. [3, 4]. Considering the proper switching time of the operating and backup power switches, as well as the time spent on detecting an accident by relay protection, the interval for determining the moment of switching on using the SA can be reduced to three periods of industrial frequency. This raises the requirements for the performance of the extrapolation function of the rotor angle motion. Also, for the success of synchronization and preservation of the dynamic stability of the SM, it is necessary to predict the moment of switching on for the time of operation of the backup power switch. This is explained by the large value of the angular slip frequency during deceleration of the SM rotor and, consequently, by the significant phase difference during synchronization due to an error during switching on.
2. Materials and Methods

2.1. Automatic synchronizers

At present, the production uses SA with a constant lead time: AST-4, SA-1, AS-M1, AS-M2, SPRINT-M [5] and a constant lead angle: UBAS [6]. The latter devices have characteristics that are unacceptable for SM synchronization:

- low accuracy due to the dependence of the lead time value (forecast of the synchronization moment) on the value of the angular slip frequency;
- limited in magnitude lead angle, no more than 180 degrees, and therefore will not be considered further. To predict the movement of the rotor angle in synchronizers, the Fourier series expansion is used [7]:

\[
\delta_{ON} = \delta_{AD} + \omega_s \Delta t_{ON} + \frac{\alpha_s \Delta t_{ON}^2}{2},
\]  

(1)

where:
- \(\delta_{ON}\) - is the angle of inclusion 360 degrees;
- \(\delta_{AD}\) - lead angle;
- \(\omega_s\) - angular slip frequency;
- \(\Delta t_{ON}\) - lead time;
- \(\alpha_s\) - sliding acceleration.

The determination of the values of \(\omega_s\) and \(\alpha_s\) is carried out by calculating the first and second derivatives of the angle of motion of the rotor \(\delta (t)\), respectively. The limitation by three terms of the series in expression (1) is explained by the assumption of uniformly slowed rotation of the rotor of a SM in the process of running. The mechanical moment on the SM shaft can have a fan characteristic, as a result of which the magnitude of the sliding acceleration changes over time, and in equation (1) it is necessary to consider the third derivative, and sometimes the subsequent ones.

However, many synchronizers are limited to the definition of the first derivative and cannot be used for the problem under consideration [8-16].

In analog synchronizers, for example, SA-1, when measuring the value of \(\delta (t)\) with a phase meter, the time interval proportional to the phase difference is converted into a voltage amplitude using a second-order Butterworth low-pass filter (LPF).

At the moment of turning off the accident by the switch of the working power, a sharp change in the phases of the measured voltages may occur. A transient oscillatory process will begin in the analog low-pass filter. It will increase in series connected aperiodic links of the differentiating circuits used to determine the values of \(\omega_s\) and \(\alpha_s\). As a result, the solution of equation (1) will be impossible, and the synchronizer is unusable for a time comparable to the interval of the synchronization process.

In digital synchronizers, for example, SPRINT-M, the time interval proportional to the phase difference is measured twice per period. The values of \(\omega_s\) and \(\alpha_s\) are calculated by the increments of the current values \(\delta (t)\), which is theoretically equivalent to the extrapolation of the function of changing the rotor angle by three values and occupies a fixed interval equal to at least two periods of the power frequency.

However, the increments of the measured values over such a short time interval are small. The implementation of the operation of double differentiation \(\delta (t)\) leads to a sharp deterioration in the signal-to-noise ratio due to the presence of interference and harmonic components of the measured signal.

At the same time, it is not possible to eliminate this disadvantage of the SA, as it is done in analog versions with the help of filtering, in a digital device based on one value of each measured value. This explains the inaccuracy of predicting the time of synchronization of the SA.

To increase the speed and, above all, the reliability of extrapolation, it is proposed to measure the phase difference of synchronized voltages in three phases, which will increase the amount of information received per unit of time three times.

In addition, since the run-out of the SM is monotonically slow and the switching to the backup power is limited to a short time interval, then all the measured values of \(\delta (t)\) recorded in the memory
of the CA are used for extrapolation. Thus, the number of these values can be large, which makes it possible to consider the nature of the load on the SM shaft, other features of the run-out, namely the exchange of electrical power in the run-out process and build an accurate forecast for the lead time.

The extrapolation process itself is carried out using the least squares method, which not only does not increase the amount of noise in the measured signals, as in the known SA, but, on the contrary, reduces their influence on the synchronization accuracy.

2.2. The algorithm of the automatic synchronizer

The operation of the proposed device is based on the representation of the functional dependence \( \delta(t) \) in the form of a regression-type model with respect to the basis vector polynomial in the time factor:

\[
\begin{align*}
\delta(t) & \equiv \delta(b, t) = b^T \cdot \phi^T(t) = b_0 + b_1 \cdot t + b_2 \cdot t^2 + \ldots + b_n \cdot t^n,
\end{align*}
\]

where:

\[
\begin{align*}
b^T &= (b_0, b_1, \ldots, b_n) - \text{vector of independent coefficients of the model;}
\phi^T(t) &= (1, t, \ldots, t^n) - \text{the basis vector of the model;}
T &- \text{the transposition symbol.}
\end{align*}
\]

Finding the numerical values (or estimates) of the coefficients of the vector \( b \) makes it possible to predict the function \( \delta(t) \) for a certain time interval due to the intrinsic time of switching on the switching equipment.

To find estimates of the parameters \( b \) in model (2), the method of least squares (MLS) was used \[17\]. Formally, the MLS estimates \( \hat{b} \) of the parameters \( b \) of the model \( \delta(b, t) \) are in accordance with the dependence:

\[
\hat{b} = (\Phi^T \cdot \Phi)^{-1} \cdot \Phi^T \cdot \delta.
\]

The matrix \( \Phi \) can be represented as:

\[
\Phi = \left( \begin{array}{c} 
\phi^T(t_1) \\
\phi^T(t_2) \\
\vdots \\
\phi^T(t_N) 
\end{array} \right),
\]

where \( t_1, t_2, \ldots, t_N \) – moments of measurements of the angle \( \delta(t) \).

The vector of angle measurements \( \delta(t) \) at times

\[
t_1, t_2, \ldots, t_N, N \geq (n + 1),
\]

\[
\hat{\delta}^T = (\delta(t_1), \delta(t_2), \ldots, \delta(t_N)).
\]

The filtering properties of estimates of the form (3) in the model are known: \( \delta(t) \equiv \delta(\hat{b}, t) \).

In the device under consideration, for \( N > (n + 1) \), they have a positive effect on increasing the accuracy and reliability of the choice of the synchronization time point, which is found from the solution of the equation with respect to \( t_{ON} \):

\[
\hat{\delta}(\hat{b}, t_{ON}) = \delta(t_{ON}).
\]

Matrix \( (\Phi^T \Phi)^{-1} \Phi^T \) is calculated once in advance before the start of operation of the device with a predetermined accuracy. The values of its elements are stored in the ROM of the computing device that implements the operation of this algorithm.

In order to improve the accuracy of estimates \( \hat{b} \) of model (2) and reduce the total time for obtaining the values \( \delta(t) \) in the proposed device, joint measurements of the angles \( \delta(t) \) are made from three phases of voltages of the synchronized running out SMs and the backup power source. In this case, it is assumed that models of the form (2) for each (i-th) phase have the form:
\[
\delta_{(i)}(t) \equiv \delta_{(i)}(b_{(i)}, t) = b_{(i)}^T \phi(t) + c_i = (b_0 + c_i) + b_1 t + \ldots + b_n t^n = \bar{b}_0 + b_1 t + \ldots + b_n t^n,
\]

\[ i = 1, 2, \ldots, 3; \quad c_i = 0; \quad \bar{b}_0 = b_0.\]

By combining the results of measurements of the angle \( \delta (t) \) at times \( t_1, t_2, \ldots, t_N \) (\( N \) is a multiple of 3) from three phases, we find the estimates of the coefficients:

\[
\begin{aligned}
\bar{b}_{(3)}^T &= (\bar{b}_{10}, \bar{b}_{20}, \bar{b}_{30}, b_1, \ldots, b_n).
\end{aligned}
\]

These estimates:

\[
\hat{b}_{(3)} = (\Phi_{(3)}^T \cdot \Phi_{(3)})^{-1} \cdot \Phi_{(3)}^T \cdot \bar{b}_{(3)},
\]

where, in contrast to formula (3), the matrix \( \Phi_{(3)} \) has the form:

\[
\Phi_{(3)} = \begin{pmatrix}
001 & \phi^T(t_1) & 001 & \phi^T(t_2) & 001 & \ldots & 001 & \phi^T(t_{N-2}) & 001 & \phi^T(t_{N-1}) & 001 & \phi^T(t_N)
\end{pmatrix}
\]

- 1st block of matrix \( \Phi_{(3)} \)

\[
\phi^T(t) = (t, t^2, \ldots, t^n).
\]

Then the vector of angle measurements \( \delta (t) \) in three voltage phases:

\[
\delta_{(3)} = (\delta_{11}, \delta_{21}, \delta_{31}, \delta_{12}, \delta_{22}, \delta_{32}, \ldots, \delta_{1l}, \delta_{2l}, \delta_{3l}).
\]

\[N = 3l,\]

where \( \delta (t_i, j) \) – the value of the angle in the \( i \)-th phase in the \( j \)-th block of measurements, at time \( t_p, p = 3 (j -1) + i \).

The algorithm implemented in this device allows, at a fixed time interval allotted to the computing device for finding estimates \( \bar{b}_{(3)} \) by formula (5), to increase the number of measurements \( N \). For this, it is necessary that the interval between measurements:

\[ \Delta t = t_i - t_{i-1} \geq \Delta t_{\text{min}}, \]

where \( \Delta t_{\text{min}} \) – the time interval characterizing the speed of the measurement and computational procedures of the device.

This increases the accuracy of finding estimates \( \bar{b}_{(3)} \), since the variance of the estimate for model (4) for \( i = 1 \) is

\[
D(\tilde{\delta}_{(1)}(\tilde{b}_{(1)}, t)) = \phi^T(t)(\Phi_{(3)}^T \cdot \Phi_{(3)})^{-1} \cdot \phi(t) \frac{\tilde{\sigma}^2}{N - 1},
\]

\[\phi^T(t) = (1, t, \ldots, t^n),\]

where:

- \( \Phi_{(3)} \) – the matrix, which has the form (5);
- \( \tilde{\sigma}^2 \) is an estimate of the variance of the noise component of measurements

\[\tilde{\sigma}^2 i j, i = 1, 2, 3; j = 1, 2, \ldots, l.\]
However, in this case, the material costs for the construction of the measuring system and the amount of memory of the computing device allocated for the storage of the matrix \((F^T (3) \Phi (3))^{-1} FT (3)\) increase. Matrix elements are calculated in advance with a predetermined accuracy.

The moment when the signal is applied for synchronization is determined by solving the equation:

\[
\delta(t) \tilde{\nu}(1,t) = \delta(t_{ON}).
\]

2.3. Full-scale tests of the synchronizer.

The purpose of the tests was to determine the possibility of switching on the backup power supply of SM by the method of precise synchronization. And also, a comparison of several synchronizer algorithms in terms of speed and accuracy. The experiments were carried out at the «Bashneft-UNPZ» plant, Ufa.

In figure 1 shows a simplified diagram of the experiment. It contains a 10 kV network, operating power switches Q1, Q2 (disconnection time 100 ms), backup power switch QB (turn-on time 220 ms), SM-M1, M2. The tests involved STD-6300 engines with a power of 6.3 MW; LF = 0.95; PF = 1.

![Simplified diagram of the STD-6300 motor synchronization.](image)

Symbols in Figure 1: W1, W2 - supply-lines voltage; Q1, Q2, Q3, Q4, QB - switches; M1, M2 - STD-6300 engines.

The test results are shown in Figures 2 – 6. To simulate the emergency mode, the power line W1 of the working power source of the motor M1 was turned off (time \(t_0\)). The relay protection detected the loss of power, opened the Q1 switch, made it possible for the synchronizer to work and switch the QB switch. The synchronizer predicted the time \(t_1\) and generated the switch control signal QB with a lead time of 220 ms. This switch was turned on when the phases of the synchronized voltages were equal (Figure 2). Synchronization was successful.

![Registration of voltage between the stator of the motor STD-6300 and the backup power supply.](image)

Figure 2. Registration of voltage between the stator of the motor STD-6300 and the backup power supply: T - time interval, s; \(\Delta U\) - voltage difference, kV; \(U_{PV}\) - primary voltage M1, kV; \(U_{BPS}\) - voltage power backup, kV.
The synchronizer recorded the nonlinear nature of the change in the rotor angle of the motor M1 (Figure 3). The no current pause was about 450 ms. Considering the time interval that turns on the action of the relay protection and switches Q1, QB, 60 ms is left for the synchronizer to work. Therefore, the rotor angle values were measured between the three phases of the stator voltage of the motor and the backup power supply.

![Figure 3](image)

**Figure 3.** Registration of changes in the rotor angle of the STD-6300 engine: T – time interval, s; δ – the STD-6300 rotor angle.

When the backup power was turned on, the STD-6300 rotor rocked without turning it (Figure 4). The engine retained its dynamic stability. The transient process lasted approximately 820 ms.

![Figure 4](image)

**Figure 4.** Registration of the active power of the STD-6300 engine: T – time interval, s; P_M – active power consumed by STD-6300 motor in normal mode, MW; P(δ) is the active power consumed by the STD-6300 motor in the transient process, MW.

Since the synchronization error in the switching angle is insignificant, there was no equalizing current (Figure 5). The increase in current during the rotor swing of the motor did not lead to a false operation of the relay protection.

![Figure 5](image)

**Figure 5.** Recording of the common-mode synchronization of the STD-6300 synchronous motor: T – time interval, s; I_SC – stator current of STD-6300 motor, A.
When the STD-6300 runs out, there was a residual voltage on its stator (Figure 6). This ensured the possibility of operation of consumers whose power source was the power line W1 (Figure 1) and, therefore, the continuity of the technological process. The voltage drop during synchronization was negligible. Therefore, the M1 and M2 engines remained stable.

The synchronizer has also been tested for STD-12500, STD-3150, STD-1600, STM-1500, DSP-116 motors.

![Figure 6. Recording the voltage on the stator of the STD-6300 motor: T – time interval, s; U_{PV} – primary voltage, kV.](image)

3. Results
An algorithm for the operation of an automatic synchronizer to turn on the backup power supply of the SM has been developed. He has the necessary characteristics to solve this problem. Namely: high speed due to the lack of time for making a decision and high accuracy, since synchronization takes place at a large slip value.

Such characteristics are obtained by increasing the number of measurements of the value of the rotor angle of the SM in a unit of time. This reduces the time interval for extrapolation and allows one to take into account the nonlinearity of changes in the mechanical moments on the motor shaft. In addition, the used mathematical apparatus reduces the influence of measurement errors.

4. Conclusion
The accuracy of the trajectory extrapolation \( \delta(t) \) mainly depends on the type of this function and the characteristics of the measuring means of the device under consideration. To predict the values of \( \delta(t) \), the angles between the vectors of the same phases of synchronized voltages are measured. This makes it possible to increase the number of measurements per unit of time and ensure high performance of the proposed automatic synchronizer.

In addition to the field tests presented in the article, experiments were also carried out for various sets of loads. They showed that a group of SMs of different power during synchronization can be considered as an equivalent SM. For this mode, the proposed synchronizer can also be used.

In addition, due to the high voltage on the SM stator (Figure 6), the asynchronous load is switched to a backup source, receiving power from a SM operating in the generation mode. This load includes asynchronous motors, 0.4 kV busbars (own needs), etc. This allows you to maintain the SM in operation, as well as ensure the continuity of the technological process.

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