Technical and economic aspects of the use of soft starters for asynchronous electric drives

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Abstract. The paper presents data on the results of computer-aided mathematical modeling and experimental studies of transient processes accompanying the start of asynchronous electric drives in order to search for the methods that enable the adjustment of a soft starter to achieve minimum oscillation amplitude of the electric motor dynamic momentum in terms of the current characteristic. The indicators of smoothness, applicable to some types of electric drives of turbine mechanisms, are revealed. It is found that the correlation between the maximum value of the starting current of the electric motor and the maximum amplitude of the momentum fluctuation, as well as between the starting time and the maximum amplitude of the momentum fluctuation, is insignificant. The most informative indicator, providing the function of adaptive self-tuning of the soft starter and maximum technical and economic efficiency of its use, is the oscillation of the dynamic momentum during the start-up. It is established that the amplitude of the dynamic momentum fluctuation can be judged by the displacement of the motor housing during start-up, which will require the modernization of the electric drive. The necessity of additionally calculating the implicit components of costs in terms of the costs of entrepreneurial risk when assessing the economic effect from the modernization of asynchronous electric drives using a soft starter is substantiated.

1. Introduction
For asynchronous drives that do not require speed control, soft starters can be used. The use of such devices allows increasing the "smoothness" of the start, i.e. to achieve a significant decrease in the oscillation of the electrodynamic momentum of an induction machine due to a gradual increase in the voltage applied to the stator windings from the initial value \( U_0 \) to its nominal value over some time, characterized by a time constant \( \tau \) [1, 2, 5]. The nature of the transient process of an asynchronous electric drive with a soft starter significantly depends both on the law of voltage variation on the stator winding, set using the tuning parameters \( U_0 \) and \( \tau \), and on the type of working machine and the specific characteristics of the electric drive [6].

As a rule, manufacturers of soft starters give general recommendations for their adjustment, which roughly allow determining the rational law of voltage variation applied to the stator windings. As our research shows, the optimal adjustment of a soft starter for a particular electric drive is not an easy task, especially in production conditions, while incorrect adjustment can reduce the efficiency of the device and even, in some cases, lead to a reduction in the service life of the electric motor [6]. Thus, making a decision on the use of soft starters requires consideration of such innovative aspects as the expected technical and economic effect, which are directly related to the dynamic characteristics of the system "Soft starter - asynchronous motor - working machine" obtained as a result of using the soft starter. The guaranteed achievement of high efficiency of additional capital costs for a soft starter
requires solving the problem of automating its adjustment. Formalization of the process of adjusting the soft starter can be achieved using scientifically grounded "smoothness indicators", which is a function of the goal in the problem of parametric optimization for $U_0$ and $\tau$ [6].

This paper studies the influence of the law of the voltage change on the stator windings on the dynamic properties of an asynchronous electric drive using the example of various turbine mechanisms, and searches for the "smoothness indicators" expressed through the current starting characteristics.

Also, the economic aspects of the use of soft starters using the category of implicit costs are considered.

2. Materials and methods
An asynchronous electric drive of a turbine mechanism with a soft start device was adopted as the object of research, and the subject of research is its dynamic characteristics depending on the law of voltage change on the stator winding: current, acceleration and characteristics of the electrodynamic momentum of the electric motor in their relationship with the technical and economic indicators of the efficiency of the electric drive.

The research used methods of computer-aided mathematical modeling, a physical experiment and statistical processing of the experimental data. The calculations used the methods and software of structural modeling in the MATLAB-Simulink environment, simulation modeling, numerical methods of differentiation, regression and correlation analysis in the Statistica program, filtering and visualization of experimental data in Microsoft Excel spreadsheet, calculations of the economic efficiency of modernization of asynchronous electric drives using soft starters based on the methods of estimating opportunity costs.

Physical modeling was carried out on a specially created experimental setup, including: asynchronous electric drive of the turbine mechanism (blower); sensors for stator current, rotor angular speed and electrodynamic moment of the electric motor; a measuring system based on a personal computer and a multifunctional board for inputting signals from the ADC. Also, a special software developed by the Advantech company was used.

Based on the theoretical assumptions, the main result of the research should be the substantiation of the "smoothness indicators" of the starting process of the "Soft starter - asynchronous motor - working machine" system, allowing simplifying and formalizing the adjustment of the soft starter to achieve maximum efficiency of its use.

3. Indicators of the smoothness of the starting process of the system "Soft starter - asynchronous electric motor - working machine"
For a comparative assessment of the transient characteristics of the soft start process of an asynchronous electric drive with a soft starter, single and complex smoothness indicators can be used. Single indicators are determined by individual characteristics, and complex indicators include two or more single indicators, determined by different transient characteristics. Since the transient process of an asynchronous electric drive is described by the current, acceleration characteristics and the characteristic of the electrodynamic momentum of the electric motor, it is possible to use, respectively, energy, acceleration and mechanical indicators.

Energy indicators include the multiplicity of the maximum instantaneous value of the inrush current $I_{\text{max}}$ and the multiplicity of the integral of the square of the inrush current $I$ over the start time $T_s = \int_0^{T_s} I^2 dt$—where $t$ is time. Obviously, the integral of the square of the starting current during the start-up characterizes the energy losses, which are expressed in the heating of the electric motor and electrodynamic effects on the winding, leading to its aging.

The accelerating smoothness indicators include the starting time $T_s$ and the acceleration of the angular velocity. These indicators can be important when setting up electric drives, for which the speed of revolution rate change plays an important role, for example, pumps from the perspective of water hammers or electric drives of mechatronic systems.

The characteristics of the electrodynamic momentum include, first of all, the maximum amplitude of oscillation of the dynamic momentum of the electric motor during the start-up time $\Delta \mu$. This is the
most important characteristic that soft starters are used to minimize. If the energy and acceleration unit smoothness indices can be relatively easily calculated from the transient characteristic of the current, then the determination of $\Delta \mu$ requires the use of a momentum sensor. The direct measurement of the dynamic torque on the motor shaft is not a simple technical task. It is of interest to identify such smoothness indicators, which, based on the current characteristic, make it possible with a sufficient degree of accuracy to determine the rational tuning parameters of the soft starter in order to achieve the minimum oscillation of the momentum. Complex smoothness indicators should have the following requirements:

- calculated according to the current characteristic as the simplest one from the point of view of practical definition (current sensors are embedded into many soft starters);
- have a high degree of correlation with the amplitude of the oscillation of the dynamic momentum of the electric motor during the start-up $\Delta \mu$;
- have one extremum, which will allow automatically solving the parametric optimization problem with respect to $U_0$ and $\tau$.

MATLAB and its component Simulink [3, 4] have ample possibilities for calculating transient processes of asynchronous electric drives. With the help of mathematical modeling of the system "Soft starter - asynchronous electric motor - working machine" in MATLAB-Simulink, calculations were made for various turbine mechanisms: pumps, fans and crushers. Simulink standard blocks and MATLAB scripts were used.

As a result of calculations, it was revealed that for some electric drives the current characteristic can be used to determine such adjustment parameters of the soft starter, which will significantly reduce the amplitude of the oscillation of the dynamic moment $\Delta \mu$ of the electric motor with minimal energy losses. However, such properties of electric drives as reduced moment of inertia $J$, parameters of an asynchronous electric motor, and mechanical characteristics of a working machine significantly affect the dynamic properties of an electric drive with a soft starter.

![Figure 1](image)

**Figure 1.** The response surface of the complex smoothness index $I_{max} \int_0^{T_s} I^2 dt$ depending on the tuning parameters of the soft starter (a) and the characteristic of the electrodynamic moment of the electric motor at optimal settings.

For low-inertia electric drives, such as submersible electric pump units, the above requirements are met by the smoothness index $I_{max} \int_0^{T_s} I^2 dt$. Obviously from Figure 1, the dependence of such an indicator on the tuning parameters of the soft starter (the initial opening angle of thyristors $\alpha_s$, and the voltage rise time constant $\tau$) has one extremum. The oscillation of the dynamic moment at the end of the start is due to the fact that the mechanical characteristic of the pump has an increased starting moment due to the effect of adhesion of the heel to the thrust bearing, the start must be carried out at a higher initial voltage to overcome the starting moment, and the reduced momentum of inertia is less than for conventional pumps. In this case, the start-up time is increased, which avoids water hammer in the pipeline.

Shredders for fodder (dry and succulent) also belong to turbo mechanisms with an increased starting momentum comparable to the nominal momentum of the electric motor. In addition, shredders
have a significantly reduced momentum of inertia $J$. For such mechanisms, the oscillation of the transition moment is of great importance, since the working machine has clearances in the gearboxes and transmissions. Direct starting of such mechanisms is subject to shock and significant wear. As our calculations have shown, using only the data of the current characteristic, it is not possible to determine the tuning parameters of the soft starter. However, the dependence of the complex indicator $\Delta \mu \cdot T_s$ on the tuning parameters of the soft starter has one extremum. Obviously, such an objective function allows calculating the optimal tuning parameters of soft starters according to the known characteristics of electric drives to achieve high performance and is difficult to implement, since requires a momentum sensor. Figure 2 shows the transient characteristics of the electric motor momentum at direct (a) and optimal (b) starts of the "Volgar-5" grinder in terms of $\Delta \mu \cdot T_s$ indicator.

![Figure 2](image)

Figure 2. Transient characteristics of the torque of the electric motor of the "Volgar-5" grinder: a) with direct start; b) at a soft start with optimal settings of the soft starter in terms of $\Delta \mu \cdot T_s$ indicator.

For electric drives of pumps and blowers with different powers of electric motors, it was found that the initial voltage at which the rotor of the electric motor begins to move is different and depends on the parameters of the equivalent circuit of a particular electric motor, while no significant dependence on the reduced moment of inertia of the electric drive was revealed. The voltage rise time that provides the minimum amplitude of the torque fluctuation depends on the electric motor and the reduced moment of inertia of the system. For such electric drives, the extremum has a smoothness index of the form $I_{max} \cdot \left| \int_0^{T_s} t^2 \, dt - \int_0^{T_{so}} t^2 \, dt \right|$, where $T_{so}$ is the direct start time. This indicator makes it possible to achieve such a decrease in the amplitude of the oscillation of the dynamic momentum, at which the electrical energy losses during the soft start will not exceed the losses for direct start. However, the degree of decrease in $\Delta \mu$ is not high and reaches only 1.1-1.2 times.

Thus, by means of mathematical modeling, we were unable to identify a universal complex smoothness index for all types of turbo mechanisms, which allows adjusting the soft starter to the minimum amplitude of the dynamic momentum fluctuation in terms of the current characteristic.

For experimental studies of the processes of direct and soft start-up of an asynchronous electric drive of a turbo mechanism, we used a setup, the structural diagram of which is shown in Figure 3. In these experimental studies, it is not the absolute value of the momentum that is of interest, but the degree of influence of the tuning parameters on its oscillation, therefore, a rotating platform on a bearing support, and the magnitude of the moment is judged by the deformation of the metal plate fixed at one end. A BF350-3AA strain gage is glued to the plate, which is an integral part of the circuit for converting the amount of strain into voltage using a special amplifier.
Current sensors based on a shunt resistor and a transformer, angular velocity and momentum are connected to the switching board, and through it to the multifunctional PCI-1711LS Advantech I/O board installed in a PC slot. The board contains an instrumental analog-to-digital converter and a FiFo buffer, which allows capturing the characteristics at a frequency of 1000 Hz. To record and process the captured data, the Data Logger utility developed by Advantech is used, which enables the primary analysis of graphs and saving the data to a text file.

In the experiments, an exponential voltage rise law was used, in which the time constant $\tau$ was set by changing the capacitance of the capacitor $C_\tau$. The experimental transient characteristics required further processing to reduce the "noise" level. Such processing was carried out in MS Excel by using an approximation. The characteristics of the smoothest starting transient that have been achieved are shown in Figure 4. The sensors have not been calibrated, so the values input into the A/D converter in volts are shown. With optimal settings of the soft starter, it is possible to reduce the amplitude of the fluctuation of the transient torque by 70 times during soft start in relation to direct start.

![Figure 3. Block diagram of the experimental setup](image)

**Figure 3.** Block diagram of the experimental setup

**Figure 4.** Experimental transient characteristics of soft start: a) current; b) dynamic momentum of the electric motor

Figure 5 shows the experimental dependences of the ratio of the momentum oscillation at soft start $\Delta \mu_0$ to the torque oscillation at soft start $\Delta \mu_s$ on the capacitance value of the capacitor $C_\tau$ of the circuit that forms the voltage rise law and the initial voltage $U_0$. It is characteristic that when the initial voltage is set, which ensures the equality of the starting momentum of the engine and the initial
moment of resistance of the working machine, with an increase in the time constant \( \tau \) at the beginning, the oscillation of the torque decreases and then, it does not change. The capacitance of the capacitor, within the values of the capacitor values corresponding to the linear section of the dependence Figure 5a (more than 16 \( \mu F \)), does not significantly affect the dependence of the momentum oscillation on the initial voltage.

\[
\Delta \mu / \Delta \mu_0 = C \tau, \ \mu F
\]

\[
U_0, \ V
\]

**Figure 5.** Dependences of the oscillation of the momentum on the capacitance of the capacitor of the circuit, which forms the law of voltage rise (a) and the initial voltage (b)

The correlation analysis of experimental data [7] showed that the relationship between the maximum value of the starting current of the electric motor and the maximum amplitude of the momentum oscillation is straight line with a correlation coefficient of 0.797 and a coefficient of determination of 0.629. The correlation between the start time and the maximum amplitude of the momentum fluctuation is inverse and strong enough for the linear section of the dependence in Figure 5a (more than 16 \( \mu F \)): the correlation coefficient varies from -0.88 to -0.99, the determination coefficient is 0.8..0.99 for different capacitances of the capacitor of the circuit that forms the law of voltage rise. However, for the entire set of experimental data with capacitances from 0.5 \( \mu F \) to 58 \( \mu F \), the correlation coefficient is 0.69 with the coefficient of determination of 0.46.

4. **Economic aspects of the use of soft starters**

Despite a significant progress in the creation of soft starters for asynchronous electric drives and the history of their successful application over several decades, the introduction of innovative developments in agricultural production is hindered by a number of factors. Among the latter, the economic efficiency of investing in modern types of equipment occupies a special place, which, from the point of view of many leaders of agricultural organizations, is not high enough. In our opinion, in most cases this is due to the use of outdated methods for calculating indicators that do not correspond to the characteristics of the market economy.

Feasibility studies of the modernization of existing production facilities using new types of equipment are usually based on the method of comparing the indicators of net profit and, accordingly, economic efficiency, in the conditions of operation of existing and innovative equipment. Profit is determined on the basis of the accounting approach by reducing the amount of income derived from the use of the relevant technical means by the amount of expenses incurred during the use of the same means. Only the explicit costs recorded in the relevant accounting registers are included in the calculation. Meanwhile, the peculiarities of entrepreneurial activity in a market economy determine the existence not only of explicit but also of implicit costs, which together form the economic costs of production [8]. According to the theory of market relations, the implicit component of costs includes normal profit (entrepreneurial income), interest on equity and rents. Studies have shown that the existing cost accounting system in Russian agricultural organizations does not affect imputed costs, as a result of which management decisions taken are based on information about the actual (accounting) cost [9, 10]. The financial and economic valuation of investment projects from the totality of implicit costs only partially takes into account interest on equity. It is essentially included in the calculation of efficiency factors and net discounted value, which are determined by the level of profitability of the
invested funds when they are alternatively placed in publicly available financial assets, and not used in this investment project. We believe that the calculation should take into account the implicit costs of business risk. In the context of soft starters, such costs will include a cost assessment of the risk of production accidents associated with the incorrect configuration of the smooth start device. Due to their implicit nature, these costs are determined at the level of average losses from risks, as a rule, over a five-year period.

As an example, let us consider the replacement of the contactor control system for the electric drive of a milk tank agitator, made according to the traditional scheme, with an innovative development involving the use of a soft starter with adaptive self-tuning. This upgrade requires additional costs due to the higher cost of the equipment. During the operation of the new facility, this will manifest itself in an increase in the amount of accrued depreciation, as well as the percentage of capital. However, the use of soft starters with self-tuning is guaranteed to increase the service life of electric drives, as well as technological installations in which they are used [6]. In addition, the innovative self-tuning function can significantly reduce the cost of commissioning the soft starter. Traditional methods of calculating economic efficiency determine the advantages of modernization in the form of improving the reliability of technological equipment and, as a result, reducing the costs of repair and maintenance of equipment, as well as reducing losses from failure of the electric drive, that is, a clear component of production costs. The savings in implicit costs in the form of risk costs should be added to the resulting economic impact. For example, in the considered example with a milk tank agitator, due to a break for the restoration of the electric drive, it is possible to disrupt the supply of finished products to the consumer. In animal husbandry, water-lifting equipment accidents cause both additional costs associated with replacing the electric drive and losses from interruptions in water supply. The latter are manifested not only by obvious costs in the form of costs for alternative water supply methods during repair (supply of water by vehicles and others), but also implicit ones, which may be included, for example, penalties from buyers for violation of the terms, volumes, quality of products sold, up to the termination of supply contracts. Consequently, the total effect from the introduction of new equipment will be higher.

Thus, the use of the category of implicit costs allows for a more accurately and objective assessment of the effect of the introduction of new equipment, which is necessary for making competent management decisions.

5. Conclusion

As a result of the studies carried out, the need to adjust the soft starter to a specific electric drive was confirmed to achieve the maximum possible technical and economic effect from its use. Research in the field of identifying methods and methods for the automated adjustment of soft starters to the minimum oscillation of the dynamic momentum during start-up is promising.

The mathematical modeling allowed identifying the smoothness indicators, which can be used to optimize the search for an extremum in the self-tuning algorithm, which in turn allows, using the current characteristic, adjusting the soft starter to the minimum oscillation of the dynamic moment. However, these indicators are suitable only for certain types of electric drives and have narrow limits of applicability.

It was experimentally established that the correlation between the maximum value of the starting current of the electric motor and the amplitude of the momentum oscillation is insignificant. The correlation between the starting time and the amplitude of the momentum oscillation is inverse and strong enough for the values of the voltage rise time constants on the stator windings corresponding to the minimum oscillation of the dynamic momentum. However, for the entire set of experimental data, the correlation is insignificant. Thus, using the maximum starting current and starting transient time to tune to minimum oscillation cannot be used in practice.

The most informative indicator that allows making adjustments and ensuring the maximum efficiency of using a soft starter is the oscillation of the dynamic momentum during start-up. We have found that the magnitude of the amplitude of the dynamic momentum fluctuation can be judged by the displacement of the electric motor housing during start-up, which will require the modernization of the electric drive.
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