Modelling of soft starters for automated electric drive

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Abstract. In this paper we investigated the conditions of favorable start-up of fixed-speed induction motors in order to increase the functional reliability of the engines. The methods of controlled soft start of induction electric motors with a squirrel-cage rotors are investigated. The study of the mathematical model of induction motors for determining the dependencies of reducing the dynamic component of the transient electromagnetic moment and the magnitude of the starting current. A computer simulation to identify the effectiveness of different methods of controlled start-up of induction motor was carried out. To generate the starters’ models, the MatLab modelling application, Simulink and SimPowerSystems block libraries were used. Based on the results of transient processes simulation in MatLab, the comparative characteristics for different methods of starting an induction motor were given.

1. Introduction
Mode of operation of industrial plants is characterized by a continuous change in the load on the Executive bodies, frequent processes of starting and braking drives. Alternating electromagnetic transients developed during the start-up process lead to induction motor (IM) increase in the level of dynamic loading of the electric drive and cause shocks and deformations in the transmission elements, increased wear and breakage, which leads to a decrease in reliability and service life.

The main reason for accelerated wear and damage to the insulation of the stator winding of electric motors is the transients that occur during the start-up of IM.

The use of an automated electric drive allows for smooth and wide speed control of the Executive body, thereby ensuring optimal technological modes [1]. The use of an adjustable electric drive makes it possible to simplify kinematic connections, i.e. to achieve greater accuracy from the mechanism. In parallel with this, the automation of the technological process and improving the reliability of the operated machines and mechanisms are carried out. Therefore, the most important task of the theory and practice of modern automated electric drive is the study and creation of effective controlled electric drives [2].

2. Problem Definition
The problem of smooth start of the electric drive of induction motors with squirrel-cage rotor is essential to improve the operational reliability of unregulated induction electric drives of industrial plants.

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Soft start of the electric motor prevents the voltage drop in the network and significantly reduces the possibility of mechanical damage to the moving parts of the equipment. Soft starters extend the life of industrial plants, improve equipment reliability and reduce production costs [3].

The study of the conditions for the formation of a favorable start of unregulated induction electric drives by modeling various methods of soft start, is designed to improve the functional reliability of the drives.

The main direction of the work is the use of analytical studies, mathematical models of electrical systems of industrial plants, their individual components and computer modeling to identify the effectiveness of various methods of controlled start-up of IM.

In the process of research there were tasks:
- Analysis of existing methods of controlled start induction electric drive;
- Selection and study of the mathematical model of BP to determine the dependencies aimed at reducing the dynamic component of the transient electromagnetic moment and the magnitude of the starting current;
- Carrying out simulation in MatLab transients at various ways of start-up IM.

3. Solutions

From the theory it is known that at direct start the current consumed by IM from a network exceeds a nominal current in 5 ÷ 10 times. In order to eliminate the starting current surges, jumps and moment fluctuations, to ensure a smooth shock-free acceleration of the operating mechanism, frequency converters are used [4].

However, in cases where speed control of the operating mechanism is not required, the use of frequency converters is not economically feasible. At the same time, the most simple solutions to mitigate the conditions of start-up are:

1) Start with switching the motor windings from the scheme "star" to the scheme "Triangle" (discrete voltage amplitude control);
2) The inclusion of resistors in the stator circuit at start-up;
3) The use of soft starter (smooth adjustment of the voltage amplitude).

There are several ways to implement a smooth start of IM, one of which is to start a task with non-zero initial electromagnetic conditions [5].

Electromagnetic transients occur when the magnetic state of an asynchronous machine changes, associated with both switching its circuits and with a sharp change in speed. Any change in the magnetic state of the machine causes the appearance of an aperiodic free component of the magnetic flux, the value of which determines the initial value of the electromagnetic transition moment.

At zero initial conditions (if there is no magnetic flux at the moment of switching), depending on the mutual spatial orientation of the magnetic fluxes of the machine, the rate of flow change can vary significantly. With a rapid change in the speed of the IM in its rotor, an EMF is induced, associated with a change in the rotor currents and the greater the change. Induced EMF tends to prevent the change of currents. As a result, there is a mismatch between the actual value of the rotor currents and the value that should be at a given slip. Steady-state mode is achieved only after several oscillations around the equilibrium point when the transient currents are damped [6].

To suppress the free component, it is necessary to ensure the equality of the mutual spatial orientation of the flux vectors of the stator and the resulting stator voltage vector with the position they take after switching on the IM at a given rotor speed. The condition of the minimum increment of the magnetic flux and the most favorable flow of the transition process is determined by the equality:

\[ \vec{\Psi}_s(0) = -\frac{j\vec{u}_s(0)}{2} ; \]

The initial flow coupling \( \vec{\Psi}_s(0) \) can be created by a current of one or more phases. In this case, its position in space depends on the direction of these currents. The resulting voltage vector of the three-phase systems \( \vec{u}_s \), which determines \( \vec{\Psi}_s(0) \) the direction is expressed in terms of the instantaneous
values of the phase stresses and coincides with their maxima. Therefore, if the vector $\vec{\Psi}_s(0)$ is perpendicular to any of the windings, the IM connection should occur at the maximum voltage of this phase [7].

The practical implementation of this method is as follows: first, two phases are included on the line voltage, and the inclusion of the third phase in any of the maxima of its voltage [8-9]. To eliminate the aperiodic component of the magnetization current at the first connection of two phases, it should be carried out only at the maximum of the linear voltage of these phases.

4. Experiment

As the object of study was chosen induction motor with squirrel cage rotor power $P=4000$ W, nominal rotor speed $n=1430$ rpm, the effective value of the line voltage $U_l=400$ V and the frequency of the supply network $f=50$ Hz.

In the course of the work, the following methods of soft start of IM were simulated:
- Direct start;
- Start with a limit of rise of the applied voltage;
- Start with the formation of non-zero initial electromagnetic conditions;
- Start setting of the current limit;
- Quasi-frequency start-up control.

In the program of computer simulation of electrical devices MatLab SimuLink for each method was built a model of Electromechanical system of soft starter 3-phase induction motor with squirrel-cage rotor and investigated the characteristics of the motor in the start mode [10].

Models from the MatLab component library - SimScape / SimPowerSystems / Specialized Technology / Machine were used [11].

According to the results of the analysis of the models, two most promising soft-start devices were identified: "start with the formation of non-zero initial electromagnetic conditions" and "quasi-frequency start control".

It should be noted at once that the mathematical model of the device "start with the formation of non-zero initial electromagnetic conditions" takes into account the features of the study of asymmetric modes of operation of IM [12]. The result is a SimuLink model of BP, which takes into account most of the factors that determine the state of the Electromechanical system of this object.

A: The result of a computer experiment "start with the formation of initial non-zero electromagnetic conditions" (Figure 1).

Figure 1. Model of soft starter with formation of initial non-zero electromagnetic conditions
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Blocks Ideal Switch Ideal Switch1, Switch2 Ideal play the role of keys, switching, respectively, the phase A, b, C in the required time for the formation of the initial non-zero electromagnetic conditions. The setting action is applied to the control inputs of the Ideal Switch, Ideal Switch1, Ideal Switch2 blocks using Step1 (phases a and B) and Step2 (phase C).

The moments of switching time of the keys is determined empirically and is \( t_{A,B} = 0.0032 \) s, \( t_c = 0.008 \) s.

According to the simulation results, the dependences on the time of the rotor speed (Figure 2), the electromagnetic moment (Figure 3) and the effective current value are obtained (Figure 4). It can be concluded that this method of starting allows you to limit the amplitude of the electromagnetic momentum to the level \( M = 83 \) N m and its alternating component without losing system performance. However, the starting current level remains at the same level.

![Figure 2. Rotor speed](image1)

![Figure 3. Electromagnetic moment](image2)
This method of start-up control is used in cases where the moment of resistance forces is significantly higher than the moment developed by the drive at the short-circuit current [13]. For example, devices operating on the basis of the quasi-frequency principle are used in the mining industry, in particular for the start of heavily loaded scraper conveyors.

Quasi-frequency start mode provides the drive with a steady reduced rotor speed. This makes it possible to realize the stepwise nature of the change in the drive speed during start-up. Acceleration to the nominal speed of rotation of the rotor IM is carried out by discretely changing the frequency of the supply voltage from low to nominal.

Due to the switching of thyristor groups according to the law, which provides a change from the reduced frequency of the \( f_m \) network to the nominal \( f_c \) while maintaining the signal amplitude, a quasi-sinusoidal voltage is formed [14].

The schematic diagram of the implementation of this method of starting the engine is shown in Fig.5. The Subsystem block is three pairs of thyristors, included counter-parallel, with which the supply voltage to the stator winding of the engine to form a quasi-sinusoidal voltage of the required frequency.

**Figure 4.** Stator current

**Figure 5.** Robot control software interface
Control actions applied to the information inputs of thyristors are formed in the Subsystem3 block, which is a subsystem consisting of multiport Switch switching blocks and subsystem subsystems, where, in fact, enclosed pulse generators Pulse Generator. The control inputs of the Multiport Switch are, given signals at set intervals, which determine the moments of change in the frequency of the quasi-sinusoidal voltage. Each pulse Generator is responsible for a certain thyristor in one of the intervals of the constant frequency, and their dispersion in subsystems is determined by the value of this frequency [15].

As a result, of modeling the rotor speed dependences were, obtained (Fig. 6), electromagnetic moment (Fig. 7) and the current value of the stator current (Fig. 8) from time to time. Analyzing the data obtained, it can be concluded that while maintaining the value of the stator current at the same level (compared to direct start), an increase in the electromagnetic moment developed by the engine was achieved by 10 times.

![Figure 6. Rotor speed](image)

![Figure 7. Electromagnetic moment](image)
5. Conclusion
It is revealed that the soft start device limits the starting current and torque, which can reach critical values when the drive is started. The limitation of these parameters is carried out due to a smooth increase in the voltage applied to the windings of the induction motor at a specified time interval. One of the main tasks of the soft start device is to reduce the peak loads on the electrical network and drive mechanisms at the time of acceleration and deceleration of the electric motor.

The best of the considered methods for controlling the start-up of IM, aimed at limiting the alternating component of the electromagnetic moment without reducing the speed of the drive, is a phase-by-phase start-up method (start-up with the formation of initial non-zero electromagnetic conditions).

Quasi-frequency control of the start-up of the IM is accompanied by significant fluctuations in the magnitude of the electromagnetic moment and the starting current, which adversely affects both the state of the mechanical components of the machines and the state of the starting motor, reducing their operational life. Therefore, this type of controlled start should be used only in cases where an increased starting torque is required and other methods cannot ensure the start of a heavily loaded induction electric drive.

Thus, the results of computer simulation show that the controlled start can significantly limit the starting current of the IM and the oscillations of the electromagnetic moment, and the choice of the method of its implementation is determined by the specific operating conditions.

6. References
[1] Schnfeld R and Habiger E 1981 Automatisierte Elektroantriebe (VEB Verlag Technik, Berlin) p 464
[2] Bose Bimal K 2002 Modern Power Electronics and AC Drives (Prentice Hall PTR) p 711
[3] Richard C. Dorf and Robert H. Bishop 2002 Modern control systems (Addison-Wesley) p 832
[4] Otto Mildenberger and Eberhard Seefried 1995 Technology & Engineering (Berlin: Heidelberg UA.: Springer)
[5] Eberhard Seefried 2001 Elektrische Maschinen und Antriebstechnik. Grundlagen und Betriebsverhalten (Berlin: Vieweg) p 234 DOI: 10.1007/973-3-322-89150-1
[6] Reshmin B 2016 Imitacionnoe modelirovanie i sistemy upravleniya (Moscow: Infra-ingeneriya) p 74
[7] Jens Weidauer and Richard Messer 2014 Electrical Drives: Principles, Planning, Applications, Solutions (Wiley) p 397
[8] Dierk Schröder 1994 *Elektrische Antriebe 1* (Springer-Verlag, Berlin Heidelberg GmbH) p 409 DOI: 10.1007/978-3-662-06950-9
[9] Dierk Schröder 1995 *Elektrische Antriebe 2. Regelung von Antrieben* (Springer-Verlag, Berlin Heidelberg GmbH) p 625 DOI: 10.1007/978-3-662-06951-9
[10] Jens Weidauer 2013 *Elektrische Antriebstechnik: Grundlagen, Auslegung, Anwendungen, Lösungen* (Berlin: Publicis Publishing) p 415
[11] Saffet Ayasun and Chika O. Nwankpa 2005 *Induction Motor Tests Using MATLAB / Simulink and Their Integration In to Undergraduate Electric Machinery Courses* (IEEE TRANSACTIONS ON EDUCATION, Vol. 48) pp 37–46
[12] Pereverzev S and Nesterovskiy A 2010 *Ustriystvo upravleniya puskom nereguliruemykh asinkronnykh elektrroprivodov* (Vestnik KuzGTU) pp 97–100
[13] Krause P, Wasyczuk O and Sudhoff S 2002 *Analysis of Electric Machinery and Drive Systems* (IEEE Press) p 613
[14] Ansari DM, Deshpande 2010 *Mathematical Model of Asynchronous Machine in MATLAB Simulink* (Int. J. Eng. Sci. Technol., Vol. 2) pp 1260–1267
[15] Moradi M and Khorasani P 2008 *A new Matlab simulation of induction motor* (Australas. Univ. Power Eng. Conf.)