ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

ЕНЕРГЕТИКА

ENERGETICS

UDC 62-83:621.313

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STUDY OF THE MODES OF RE-ENABLE THE ASYNCHRONOUS ELECTRIC DRIVE OF A CENTRIFUGAL PUMP

А. Бойко, В. Пліс, С. Заброцький, Є. Соколов. **Дослідження режимів повторного ввімкнення асинхронного електропривода відцентрового насоса.** Виконано дослідження динамічних режимів повторного ввімкнення асинхронного двигуна відцентрового насосу для заданої схеми електропостачання. Дослідження проводилися в умовах поставлених технічних вимог та наявності технічних даних елементів системи електропостачання, електроприводу та механізму. Застосовувалися авторські математичні моделі асинхронних двигунів на базі узагальненої машини, що описується у трифазній нерухомій системі координат з урахуванням нелінійностей двигуна – втрат у сталі, ефектів витіснення струму ротора та насичення по шляхах розсіювання та головного магнітного потоку. Дано оцінку якісних та кількісних показників перехідних процесів електроприводу – струмів, напруг, моментів двигуна. Аналізовано динаміку напруг і струмів у фазах двигуна. Розглянуто вплив ненульових початкових електромагнітних умов на характер перехідних процесів. Показано, що перенапруги, які виникають при повторному включенні двигунів, у колі з глухопідключеними конденсаторами, несприятливо позначаються на діючому електрообладнанні. Наводиться вирішення проблеми – необхідність впровадження роздільної комутації двигуна та секцій конденсаторів, застосування тиристорних пристроїв для забезпечення сприятливих умов ввімкнення, що дозволяє знизити напруги та струми, мінімізувати пікові значення моментів і забезпечити стабільну роботу системи, а також вказано на переваги використання керованих пускових пристроїв, які дозволяють досягти сприятливих умов комутації двигунів як при пуску, так і при повторних увімкненнях.
Ключові слова: асинхронний двигун, компенсаційний конденсатор, відцентровий насос, перехідні процеси, повторне ввімкнення

A. Boiko, V. Plis, S. Zabrotskyi, Y. Sokolov. **Study of the modes of re-enable the asynchronous electric drive of a centrifugal pump.** A study of the dynamic modes of re-enable an induction motor of a centrifugal pump for a given power supply scheme has been carried out. The studies were conducted under the conditions of the specified technical requirements and the availability of technical data on the elements of the power supply system, electric drive and mechanism. The author's mathematical models of induction motors were used based on a generalized machine described in a three-phase fixed coordinate system taking into account the nonlinearities of the motor – iron losses, rotor current displacement effects and saturation along leakage paths and the main magnetic flux. An assessment is given of the qualitative and quantitative indicators of transient processes of the electric drive – currents, voltages, motor torques. The dynamics of voltages and currents in the phases of the engine are analyzed. The influence of non-zero initial electromagnetic conditions on the nature of transient processes is considered. It has been shown that overvoltage that occur when motors are switched on again in a circuit with permanently connected capacitors have an adverse effect on the operating electrical equipment. A solution to the problem is provided – the need to implement separate switching of the motor and capacitor sections, the use of thyristor devices to ensure favorable switching conditions, which allows reducing voltages and currents, minimizing peak torque values and ensuring stable operation of the system and also points out the advantages of using controlled starting devices.
Keywords: induction motor, compensating capacitor, centrifugal pump, transient processes, re-enable

Introduction

A centrifugal pump is a type of dynamic vane pump in which the liquid is moved continuously due to the interaction of its flow with the rotating rotor blades and the fixed casing blades. The liquid is transferred under the action of centrifugal force, while the movement occurs in the radial direction, perpendicular to the axis of rotation of the rotor. Centrifugal pumps are widely used in industry and utilities, including municipal water supply systems. In most cases, they are driven by AC motors. For capacities from 1 MW and above, high-voltage synchronous motors are used, and for smaller capacities, three-phase squirrel-cage motors operating at 220/380 V are used. In the simplest control systems, where there is no frequency regulation, the induction motor (IM) is started by direct connection to the mains, and the water pressure and flow are controlled using a throttle valve.

DOI: 10.15276/opu.1.71.2025.06

Literature review and problem statement

When powered from the mains, the AD inevitably consumes reactive power, regardless of the shaft load [1]. To reduce the load on the grid, reactive current compensation is used with capacitor banks. There are various connection schemes and switching algorithms for capacitors and motors [2]. One of the options involves hardwiring capacitors to the motor stator winding. In this case, the motor and capacitors are switched on and off simultaneously by one switching device. However, this scheme has a number of significant drawbacks [3]:

1. Capacitor charging currents during motor startup. If the capacitors are discharged, significant capacitor charging currents occur when the motor is connected to the network, which increases the load on the switchgear. This, in addition to the standard motor starting currents, can lead to overloading of the device and even emergency situations, including welding of contacts [4];

2. Self-excitation mode when the motor is disconnected. After disconnecting from the mains, the AD and capacitors can enter the self-excitation mode, which causes an increase in the voltage on the stator windings and the occurrence of a braking torque on the motor shaft. This can damage the pump and piping [5];

3. Simultaneous transients during startup. When the system is turned on, two transients occur: charging of the capacitors and electromagnetic transients of the motor start-up. In the case of powerful pumps and limited power supply network capacity, complex electrodynamic interactions between the network, capacitors, and motor are possible, which can lead to unpredictable effects [6].

To eliminate these disadvantages, a scheme with capacitors that are blindly connected to the network can be used. [7]. In this configuration, motor disconnection or switching on is not accompanied by a charging current of the capacitors or self-excitation. However, in this case, a new disadvantage is possible – overcompensation when the motor is turned off [8]. To avoid this, a separate device should be provided to switch the capacitors [9].

Purpose and objectives of the study

The aim of this work is to study the dynamic modes of re-enabling an asynchronous short-circuited electric drive of a centrifugal pump.

You need to solve problems:

– study of dynamic modes of re-activation of an asynchronous electric drive of a centrifugal pump;

– evaluation of the drive transient parameters, such as currents, voltages, and motor torques.

Materials and methods of research, parameters of the devices under study

The research was carried out under the conditions of the set technical requirements and the availability of technical data on the elements of the power supply system, electric drive, and mechanism. We used the author's mathematical models of induction motors based on a generalized machine described in the three-phase fixed coordinate system A, B, C [10]. The influence of the power supply network was taken into account by introducing pre-connected active-inductive resistances into the models. The modelling results were confirmed by experiments at the operating pumping unit КНС6-Б (pumping unit No. 6) of the Infoksvodokanal branch of Infoks LLC, Odesa.

The mechanical characteristics of the centrifugal pump are typical, of a “fan” nature. The pump motor is АИР355S4, 250 kW, 1500 rpm, 380/220 V. The rated power of the pump corresponds to the rated power of the motor. The moment of inertia of the pump is 20% of the moment of inertia of the drive motor.

Mechanical characteristic of the pump in relative units during operation with the main valve open [11]:

$$M_{st} = 0.05 + 0.95\left(\frac{\omega}{\omega_n}\right)^2. \tag{1}$$

The same when working on a closed throttle:

$$M_{st} = 0.05 + 0.20\left(\frac{\omega}{\omega_n}\right)^2. \tag{2}$$

The capacitors are selected from the condition of full compensation of the reactive component of the current used by the AD. It is necessary to fulfil the equality [5]:

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

$$X_{st} = X_0 + X_1, \tag{3}$$

where: $X_{(0)}$ and $X_{(1)}$ are the reactive impedances of the AD replacement circuit, Ohm.

Where can the capacitance of the starting capacitor be found:

$$C = \frac{1}{314}(X_0 + X_1). \tag{4}$$

For the given parameters of the АИР355S4 motor, when the capacitors are connected in a star pattern, the capacitance of the capacitor will be $C_{\Upsilon} = 1345$ μF, when connected in a triangle, $C_{\Delta} = 448$ μF. The capacitors are represented in the models as ideal, lossless. The existing power supply system connects a transformer substation (TS), a capacitor installation in a distribution point (DP), and a drive induction motor (IM) of a centrifugal pump (P), Fig. 1.

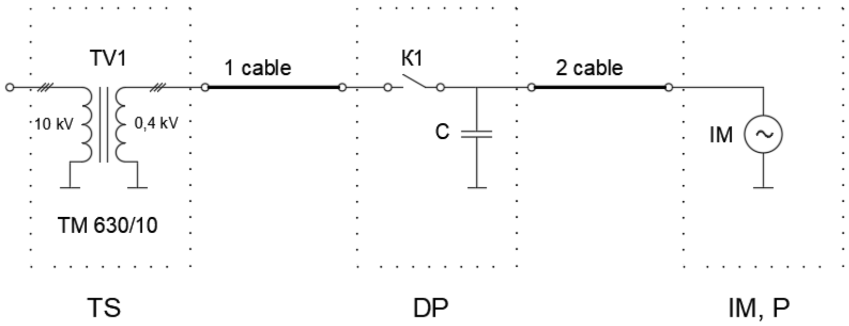

Fig. 1. Diagram of the power supply system for the pump motor

The cross-section of the cables ensures the transmission of the full power of the TM-630/10 transformer to the switchgear, and from the switchgear to the AD. The cable line AVBbShv-1 (3×150) is 200 m long between the transformer substation and the distribution center, and 50 m long between the distribution center and the pump motor. The cables are laid in the ground. The resistance of the conductors approaching the capacitor bank is not taken into account due to its direct location in the switchgear. The equivalent active resistance of the network is determined mainly by the parameters of the cable lines, and the equivalent reactive resistance is determined by the inductive resistance of the transformer or motor. This should be taken into account when analyzing options using a transformer of a different capacity or cable lines of other cross-sections and lengths [12].

These studies are a continuation of the solution of the complex problem of studying the operating modes of an induction electric drive of a centrifugal pump. The study of the modes of starting and disconnecting from the AD network is discussed in detail in [11].

Research results

The article considers the process of disconnecting the motor from the mains, running for some time and then restarting it. Such processes occur when switching from manual to automatic control modes, automatic reclosing on the high voltage side, human error, and possibly other cases. At the same time, the drive behaves ambiguously. In some cases, the connection to the mains is normal, while in others it causes unforeseen current surges and tripping of the emergency protection. For a clearer picture, we first consider the processes without capacitors, and then evaluate the impact of blindly connected capacitors [13].

Disconnecting the induction motor from the mains

The presence of a short-circuited winding or a squirrel cage on the rotor of the motor leads to the fact that after disconnection from the mains, the rotor current dies down for some time (in powerful motors, tenths of a second or even seconds). There is a damped EMF at the motor stator terminals, which is the cause of the self-excitation mode and voltage increase on the windings if capacitors of appropriate capacity are connected to them. After a pause, the motor can be reconnected to the mains and the electromagnetic parameters of the motor at the time of switching on are very important. If the pause was long and all processes have been extinguished (currents and voltages are zero), then the reconnection process is unambiguous and corresponds to normal conditions. In this case, we should talk about the presence of zero initial electromagnetic conditions (zero EMC). If during the pause the processes in the motor did not stop (non-zero EMC), then the new switching on proceeds ambiguously, possibly under favorable and unfavorable conditions [11]. The explanation can be seen in Fig. 2*a*, which shows the phase voltage of the mains U_f, the stator winding EMF E_f, and the voltage at the magnetic starter contact U_k after the motor is disconnected. In the steady-state mode, before tripping, the EMF is practically in the opposite phase with the mains voltage, and therefore, immediately after tripping, the voltage at the contact is small in magnitude. Further, the vectors U_{ph} and E_f behave differently. The mains voltage vector rotates with a constant frequency of 50 Hz and is constant in amplitude. The EMF vector rotates at a rotor frequency lower than the mains frequency and decreases in amplitude. The summation of two voltages of different frequencies gives a well-known picture of the voltage fluctuation observed in the graph U_k. Here we can see nodes (voltage minimums) and voids (voltage maximums). Nodes correspond to cases when the vectors are out of phase, and voids correspond to cases when they are in phase. The greater the difference in the frequencies of the analyzed vectors, the more frequently nodes and voids alternate [5]. Working on an open gate causes a significant slowdown of the drive and a decrease in the frequency E_{ph}, so the frequency of repetition of knots and voids increases. In the limit, after the EMF vector has died out or the motor stops, this EMF ceases to affect and the voltage at the contact becomes equal to the mains voltage. In another case, for example, when the motor is disconnected from the idle state, when the slip is 0.999, the frequencies U_{ph} and E_f differ little, the motor speed does not change, and the period of occurrence of voids and nodes increases significantly, Fig. 2*b*. In this case, in 1 s after the disconnection, the EMF manages to attenuate almost twice, and the moment of void has not yet occurred.

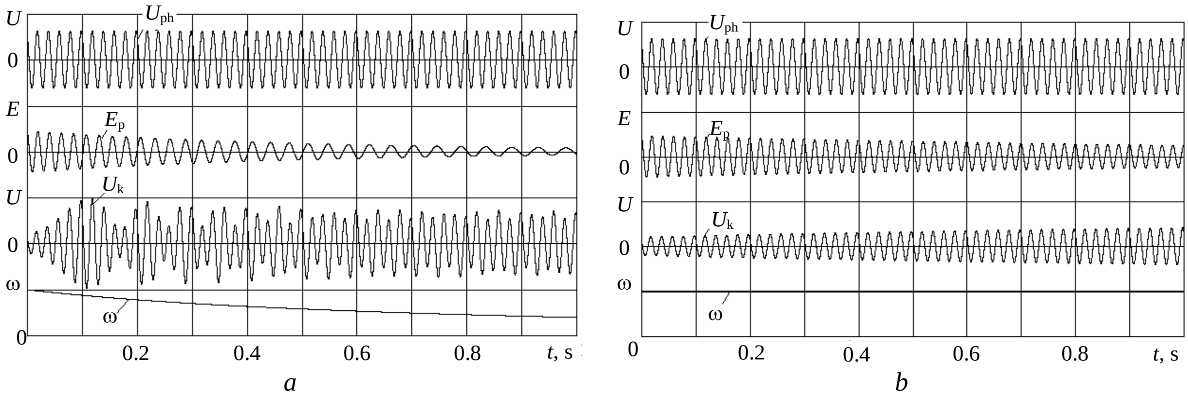

Fig. 2. Transient plots of the AD shutdown and its operation: *a* – on open valve; *b* – at idle.
Scale: 500 V/div; ω_0/div

Reconnect the induction motor to the mains

In all cases where the voltage and EMF vectors are directed in opposite directions, the total voltage in the phase and line circuits will be minimal and, accordingly, the reconnection process will be milder [14]. Such reconnection conditions can be called favorable, and they correspond to the nodes in the U_k pattern. In this case, if the pause during reclosing is minimal, for example, 0.01 s or equal to 0.18 s, reclosing will be favorable. If the mains voltage and motor emf vectors are aligned, the total voltage in the circuits will be higher (higher than the mains voltage if the emf has not faded) and the restart will occur under harsh, unfavorable conditions. These conditions correspond to pauses of 0.12 or 0.30 seconds before reclosing. Two possible variants of favorable and unfavorable conditions are shown here. These conditions exist and alternate further until the EMF is completely extinguished. However, due to a significant drop in motor speed, the frequency of their repetitions has increased so much that it has become difficult to distinguish them visually. Figs. 3*a*, 3*b* show the transient diagrams for the interval of current-free pause and restart. Despite the different pause durations, they all correspond to favorable electromagnetic switch-on conditions. Fig. 3*a*, where the pause is minimal and amounts to 0.01 s, may seem uninformative, but it proves that for such a short period of time at asynchronous speed, the electromagnetic state of the motor has changed little and after re-enabling, the steady-state mode occurs almost immediately without a transient process. With a pause of 0.18 s, Fig. 3*b*, the motor speed at the time of re-enabling significantly decreases and a transient process of acceleration to the rated speed begins, but it takes place under favorable conditions, the current amplitude reaches 2.6 kA, and the torque throw does not exceed $2M_n$. In none of the cases of favorable switching on, negative values of the transient torque and speed dips during re-energization are observed.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

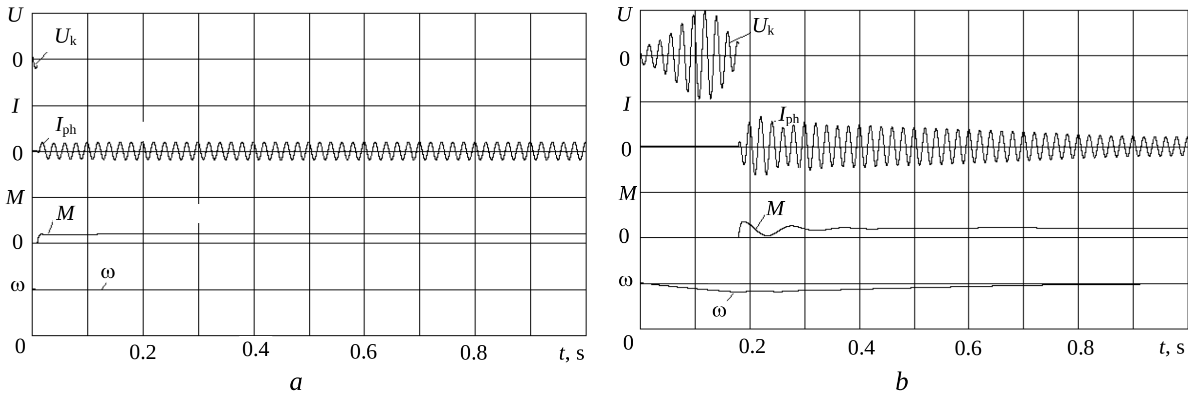

Fig. 3. Transient plots of AD re-activation under favorable conditions and pause: *a* – 0.01 s; *b* – 0.18 s. Scale: 500 V/div; 4.0 kA/div; $1M_n$/div, ω_0/div

In Fig. 4*a* and Fig. 4*b* show the graphs of the pump motor restart under unfavorable conditions. In both cases, negative torque peaks of up to $-5M_n$ are observed, which lead to additional speed dips and current surges with an amplitude of up to 4000 A.

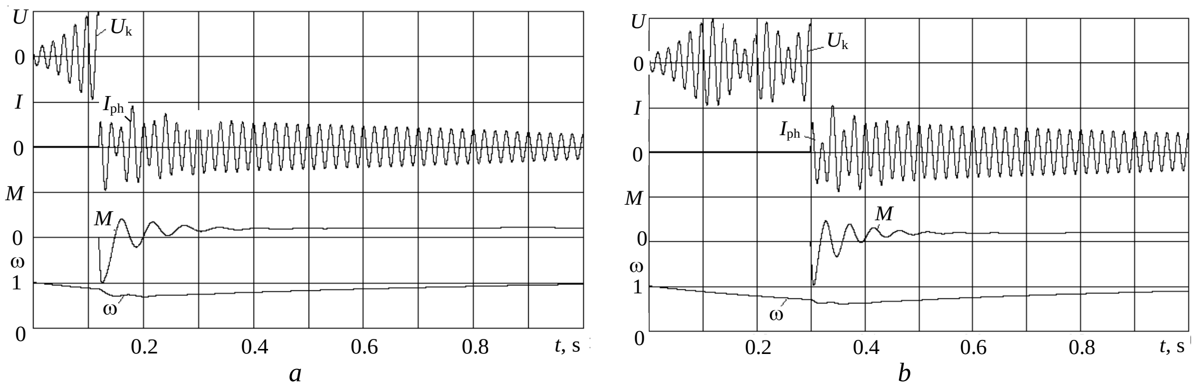

Fig. 4. Transient plots of the AD re-activation process under unfavorable conditions and pause: *a* – 0.12 s; *b* – 0.30 s. Scale: 500 V/div; 4.0 kA/div; $5M_n$/div, ω_0/div

Reconnect the capacitor bank to the mains

Similar to a motor, a capacitor bank may also have non-zero initial conditions at the time of restart. In this case, favorable switch-on conditions are observed when the voltage across the capacitor and the grid are equal at the moment of switch-on. In this case, there are no free current components and the steady-state mode immediately sets in [15]. The greater the difference between the voltage across the capacitor and the grid at the time of reconnection, the greater the transient voltages and currents. For illustration purposes, Fig. 5 and Fig. 6 show the graphs of reconnection at zero and at the maximum line voltage at different initial capacitor voltages. Under favorable conditions (curve *3* in Fig. 5 and curve *5* in Fig. 6), there are no transient currents and voltages. Under the most unfavorable conditions, the transient current amplitude can reach 2.5 kA and the voltage amplitude up to 1.5 kV.

Unless special measures are taken to control the initial electromagnetic conditions, the occurrence of favorable or unfavorable conditions appears to be a random process, as they depend on many factors, such as the rate of speed decline during a pause (open or closed valve, consistency of the pumped liquid), voltage fluctuations, and network frequency. In addition, the occurrence of favorable conditions for the pump motor and the condenser to restart may not coincide in time [16]. Therefore, it is necessary to count on a combination of the most unfavorable conditions for both the motor and the capacitor. In this case, the maximum expected current amplitude can be 6.5 kA, which is more than 1.5 times the motor starting currents. In some cases, the presence of a blindly connected capacitor can further aggravate this process. For example, if for some reason during the pause period the motor entered the self-excitation mode, the unfavorable conditions during the restart may be more severe than those considered for both the motor and the capacitor. In this case, this drive system can be considered as one that can lead to severe fault conditions.

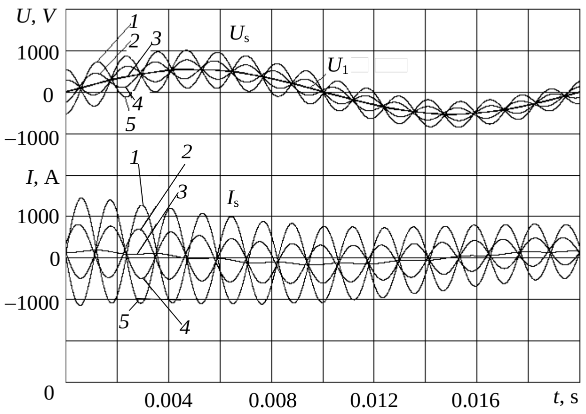

Fig. 5. Transient diagrams of the two-phase switching of a 915 μF capacitor at zero line voltage and different initial capacitor voltages:
1 – $U_{\text{s on.}} = -U_{\text{lin. max}}$; *2* – $U_{\text{s on.}} = -0.5U_{\text{lin. max}}$; *3* – $U_{\text{s on(.)}} = 0$; *4* – $U_{\text{s on}} = 0.5U_{\text{lin. max}}$; *5* – $U_{\text{s on}} = U_{\text{lin. max}}$

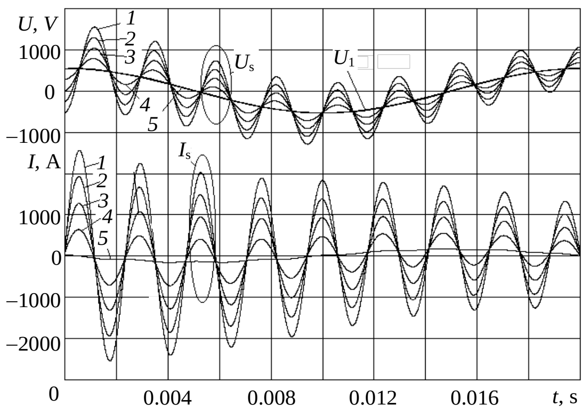

Fig. 6. Transient diagrams of the two-phase switching of a 915 μF capacitor to the maximum line voltage at different initial capacitor voltages:
1 – $U_{\text{s on}} = -U_{\text{lin. max}}$; *2* – $U_{\text{s on}} = -0.5U_{\text{lin. max}}$; *3* – $U_{\text{s on}} = 0$; *4* – $U_{\text{s on}} = 0.5U_{\text{lin. max(.)}}$; *5* – $U_{\text{s on}} = U_{\text{lin. max}}$

Reconnect the motor and capacitor bank to the mains.

Conclusions

1. The presence of capacitors blindly connected to the motor has an adverse effect on electrical equipment in all respects, contributing to an increase in accidents on lines, motors, and the capacitors themselves. Other negative consequences are possible on the high voltage side of the power transformer: on the transformer itself, in the networks and in the equipment of neighboring consumers.

2. The main technical method recommended to prevent emergency modes of such an electric drive is to separate the circuits and separate the motor and capacitor. However, even this does not completely solve the problem, because even with separate switching, each switching of the capacitors will cause overvoltages in the power line and all motors and consumers that are connected to it at that moment.

3. The optimal and at the same time radical solution to the problem of failures is to switch the pump motor and capacitor sections separately. The capacitors must be switched by a thyristor device, which ensures only favorable conditions and eliminates transient currents.

4. Motor switching conditions, both at startup and during restarts, can also be significantly improved by using controlled starters. However, this will cause a significant increase in the cost of the system, since the capacities of the starters must match the capacities of the induction motors used.

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Received March 03, 2025

Accepted April 21, 2025