Study of Start-up and Shutdown Modes of an Asynchronous Electric Drive for a Centrifugal Pump

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Abstract. The aim of this study is to investigate the commutation processes of an asynchronous short-circuited electric drive for a centrifugal pump. The set goal is achieved by solving two tasks: analyzing the dynamic modes of connection to and disconnection from the network of the asynchronous motor of the centrifugal pump for a given power supply scheme; assessing the qualitative and quantitative indicators of the transient processes of the electric drive. Among the most significant results of the study, it is possible to highlight the ability to form practical recommendations on the operation peculiarities of electric drives for a wide class of mechanisms. The conducted research allowed asserting that in an electrical system with capacitors directly connected to the stator winding and during both the connection and disconnection of the drive motor of the centrifugal pump, voltages significantly exceeding the nominal ones may occur. It has been determined that considering the harsh operating conditions of pump units, such overvoltages represent a danger to the motor winding insulation. During the motor disconnection, significant overvoltages on the stator windings are possible if, for any reason, the capacitor's capacitance exceeds the calculated base value for the applied motor. The practical significance of the obtained results lies in the fact that the assumption of the motor transitioning to intensive braking mode and subsequent hydraulic shock upon disconnection from the network due to self-excitation did not prove to be true. The electric drive provides braking under the action of the load torque without mechanical overloads.
Keywords: asynchronous motor, compensating capacitor, centrifugal pump, transient processes, motor start-up, motor disconnection.

Investigarea modurilor de pornire și deconectare a unui sistem de acționare electrică asincronă a unei pompe centrifuge
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Rezumat. Scopul acestui studiu este de a investiga modurilor de pornire și deconectare de la rețea a acționării electrică asincrone a unei pompe centrifuge. Scopul stabilit este atins prin rezolvarea a două sarcini: analiza modurilor dinamice de conectare și deconectare de la rețea a motorului asincron al pompei centrifuge pentru o schemă de alimentare dată; aprecierea indicatorilor calitativi și cantitativi ai proceselor tranzitorii ale acționării electrice – curenți, tensiuni, cupluri ale motorului. Necesitatea cercetării este justificată de problemele practice de producție apărute în timpul funcționării unui antrenament electric asincron pentru o pompă centrifugă. Cercetarea a fost efectuată în conformitate cu cerințele tehnice specificate și disponibilitatea datelor tehnice pentru elementele sistemului de alimentare cu energie, acționării electrice și mecanismului. Printre cele mai semnificative rezultate ale studiului, este posibil să evidențiem capacitatea de a forma recomandări practice cu privire la particularitățile de funcționare ale acționărilor electrice pentru o clasă largă de mecanisme. S-a stabilit că, având în vedere condițiile grele de funcționare a unităților de pompare, astfel de supratensiuni reprezintă un pericol pentru izolația înfășurării motorului. În timpul deconectării motorului, sunt posibile supratensiuni semnificative pe înfășurările statorului dacă, din orice motiv, capacitatea condensatorului depășește valoarea de bază calculată pentru motorul aplicat. Semnificația practică a rezultatelor obținute constă în faptul că ipoteza tranziției motorului în modul de frânare intensivă și șoc hidraulic ulterior la deconectarea de la rețea din cauza autoexcitației nu s-a dovedit a fi adevărată.
Cuvinte-cheie: motor asincron, condensator compensator, pompă centrifugă, procese tranzitorii, pornire motor, deconectare motor.

Исследование режимов пуска и отключения от сети асинхронного электропривода центробежного насоса

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Аннотация. Выполнено исследование динамических режимов включения в сеть и отключения асинхронного двигателя центробежного насоса для заданной схемы электроснабжения. Исследования проводились в условиях поставленных технических требований и наличия технических данных элементов системы электроснабжения, электропривода и механизма. Применялись авторские математические модели асинхронных двигателей на базе обобщенной машины, описываемой в трехфазной неподвижной системе координат с учетом нелинейностей двигателя - потерь в стали, эффектов вытеснения тока ротора и насыщения по путям рассеяния и главного магнитного потока. Дана оценка качественных и количественных показателей переходных процессов электропривода - токов, напряжений, моментов двигателя. Определено, что в электрической системе с глухо подключенными к обмотке статора конденсаторами и при включении, и при отключении приводного двигателя центробежного насоса могут возникать напряжения, значительно превышающие номинальные. Особенно большие перенапряжения возникают при включении асинхронного двигателя и при его отключении, если емкость конденсатора превышает величину, требуемую для компенсации реактивного тока двигателя. С учетом тяжелых условий эксплуатации насосных установок, такие перенапряжения представляют опасность для изоляции обмоток двигателя. Показано, что в процессе пуска двигателя, наличие свободных составляющих тока заряда конденсатора ухудшает, и без того тяжелые условия прямого пуска мощных двигателей и контактной аппаратуры. В процессе отключения двигателя возможны заметные перенапряжения на обмотках статора, если по каким-либо причинам емкость конденсатора превышает расчетную базовую величину емкости для применяемого двигателя. Предположения, что при отключении от сети двигатель насоса может перейти к режиму интенсивного торможения из-за возникающего режима самовозбуждения, что, в свою очередь, может вызвать гидравлический удар, не подтвердились. Тормозные моменты оказываются небольшими и электропривод осуществляет торможение под действием момента нагрузки.

Ключевые слова: асинхронный двигатель, компенсационный конденсатор, центробежный насос, переходные процессы, пуск двигателя, отключение двигателя.

INTRODUCTION

A centrifugal pump is one type of dynamic blade pumps where the movement of the working fluid - liquid - occurs continuously, due to the interaction of this flow with the movable rotating blades of the rotor and the stationary blades of the casing. The transfer of fluid motion occurs due to centrifugal force and flows in a radial direction, perpendicular to the axis of rotation of the rotor. Centrifugal pumps are widely used in all industrial sectors and municipal services, particularly in urban water supply systems. They are powered by electric motors, predominantly alternating current ones. Typically, for powers of 1 MW and above, high-voltage synchronous motors are used, while for lower powers, three-phase asynchronous short-circuited motors (AM) with a voltage of 220/380V are utilized. In simple cases, without frequency control of the motor, direct starting is employed, and the control of head and flow is achieved through a throttle valve in the water supply pipeline.

When powered from the grid, an asynchronous motor consumes reactive power regardless of the current load on the shaft [1]. To relieve the grid from reactive current, compensation is applied using cosine-compensating capacitors. In [2], the authors provide examples of various connection schemes and algorithms for switching capacitor banks and motors. In the proposed scenario for consideration, the capacitors are directly connected to the motor stator winding. In this case, switching on and off for both the motor and capacitors is performed by a single switching device simultaneously. Authors in [3] have shown that such a connection has several significant drawbacks:

- when capacitors are discharged, the AM is switched on to the grid with zero initial conditions. Work [4] claims that besides starting currents, the switching device experiences significant overloads from the charging current of the capacitors. In extreme cases, emergency modes are possible [5], up to welding of contacts, for example;

- upon disconnection from the grid, the AM and compensating capacitor may enter a self-excitation mode, as illustrated in work [6]. This can cause an increase in voltage on the motor stator and the emergence of braking torque on its

shaft, which could harm the pump and pipelines rather than benefit them [7];

- when the AM is connected to the grid, two transient processes occur simultaneously in the system - capacitor charging and electromagnetic transient process of motor start-up [8]. Work [9] states that considering the possibility of using high-power AM pumps, the power of the feeding grid cannot be accepted infinitely large, and the grid voltage remaining constant. Therefore, complex cases of electrodynamic interaction of the three elements of the system - the grid, capacitors, and motor with unpredictable effects are possible [10].

At the same time, when using a scheme with capacitors directly connected to the grid, the commutation of the AM windings during startup and shutdown will not be accompanied by any of the listed negative consequences [11]. However, the appearance of a new drawback is possible - overcompensation when the motor is disconnected. In this case, the authors [12] propose to provide for the commutation of starting capacitors by a separate device.

The aim of the study is to investigate the commutation processes of an asynchronous short-circuited electric drive for a centrifugal pump.

To achieve the stated goal, the following tasks need to be solved:

- conduct a study of the dynamic modes of connection to and disconnection from the network of the asynchronous motor of the centrifugal pump for a given power supply scheme;

- provide an assessment of the qualitative and quantitative indicators of the transient processes of the electric drive - currents, voltages, motor torques.

I. MAIN METHODS AND RESEARCH

The research was conducted under the specified technical requirements and the availability of technical data for the elements of the power supply system, electric drive, and mechanism. Authorial mathematical models of asynchronous motors based on a generalized machine described in a three-phase fixed coordinate system A, B, C were used. It was mandatory to account for the nonlinearities of the AM - losses in steel, rotor current displacement effects, and saturation effects via scatter and main magnetic flux paths. The

influence of the power supply network was taken into account by introducing pre-connected active-inductive resistances into the models [13]. The simulation results were confirmed by experiments on the operating pump unit No. 6 LLC " INFOX", Odessa.

II. PARAMETERS OF THE STADIED DEVICES

The mechanical characteristic of the centrifugal pump is typical and of the "fan" type. The asynchronous motor of the pump has the following parameters: 250 kW, 1500 rpm, 380/220 V.

The pump's moment of inertia is 20% of the inertia of the drive motor.

The mechanical characteristic of the pump in relative units when operating with the discharge valve open is [14]:

$$M_{load}^* = 0,05 + 0,95\,(\omega/\omega_{\text{н}})^2 \qquad (1)$$

The same is when operating with the discharge valve closed:

$$M_{load}^* = 0,05 + 0,2\,(\omega/\omega_{\text{н}})^2 \qquad (2)$$

The capacitors are chosen to achieve complete compensation of the reactive component of the current used by AM. It is necessary to satisfy the equality [5]:

$$X_c = X_0 + X_1 \qquad (3)$$

where X_0 and X_1 are the reactive resistances of the AM equivalent circuit, measured in Ohms. The capacitance of the starting capacitor can be found from:

$$C = 1/314(X_0 + X_1) \qquad (4)$$

For the given motor parameters, the capacitance of compensating capacitors has been determined, which are represented in models as ideal, without losses.

The existing power supply system consists of a transformer substation (TS), which is connected by a cable line to a distribution point (DP) where the capacitor bank is located, then an asynchronous motor (AM) of the pump (P) is connected by cable, as shown in Fig. 1.
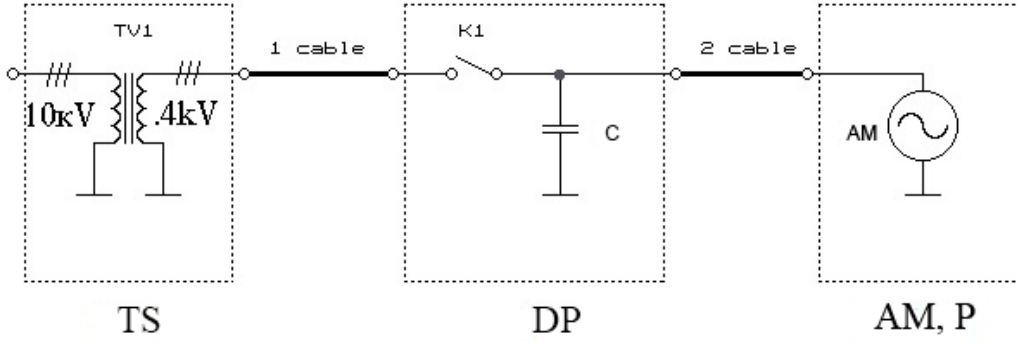
Fig. 1. Schematic diagram of the investigated system.

The equivalent active resistance of the network is mainly determined by the parameters of the cable lines, while the equivalent reactive resistance is determined by the inductive resistance of the transformer or motor [14]. This should be taken into account when analyzing options using transformers of different power ratings or cable lines of different cross-sections and lengths.

III. RESEARCH RESULTS

Drive engagement (direct motor start of the pump)

By direct engagement, we mean the motor start-up process without considering the influence of capacitor parameters and the power supply network. In Figs. 2 a-c, calculated oscillograms of motor start-up under no-load conditions, with the discharge valve closed and open, are presented. During startup, fluctuations in torque, speed, and current occur due to the electromagnetic transient processes. Typical for large and medium-power electric machines is the prolonged duration of fluctuations in time at the beginning and end of the start-up [15]. The torque multiple during startup of powerful motors is small, and therefore, despite the low resistance torque of the pump at the start, this section of the start-up is prolonged. Subsequently, the intensity of the start-up increases, and the end of the start-up is characterized by overshoots and fluctuations. At the beginning of the start-up, single impact pulses of torque and current up to 8In and 10In, respectively, are observed.

Features of capacitor connection to the network

A simplified schematic diagram of the charging circuit of the capacitor, without considering the motor, is presented in Fig. 3 a.

Here, R and L are determined by the parameters of the transformer and the first cable line [16]. The equation of electrical equilibrium for this circuit is as follows:

$$E = L\frac{di}{dt} + R_i + \frac{1}{C}\int idt \qquad (5)$$

Roots of the characteristic equation are:

$$p_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \qquad (6)$$

The condition for the oscillatory charging process of the capacitor is the fulfillment of the inequality: $X_C > R^2/4X_L$. For the case under consideration, this inequality looks like as 2.368 >> 2.472·10-3, which means that the process is oscillatory with a significant allowance of values.

For instance, to make the charging process aperiodic, it would be necessary to increase the active resistance by 31.6 times or decrease the inductive resistance by 250 times.

Such changes in the parameters of the elements of the existing power supply system can be considered unrealistic, and the charging process of cosine capacitors can be regarded as oscillatory. The angular frequency of free oscillations is:

$$f_{c\theta} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (7)$$
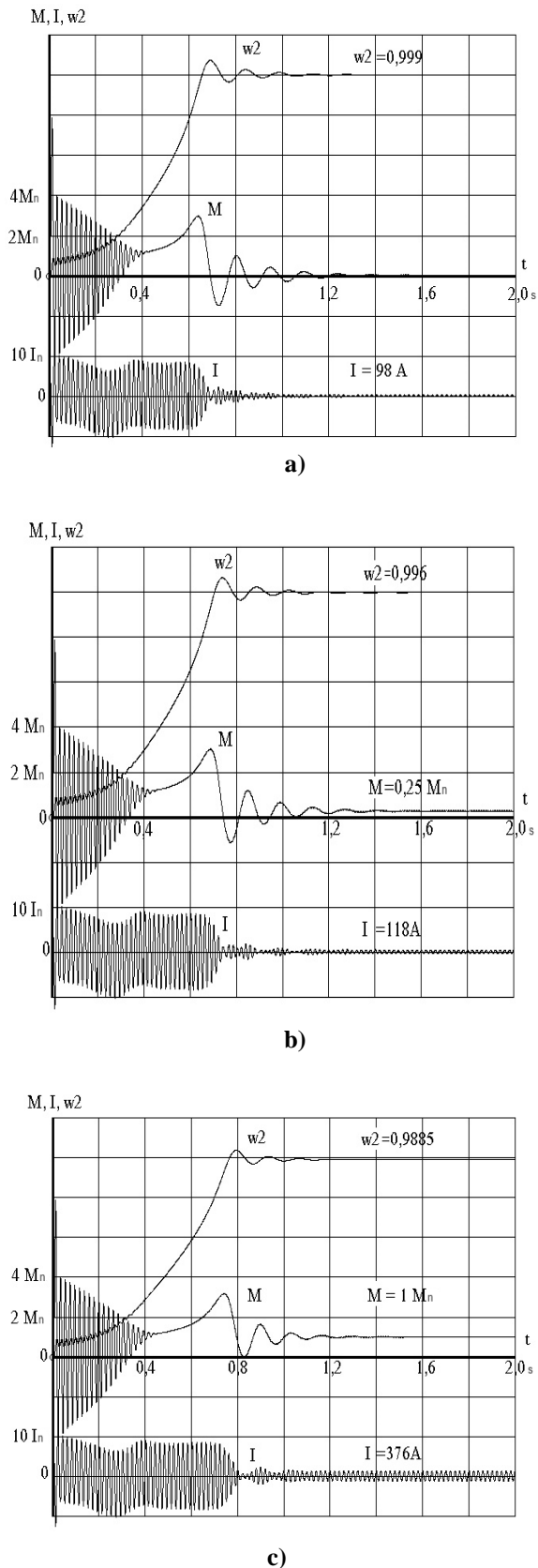
a)

b)

c)

Fig. 2. Transient processes of pump motor start-up: a - under no-load conditions, b - with the discharge valve closed, c - with the discharge valve open.
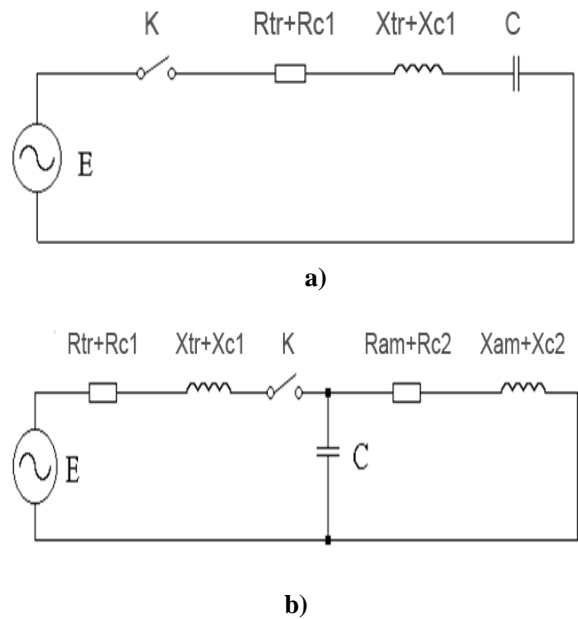

a)

b)

Fig. 3. Schematic diagrams of capacitor connection: a) without considering the AM, b) with the AM taken into account.

The free oscillatory components of current in the circuit and the voltage across the capacitor are superimposed on the forced components, causing an increase in current and voltage compared to the calculated steady-state regime. The greater the difference between the natural frequency of oscillations and the frequency of the network and the smaller the damping of the process (the smaller the R, the larger the L), the greater these differences can be [17].

In an alternating current circuit, these differences also depend on the moment of activation, i.e., on the phase of the voltage at the moment of activation.

In extreme cases, the maximum current can exceed the steady-state value by many times, and the voltage across the capacitor can be twice the amplitude of the network voltage. It should be emphasized that the considered case, by the combination of parameters, is close to the limit.
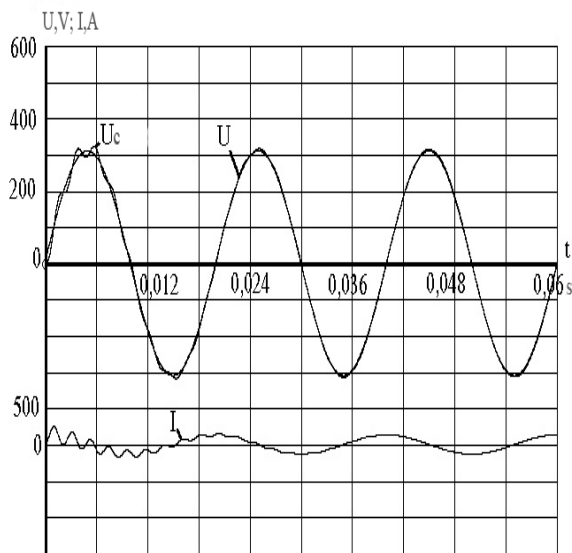
In Fig. 4a, the process of connecting the capacitor to the network at the moment of maximum network voltage is presented.

The maximum current value exceeds 1000 A, and the phase voltage across the capacitor reaches 580 V, which is 1.87 times the amplitude of the phase voltage of the network.

A similar increase in line voltage should be observed in a three-phase network.
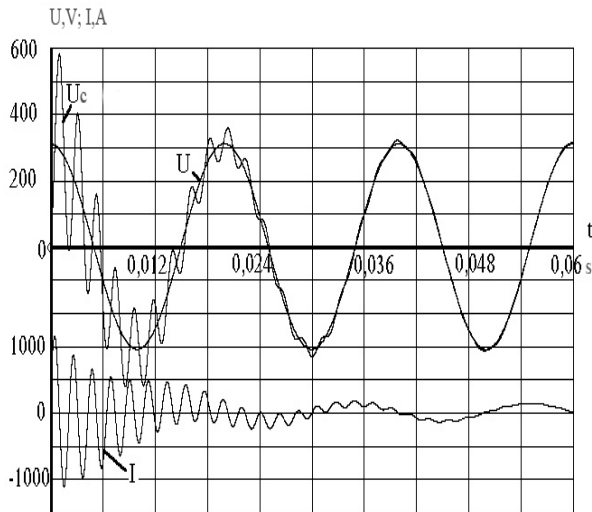
a)

b)

Fig. 4. Transient processes when connecting the capacitor to the network at the moment of: a) maximum network voltage; b) network voltage equal to zero.

In Fig. 4b, the process of connecting the capacitor to the network at the moment of zero network voltage is presented. This process occurs practically in the absence of free component parameters, so the current is close to steady-state (in this case, this current is equal to the motor magnetization current), and the voltage across the capacitor differs slightly from the network voltage. For a three-phase network, it is characteristic that no matter when the connection is made, it is never possible to

achieve the same process in all three phases [18]. In one of the phases, this process will always be expressed to the maximum extent, while in the others, it will be expressed to a lesser extent.

Simultaneous connection of the capacitor and the motor into the network

The above-discussed process of connecting the capacitor into the network does not account for the presence of a motor in the system. When synthesizing a model of the system considering the simultaneous activation of the motor and the capacitor, it is taken into account that the free component of the capacitor voltage manifests itself over a time interval of 2-3T, where T is the period of the network voltage [19]. During this time, the rotor of the pump motor changes rate insignificantly, and the motor operates practically in a short-circuit mode. In this case, there is no need to use a complete motor model, and the AM can be represented as an active-inductive load with parameters R and X [20]. Graphs of the transient process for the worst-case scenario of activation, at the moment of maximum network voltage, are presented in Fig. 5.
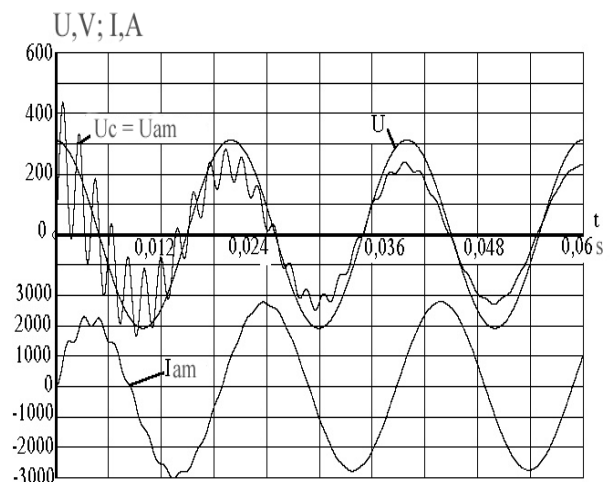

Fig. 5. Transient processes during simultaneous connection of capacitor and AM to the network.

Here, the voltage drop due to the starting currents of the AM significantly affects, so the maximum voltage is 435 V or $1.4\,U_n$, where U_n is the amplitude of the nominal voltage. In the graph in Fig. 7, $U = U_{network}$ is actually the electromotive force of the secondary winding of the supply transformer. $U_{capacitor} = U_{AM}$ is the voltage across the capacitor terminals and at the

input of the second cable line leading to the motor. These voltages are shown in this way for the convenience and safety of their measurement in the DP room, rather than directly at the operating ED of the pump. The voltage at the AM terminals will be slightly lower, taking into account the voltage drop in the cable [21].

The voltage fluctuations at the terminals of the cable supplying the motor affect the fluctuations in the starting current. The first peak of the motor current turns out to be lower than the subsequent ones because in the first period after switching on, the voltage drop is most characteristic due to the combined action of the starting current of the AM and the free component of the capacitor current.

Disconnection of the electric drive from the network, braking of the AM.

The presence of a short-circuited winding on the rotor of the AM results in the fact that after disconnection from the network, although the stator current is zero, the rotor current decays for some time (for powerful motors, tenths of seconds or even seconds). There is a decaying electromotive force (EMF) at the stator terminals of the pump motor. If a capacitor is connected to the AM at this moment, a self-excitation process begins, during which reactive energy exchange occurs between the motor and the capacitor. For the AM, this mode is a generator braking mode, during which the voltage on the stator may increase, and a braking torque is generated on the shaft [22]. In the considered case, when the capacitors are directly connected to the motor terminals and are charged to the voltage of the network at the moment of disconnection, the self-excitation process is transient, and the AM switches to the generator braking mode. The active power generated by the motor is dissipated in the winding resistances and in the steel. This effect, known as "capacitor braking," is used to create braking modes of asynchronous electric drives [23]. The degree of excitation depends on the current speed of the motor and the capacitance of the capacitor. It is convenient to express the capacitance of the capacitor in fractions of some base capacitance $C^*=C/C_b$. Each motor has its own value of the base capacitance at which complete compensation of the reactive current of the stator occurs at nominal speed. If capacitors are used for the AM braking purposes, then it is recommended that their capacitance values be in the range of $C^* = 4...5$ [20]. If capacitors are used for

compensating the reactive power of the AM and improving the power factor, then it is recommended that $C^* = 1$. In this case, the braking torques developed by the motor constitute a fraction of the nominal torque, and the voltage at the terminals of the stator winding of the AM depends on the load on the shaft and should not exceed the nominal value if the motor speed does not exceed the synchronous speed. When operating under load after disconnecting the AM, its speed begins to decrease, and the process of self-excitation and increasing voltage on the motor stator slows down as its rotational frequency decreases [24]. Subsequently, the voltage on the AM decreases. In terms of the maximum voltage on the stator during disconnection, the most "severe" mode is idle operation, where the AM remains in the sub-synchronous speed zone longer and the self-excitation process lasts longer. This pattern is already observed at $C^* = 1$. Fig. 6a.
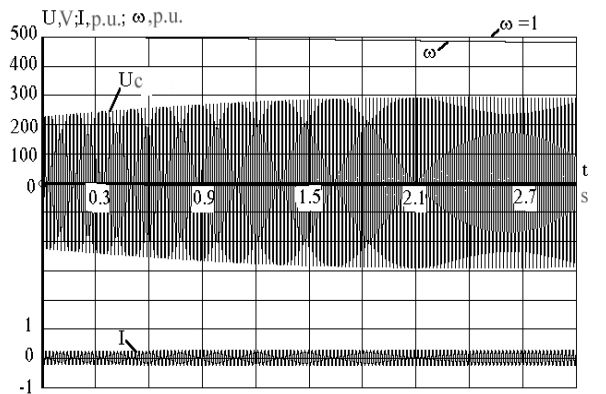
a)
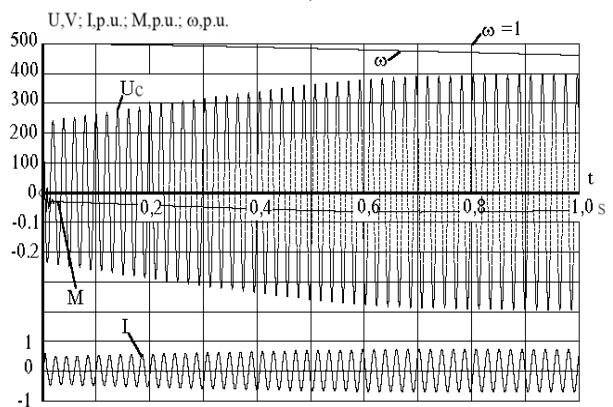
b)

Fig. 6. Transient processes during disconnection of the AM from the network, operating idle: a) $M_{load}^* = 0.05\ M_n$, $C^* = 1$; b) $M_{load}^* = 0.05\ M_n$, $C^* = 2$.

Deviations from permissible voltage values on the stator winding may be observed if the capacitance of the capacitor connected to the motor, $C^* > 1$, as shown in Fig. 6 b. During operation under load, even with a small torque $M_{load} = 0.25\ M_n$, when the pipeline valve is closed, with a capacitor capacitance of $C^* = 1$, the voltage on the stator of the pump motor decreases only upon its disconnection. If the capacitance of the capacitor $C^* > 1$, then the voltage increase begins already at $C^* = 2$, $M_{load}^* = 0.25$ (Fig. 7 a), and even at $C^* = 5$, $M_{load}^* = 1$ (Fig. 7 b). Generalized research results of overvoltage on the capacitor and motor are presented in Table 1.

Table 1

Amplitude of phase voltage at the capacitor and pump motor stator upon disconnection from the network with various load moments

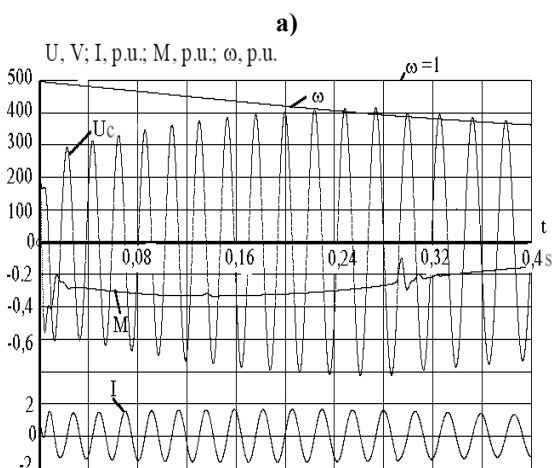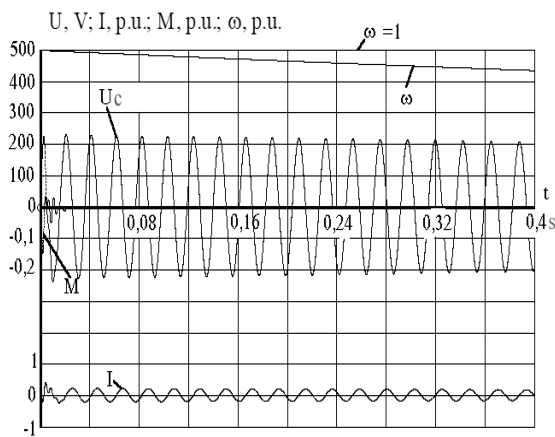| Relative capacitance value	$M_{load}^* = 0{,}05M_n$	$M_{load}^* = 0{,}25M_n$	$M_{load}^* = 1{,}0M_n$
	U_{iv}/U_{max}, B	U_{iv}/U_{max}, B	U_{iv}/U_{max}, B
$C^*=1$	212/290	230/–	240/–
$C^*=2$	230/400	240/280	260/280
$C^*=5$	270/460	280/420	290/420

a)

б)

Fig. 7. Transient processes upon disconnection of the motor under load with the valve closed, a) $M_{load}^* = 0.25$, $C^* = 2$; b) $M_{load}^* = 1.0$, $C^* = 5$.

The moments developed by the motor mainly manifest themselves in the form of rapidly decaying transient components of small amplitude.

The steady-state value of the torque at $C^* = 1$ and even at $C^* = 2$ is negligibly small and does not have a significant effect on the electromechanical and electromagnetic processes of the ED.

CONCLUSIONS

In the electrical system where capacitors are directly connected to the stator winding, both during the startup and shutdown of the drive of the centrifugal pump's asynchronous motor, voltages significantly exceeding nominal values can occur. Particularly high overvoltages are observed during the startup and shutdown of the motor if the capacitance of the compensating capacitor exceeds the required value for compensating the reactive current of the motor. Considering the harsh operating conditions of pump installations, such overvoltages can pose a danger to the insulation of the motor windings.

During the startup of the asynchronous motor, the presence of free components of capacitor charging current worsens the already challenging conditions of direct starting for powerful motors and contact apparatus.

Upon the shutdown of the motor, overvoltages may occur in the stator windings, especially if the capacitance of the capacitor exceeds the calculated base value for the given motor.

The hypothesis that upon disconnection from the grid, the pump motor may pass into an intense braking mode due to the emergence of a self-excitation mode, which in turn may cause a hydraulic shock, was not confirmed. The braking moments were found to be insignificant, and the electric drive brakes under the influence of the load torque.

References

[1] Xuesong Z., Youjie M., Zhiqiang G., Shaowei Z. Reactive Power Compensation in Motor. *2017 IEEE International Conference on Mechatronics and Automation (ICMA)*, 06-09 August 2017, pp. 1134-1151. doi: 10.1109/ICMA.2017.8015831

[2] Malyar V., Hamola O., Maday V., Vasylchyshyn I. Static Characteristics of Asynchronous Motors with Series Reactive Power Compensation. *2019 9th International Conference on Advanced Computer Information Technologies (ACIT)* , 05-07 June 2019, pp. 141-144. doi: 10.1109/ACITT.2019.8780064

[3] Steciuk P. B., Bow G., Padimiti D. S., Painter F. D. Practical Application of Transient-Free Capacitor Switch (TFCS) Technology for Starting Large Induction Motors at a Texas Natural Gas Processing Plant. *2019 IEEE Petroleum and Chemical Industry Committee Conference (PCIC),* 09-12 September 2019, pp. 674-692. doi: 10.1109/PCIC30934.2019.9074495

[4] Wang D., Zhao J. Self-excitation Control of Squirrel-Cage Induction Motor Based on Super-Twisting Sliding Mode Algorithm. *2020 IEEE International Conference on Artificial Intelligence and Information Systems (ICAIIS),* 20-22 March 2020, pp. 500-504. doi: 10.1109/ICAIIS49377.2020.9194868

[5] Shestaka A. I., Melnikova L. V., Busher V. V. Upravlinnya Momentum Dvyguna v Elektropryvodi Konteynernogo Krana [Engine Torque Control in an Electric Drive]. *Elektromekhanichni I Energozberigaichi Systemy – Electromechanical and Energy-Saving Systems*, 2020, no. 2, pp. 25-34. (In Ukrainian). doi: 10.30929/2072-2052.2020.2.50.25-34

[6] Langlang G., Dezetty M., Mokhammad S., Stieven N. R. Transient in Electrical Power System under Large Induction Motor Starting Condition. *2020 2nd International Conference on Cybernetics and Intelligent System (ICORIS),* 27-28 October 2020, pp. 1-5. doi: 10.1109/ICORIS50180.2020.9320791

[7] Michaelides A., Nicolaou T. Starting and Running the Induction Motor with a Variable Capacitor. *2017 14th International Conference on Engineering of Modern Electric Systems (EMES),* 01-02 June 2017, pp. 87-90. doi: 10.1109/EMES.2017.7980388

[8] Guha A., Narayanan G. Impact of Undercompensation and Overcompensation of Dead-Time Effect on Small-Signal Stability of Induction Motor Drive. *IEEE Transactions on Industry Applications,* 2018, pp. 1-1. doi: 10.1109/TIA.2018.2846719

[9] Wang S., Lee F. C., Wyk J. D. Inductor Winding Capacitance Cancellation Using Mutual Capacitance Concept for Noise Reduction Application. *IEEE Transactions on Electromagnetic Compatibility*, 2006, no. 48(2), pp. 311-318. doi: 10.1109/TEMC.2006.873867

[10] Lekhchine S., Bahi T., Laouar I., Leulmi R. Control and Optimization for a Photovoltaic Pumping System Using Induction Motor Vector Control**.** *14th International Renewable Energy Congress*, 2023, pp. 307-324. doi: 10.1109/IREC59750.2023.10389517

[11] Salem E. Z. M., Cheema K. M., Al-Gahtani S. F. High Gain Boost Converter Fed Asynchronous Motor Drive for Water Pumping System. *International Journal of Electronics,* 2018, pp. 1-1. doi: 10.1109/TIA.201M.2846719

[12] Fangke Lu, Haifeng Li, Yongdong Chai, Jianyun A. Modulation Method to Eliminate Common-mode Voltage of Dual Three-Phase Motor. 2019 I*EEE Transportation Electrification Conference and Expo (ITEC)*, 19-21 June 2019, pp. 2014-2031. doi: 10.1109/ITEC.2019.8790480

[13] Vydmysh A. A., Yaroshenko A. G. *Osnovy Elektroprivoda. Teoriya i Praktika. Chastyna 1.* [Basics of an Electric Drive. Theory and Practice. Part I]. Vinniza, 2020. 387 p.

[14] Popovych O. M., Golovan I. V. Study of Starting Regimes of Induction Motors Using Equivalent Parameters of Quasi-3D Field Model. *Technical Electrodynamics.*, 2019, no. 1, pp. 34-37. doi: 10.15407/techned2019.01.034

[15] Qinesh G., Kailath B. Graph-Based Circuit Simulator for Switched Capacitor Circuits. *IEEE Design & Test*, 2022, vol. 39, no. 4, pp. 81– 89. doi: 10.1109/MDAT.2021.3053225

[16] Bokovi Y., Salami A., Mawugno Kodjo K., Dotche K., Bedja K. Comparative Study of the Voltage Drops Es- timation on Electrical Distribution grid: Case study of the Togolese Company of Electricity and Energy grid. *IEEE PES/IAS PowerAfrica*, 2019, pp. 255-260. doi: 10.1109/PowerAfrica.2019.8928838

[17] Berzan V., Patsyuk V., Ribacova G., Maevsky D.A. Long Line Mode Analysis with Superconducting Transformer. *2020 IEEE 15th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET),* 2022, pp. 670 – 675. doi: 10.1109/TCSET49122.2020.235516

[18] Vaskovskyi F., Tytko Y., Makeykin O. Kravchuk I. Diagnosis of Induction Motors Based on Analysis of Starting Electromagnetic Torque .

Technical Electrodynamics, 2017, no. 3, pp. 58-64. doi: 10.15407/techned2017.03. 058

[19] Beyhan H., Yal Ç. M., Kocamaz A. F. Matching Voltage Drop and Power Losses with GIS in Middle Voltage Electric Distribution Network in Diyarbakır. *International Artificial Intelligence and] Data Processing Symposium (IDAP)*, 2019, pp. 1-6. doi: 10.1109/IDAP.2019.8875899

[20] Sunal C. E., Dyo V., Velisavljevic V. Review of Machine Learning Based Fault Detection for Centrifugal Pump Induction Motors. *IEEE Access*, 2022, vol. 10, pp. 71344-71355. doi: 10.1109/ACCESS.2022.3187718

[21] Goolak, S., Gubarevych O., Yermolenko E, Slobodyanyuk M, Gorobchenko O. Development of Mathematical Model of Induction Motor for Vehicles. *Eastern-European Journal of Enterprise Technologies*, 2020, no. 2/2 (104), pp. 24-35. doi: 10.15587/1729- 4061.2020.199559.

[22] Ejiogu E. C., Tanno Y. Capacitor Self-Excitation Braking of the Induction Motor. *Proceedings of IECON Annual Conference of IEEE Industrial Electronics*, 2019, vol. 2, pp. 891-895. doi: 10.1109/IECON.1993.339157

[23] Rüncos F, Stringari E., Gaudeaux C. Benefits and Drawbacks of Low Inrush Large Induction Squirrel Cage Electric Motors. *IEEE Petroleum and Chemical Industry Technical Conference (PCIC)*, 2018, pp. 257-268. doi: 10.1109/PCIC31437. 2018.9080483

[24] Liu Y., Bazzi A. A. Review and Comparison of Fault Detection and Diagnosis Methods for Squirrel-Cage Induction Motors: State of the art . *ISA Transactions*, 2017, no. 70, pp. 400-409. doi: 10.1016/j.isatra.2017.06.001

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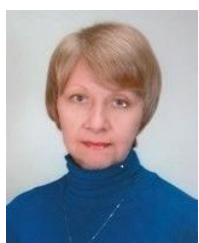
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