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Electric drive of coordinated rotation for mechanisms of flow-transport systems

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Abstract. The frequency method is currently recognized as the most technically and economically feasible approach for controlling alternating current electric drives. However, systems employing frequency-controlled electromechanical setups with stator circuits, while offering extensive capabilities, present a more intricate challenge for voltage frequency regulation compared to systems utilizing rotor circuits. This complexity arises from the fact that the power of a thyristor frequency converter is comparable to that of electric motors. Consequently, there is a pressing need in contemporary electromechanics for the development of innovative circuit solutions to regulate the performance of flow transport systems. This study aims to design a two-motor electric drive for the mechanisms of flow transport systems with medium to high power, aiming for improved energy efficiency. As a result of this study, it was found that utilizing a cascade circuit in a dual-motor electric drive, along with an additional power source in the rectified rotor current circuit, enables the synchronized rotation of two motors. This synchronization can be achieved not only with identical nominal parameters but also with differing power and synchronous frequency of rotation. The primary advantages of this coordinated rotation approach in a twin-motor electric drive using a cascade scheme include the ability to adjust the power factor of the machines and reduce the power transferred to the control circuit by the thyristor frequency converter, thereby enhancing the reliability of the electric drive's power components. Furthermore, by regulating the rotation frequency of two AC motors, it becomes feasible to enhance overall energy efficiency.

1. Introduction

Presently, energy conservation stands as a primary focus of innovative development in the Republic of Kazakhstan, reflected in the inclusion of energy-saving initiatives in nearly all significant strategic documents [1].

The integration of energy-efficient technologies is evident across six key sectors of innovative and industrial advancement: metallurgy, chemistry, petrochemistry, mechanical engineering, construction materials, and the food industry [2].

Notably, the industrial sector alone accounts for approximately 70% of total electricity consumption, with electric drives of flow-transport systems (FTS) contributing an average of 20% [3].



Flow transport systems in electricity refer to a network of interconnected conveyors or transport mechanisms within industrial settings that facilitate the continuous movement of goods or materials along production lines. These systems are integral to various industries such as manufacturing, mining, and logistics, where the efficient and seamless transfer of materials between different stages of production or processing is essential.

FTS typically consist of a series of conveyors, each designed for specific functions such as loading, transporting, sorting, and unloading. These conveyors may include belt conveyors, roller conveyors, screw conveyors, or pneumatic conveyors, depending on the nature of the materials being transported and the layout of the production facility.

Understanding the operational dynamics of FTS has become increasingly pertinent, given that the interconnected transport and technological lines within enterprises constitute a unified system. Moreover, the contemporary approach of flow production relies heavily on conveyor systems to facilitate the seamless transfer of goods between different stages of production [4]. Belt conveyors play a vital role in this process, maintaining production rhythm, enhancing labor efficiency, and bolstering output. Furthermore, they serve as primary tools for comprehensive mechanization and automation across both primary and ancillary production processes [5].

Typically, the automation system for a network of conveyor lines within an industrial facility must be capable of activating and deactivating different conveyors in a specific sequence, aligning closely with the production process. It ensures the precise speed of cargo transportation and, when needed, synchronizes the speed of various conveyors. Additionally, it manages the blocking of technological and emergency equipment as required [6].

Presently, the majority of FTS utilize adjustable direct current (DC) electric drives to power conveyor actuators [7]. Thyristor converters are employed to control the speed of DC machines within a relatively limited range, typically ranging from 500 to 1900 rpm of the motor shaft [8].

Regarding the electric drive, the FTS can be viewed as a load with static torque unaffected by speed variations. Operating continuously over extended periods, it experiences infrequent starts and stops. There are no stringent demands on the dynamics of the electric drive, and no limitations are placed on the characteristics of transient processes during start-up, braking, or speed transitions [9].

Based on the general attributes, it is evident that the operational demands on the electric drive under normal conditions are relatively modest. However, intermittent instances of sudden load spikes during operation, potentially leading to a substantial increase in static torque, up to the point of actuator jamming, cannot be discounted [10]. Moreover, electric machines operate within an environment laden with dust from construction materials. Hence, in the modernization of such electric drives, the primary focus lies in enhancing their reliability and performance characteristics. In such scenarios, transitioning to asynchronous electric drives with frequency regulation is proposed as a solution. These drives, in terms of functionality and performance, align with the technical requisites and operational conditions of the task at hand [11]. Nonetheless, in making decisions regarding modernization, it is imperative to accurately evaluate the associated costs and, more significantly, compare them with the resultant benefits.

As commonly acknowledged, the frequency method stands out today as the most technically and economically viable control method for alternating current (AC) electric drives [12]. Nevertheless, research indicates that frequency-controlled electromechanical systems utilizing stator circuits, while offering extensive functionalities, pose a technically more intricate challenge for voltage frequency regulation compared to regulation through rotor circuits. This complexity arises from the fact that the power of a thyristor frequency converter (TFC) is comparable to that of electric motors [13].

Consequently, the advancement of novel circuit solutions for regulating the performance of FTS emerges as a pressing task within contemporary electromechanics.

2. Circuit design for cascade connection of two asynchronous motors

Figure 1 illustrates a functional schematic of a dual-motor electric drive of coordinated rotation featuring a cascade arrangement of two asynchronous motors. In this configuration, the rotor windings of the asynchronous motors are linked in series via a controlled rectifier (CR) within the rotor circuit of the first motor (AM1) and an inverter (I) within the rotor circuit of the second motor (AM2), collectively referred to as a thyristor frequency converter.

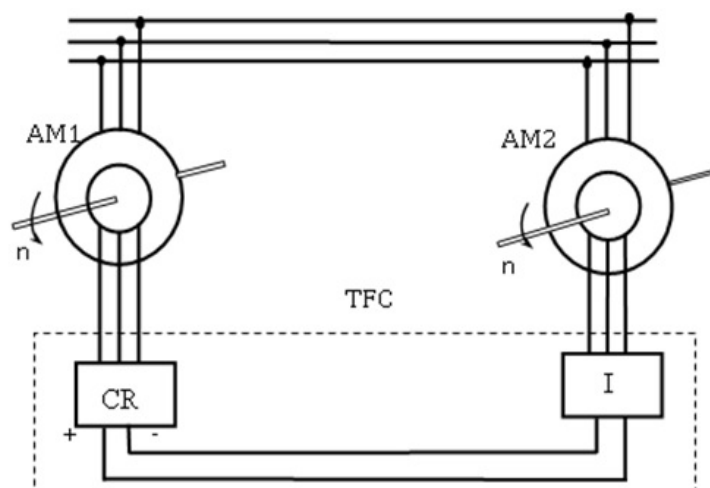


Figure 1. Functional diagram of a double-motor electric drive.

An inherent characteristic of this system is its notable energy efficiency, achieved by harnessing the regenerative energy from the first asynchronous motor to power the thyristor frequency converter within the rotor circuit of the second motor [14].

Consequently, the efficiency of the dual-motor electric drive experiences a substantial boost, particularly as the installed power of the motors increases, further enhancing the system's overall efficiency [15].

For investigating the dynamic characteristics of the coordinated rotation electromechanical system in FTS mechanisms, we conduct computer simulations of a two-motor electric drive setup. This configuration comprises two asynchronous motors with wound rotors, with one motor connected via an asynchronous valve cascade (AVC) circuit and the other connected through a dual-fed machine (DFM) circuit [16, 17].

Figure 2 shows a simulation model of a two-motor electric drive corresponding to the functional diagram shown in figure 1.

3. Results

3.1. Computer simulation results

Computer simulation of a dual-motor electric drive was carried out in the MatLab system. Dynamic characteristics of a two-motor electric drive obtained at various values β (opening angles of the thyristors of the rectifier group) are shown in figure 3 and figure 4.

Examination of the dynamic traits reveals a distinction between the second motor, linked via the dual-power circuit, and the first motor, connected through the valve cascade circuit. Despite identical parameters in the equivalent circuits of both motors, the sliding power directed to the rotor windings of the second asynchronous motor proves inadequate to replicate the characteristics of the first motor [18]. Consequently, an additional power source in the rectified current circuit of the motor rotor is deemed necessary [19].

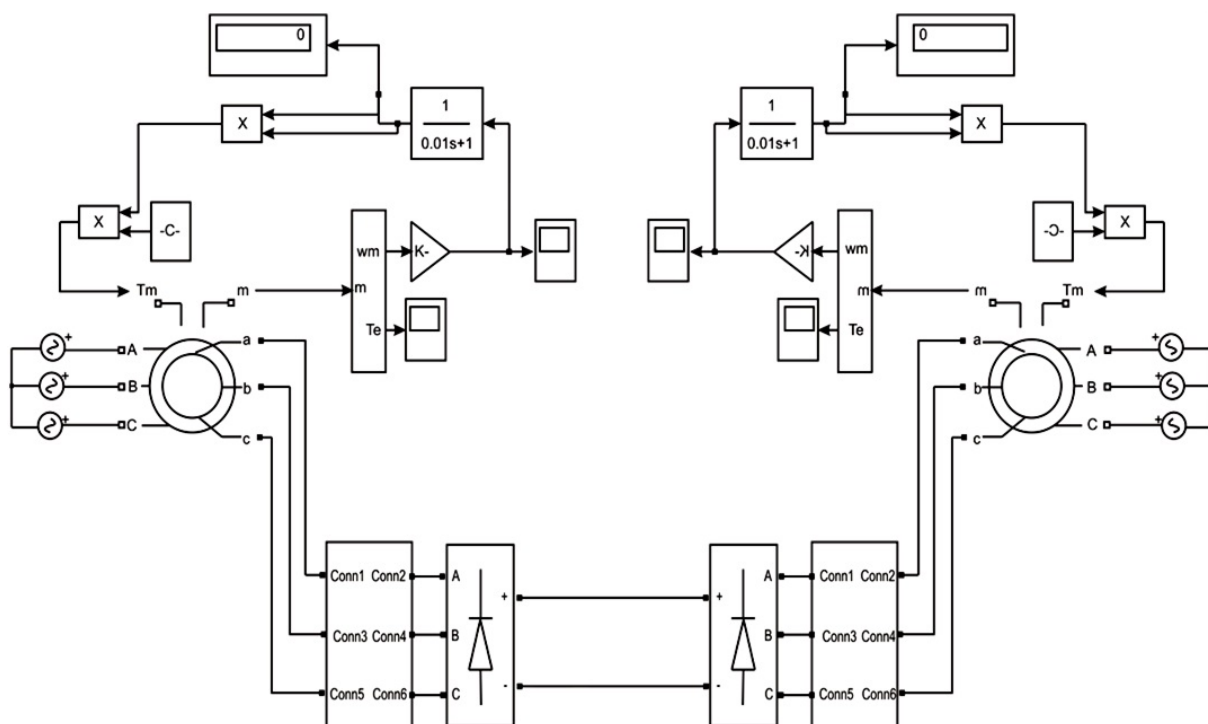


Figure 2. Simulation model of a control circuit for two asynchronous motors in the MatLab environment.

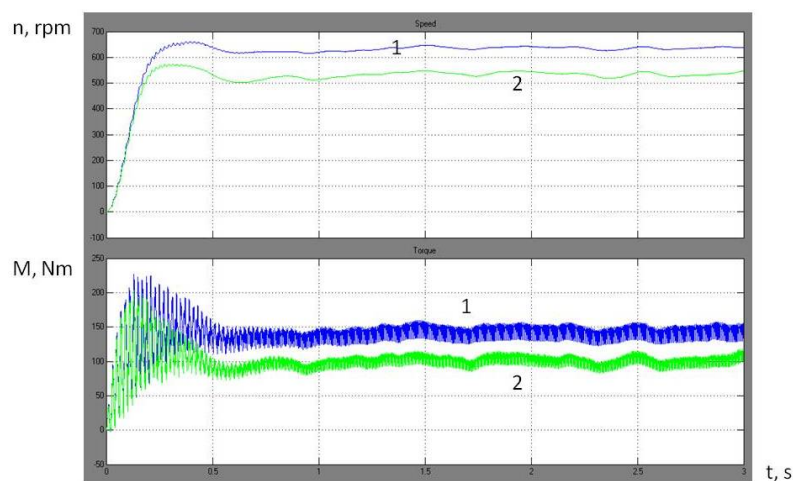


Figure 3. Dynamic characteristics of a two-motor electric drive at $\beta = 30^\circ$: 1 – characteristics of the first motor; 2 – characteristics of the second motor.

3.2. Circuit design with an additional source in the rotor rectified current circuit

A functional diagram of a two-motor electric drive with an additional power source in the rectified current circuit of the rotors of two asynchronous motors is shown in figure 5.

Then, when determining the value of the current in the rotor windings of the second motor, one must proceed from the condition [20]:

$$I_2 = k_i I_{dp} = k_i (I_d + I_{ad}) \leq I_2, \quad (1)$$

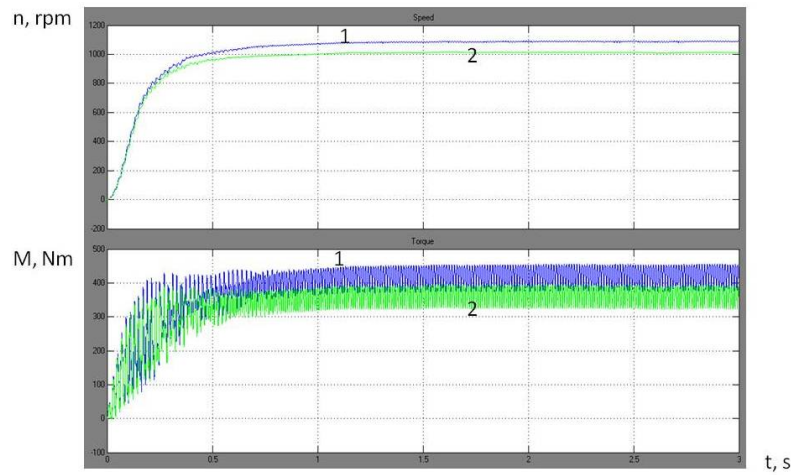


Figure 4. Dynamic characteristics of a two-motor electric drive at $\beta = 60^\circ$: 1 – characteristics of the first motor; 2 – characteristics of the second motor.

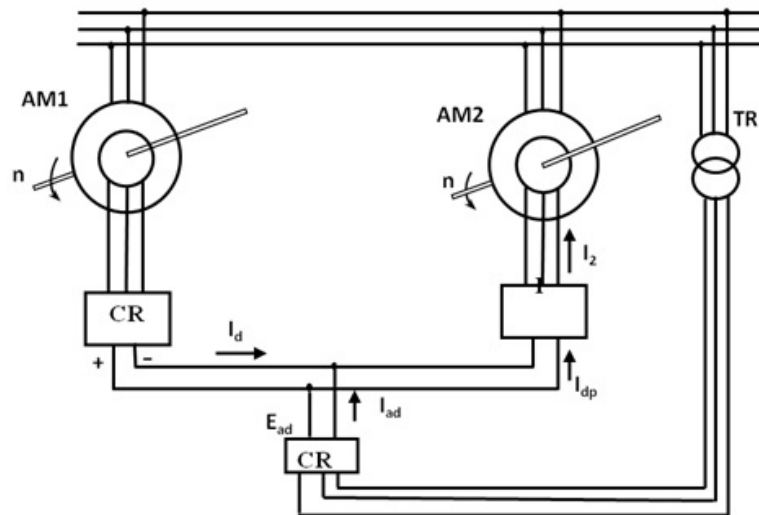


Figure 5. Functional diagram of a double-motor electric drive with an additional power source in the rotor rectified current circuit.

where $I_{dp} = (I_d + I_{ad})$ is rectified current with an additional source, $k_i = 0.815$ is coefficient for current in a three-phase bridge circuit [21].

Additional current [22]:

$$I_{ad} = \frac{E_{ad}}{R_{ad}} = \frac{k_3 U_{tr} \cos \alpha}{R_{ad}}, \quad (2)$$

where $R_{ad} = \frac{3x_{p2s2}}{\pi} + 2r_{p2} + r_{cd}$ is additional resistance [23].

To determine U_{tr} we assume that $\cos \alpha = 1$, $\cos \beta = 0$, then:

$$I_{ad} = \frac{k_3 U_{tr}}{R_{ad}}. \quad (3)$$

The rated value of the rectified current with an additional power source is determined from

the condition [24]:

$$I_{dp} = k_i (I_{dnom} + I_{ad}) \leq I_{2nom}, \quad (4)$$

where I_{2nom} is rated current in the rotor windings of the second motor.

Then:

$$\frac{k_3 U_{tr}}{R_{ad}} + I_{dnom} \leq \frac{I_{2nom}}{k_i}, \quad (5)$$

where $I_{dnom} = I_d$, at $\cos\beta = 0$, $s_{1nom} = s_1$, $I_{dnom} = \frac{\pi k_1 E_{p1}}{3x_{p1}} \frac{s_{1nom} - \lambda}{(s_{1nom}(1+k_s q) + \rho)}$ [25].

From here:

$$k_3 U_{tr} = \left(\frac{I_{2nom}}{k_i} - I_{dnom} \right) R_{ad}, \quad (6)$$

where $k_3 = 0.9$ for a three-phase bridge circuit [26, 27].

After conversion:

$$U_{tr} = \frac{R_{ad}}{k_3} \left(\frac{I_{2nom}}{k_i} - I_{dnom} \right). \quad (7)$$

Thus, at low slip values, in order to ensure synchronous rotation of two motors in a cascade circuit, an additional power source must be provided in the rotor rectified current circuit I_{ad} , the output of which changes according to the above law [28].

Figure 6 shows a simulation model of a two-motor electric drive corresponding to the functional diagram shown in figure 5.

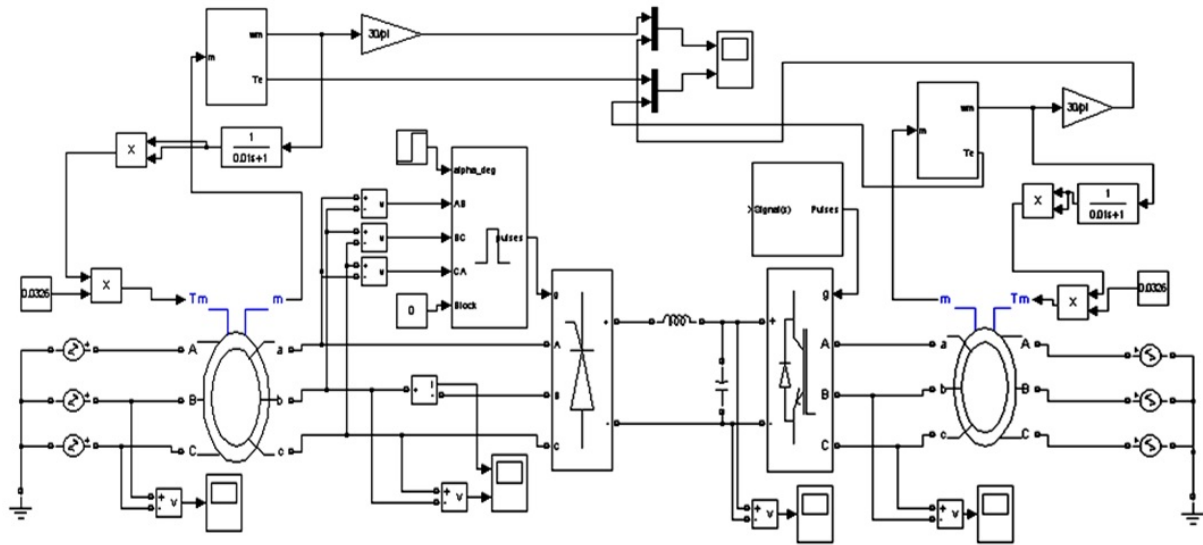


Figure 6. Simulation model of a control circuit for two asynchronous motors in the MatLab environment with an additional power source.

As can be seen from the last figure 7 and figure 8, after connecting an additional power source to the rectified rotor current circuit, the dynamic characteristics of the two motors coincide.

For computer simulation, we utilized the technical specifications of 200 kW motors of type AKN355S6U3 with a rotation frequency of 1000 rpm. The simulation was conducted using MATLAB software, simulating start-up under rated load conditions and assuming even distribution of load on the motor shaft.

To assess the energy-saving and resource-efficient characteristics of the proposed coordinated rotation electric drive scheme, we will compare various systems of double-motor electric drives (DMED) by analyzing technical and economic parameters.

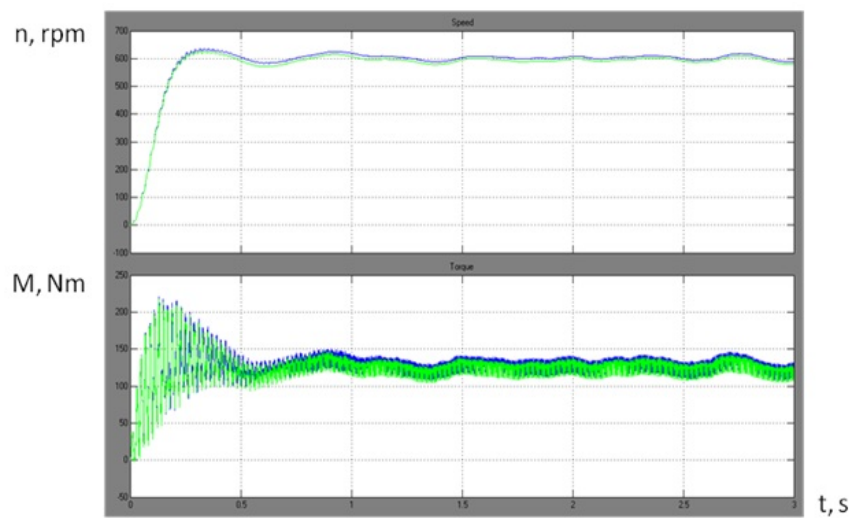


Figure 7. Dynamic characteristics of a two-motor electric drive at $\beta = 30^\circ$.

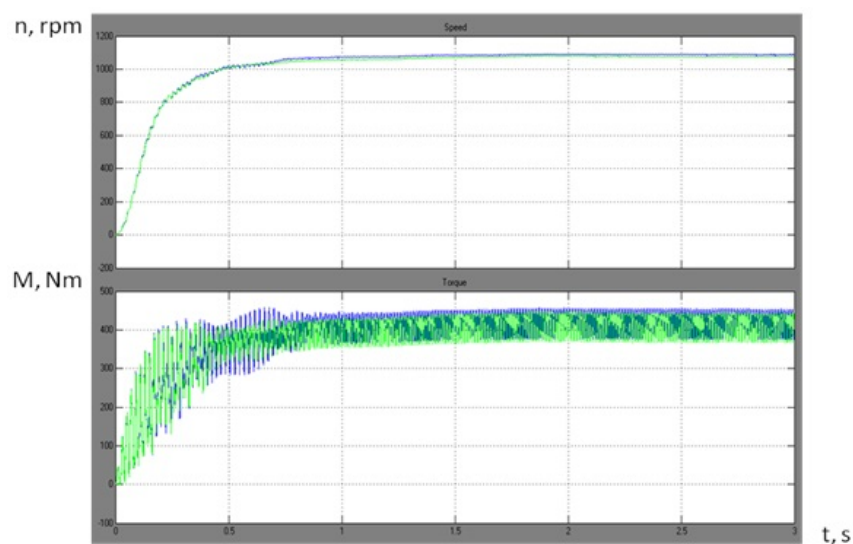


Figure 8. Dynamic characteristics of a two-motor electric drive at $\beta = 60^\circ$.

The installed power of electric motors and power thyristors or TFCs play a significant role in determining the weight, size, and cost of DMED systems. These factors are crucial indicators of DMED performance and largely hinge on the structural diagram of the DMED, the types of TFCs and electrical machines employed, as well as their operational modes. Consequently, these indicators serve as key criteria for comparing different DMED configurations.

As the weight, size, and cost of DMED are primarily influenced by power, rotation frequency, as well as the types of electrical machines and thyristor (or transistor) frequency converters, we derived dependencies of specific cost and mass of these components based on power.

The assessment of cost and weight-size indicators for electrical machines and TFCs relies on specific statistical data concerning commercially available standard sizes of these devices. Analyzing the cost of AC electric machines suggests that evaluating the unit cost as the ratio

of the machine's cost to its power is a more practical approach, i.e.

$$C_m = \frac{C_e}{P} = \frac{K_s}{\sqrt[4]{P}}, \quad (8)$$

where C_e is the cost of an electric machine, in conventional units (cu); P is machine power, kW; K_s is specific cost indicator at a given rotation frequency and $f = 50$ Hz. If we take an asynchronous motor with a power of 100 kW as the base machine, then at $n_s = 750$ rpm, $K_s = 60$; at $n_s = 1000$ rpm, $K_s = 48$; at $n_s = 1500$ rpm, $K_s = 35$.

It's important to highlight that the specific cost of an asynchronous motor with a wound rotor is typically 10–12% higher than that of an asynchronous motor with a squirrel-cage rotor, given the same power and speed.

Figure 9 illustrates the relationship between the specific cost of an asynchronous machine with a wound rotor and power at different rotation frequencies. From the graph, it's evident that the specific cost of the machine increases as the synchronous rotation frequency decreases. This indicates that high-speed electric machines are more cost-effective than their low-speed counterparts.

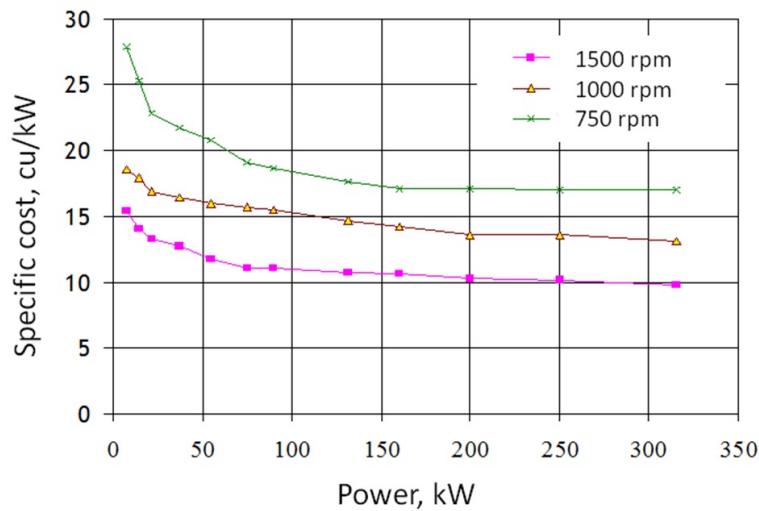


Figure 9. Dependence of the unit cost of an asynchronous machine on power at various rotation frequencies.

A similar dependence would be applicable for TFCs, indicating that

$$C_{TFC} = \frac{C_{TF}}{P_{TFC}} = \frac{K_{TF}}{\sqrt[4]{P_{TFC}}}, \quad (9)$$

where C_{TF} and P_{TFC} are the cost in USD and power in kW TFC; K_{TFC} is specific indicator of TFC power; $K_{TFC} = 510$ and $K = 0.333$ for a transistor frequency converter.

To conduct a technical and economic evaluation of DMED, we examined the following systems:

1. Frequency-controlled dual-motor electric drive (with TFC situated in the stator circuit of each motor).
2. Double-motor electric drive utilizing a dual-power machine (with TFC positioned in the rotor circuit of each motor).

3. Two-motor electric drive incorporating an asynchronous valve cascade and a dual-power machine (with one TFC situated in the rotor circuit of two motors).

The specific cost of a frequency-controlled DMED, with TFC located in the stator circuit, is determined by the following expression:

$$C_{1DMED} = 2(C_{as} + C_{TFC}), \quad (10)$$

where C_{as} is the specific cost of one asynchronous motor; C_{TFC} is cost of TFC.

The specific cost of DMED based on dual-fed machines (figure 1), when the TFC is in the circuit of each rotor, is determined by the following expression

$$C_{2DMED} = 2(C_{as} + C_{CTFC}), \quad (11)$$

where C_{CTFC} is cost of the TFC in the rotor circuit.

The specific cost of DMED based on AVC–DFM, when there is one TFC in the rotor chain of two engines, is determined by the following equality

$$C_{3DMED} = 2C_{as} + C_{CTFC}. \quad (12)$$

It's worth mentioning that the power rating of the TFC in the stator circuit closely matches that of asynchronous motors. Consequently, the variable frequency electric drive system along the stator circuit is more costly compared to the electric drive utilizing the dual-power machine circuit.

The TFC power in the rotor circuit will be equal to

$$P_{TFC} = sP_1, \quad (13)$$

where s is slip, the maximum value of which depends on the control range (for most general industrial motors $s_{max} = 0.3$); P_1 is the power of an asynchronous motor with a wound rotor.

Figure 10 illustrates the relationship between the specific cost of different DDPS systems and the power of the primary engines. It's evident from the graph that this indicator remains relatively constant across a wide power range. The DMED system following the AVC–DFM scheme proves to be more economical compared to DMED systems employing the TFC scheme in both the stator and rotor circuits of each engine. An examination of the weight and size parameters of electric machines can be conducted based on specific static data regarding commercially manufactured motors.

As is known, for an alternating current machine the following equality is true:

$$G_{em} = \frac{G}{P} = \frac{K_g}{\sqrt[4]{P}}, \quad (14)$$

where G is the mass of the electric machine, kg; P is machine power, kW; K_g is specific mass indicator at a given rotational speed and $f = 50$ Hz. If we take an asynchronous machine with a power of 100 kW as the base machine, then at $n_s = 750$ rpm, $K_g = 24$; at $n_s = 1000$ rpm, $K_g = 19.8$; at $n_s = 1500$ rpm, $K_g = 16$.

As demonstrated, a comparative assessment of DMED systems concerning cost, weight, and size indicators reveals that the DMED system following the AVC–DFM scheme is considerably more economical across the entire power spectrum compared to DMED systems adopting the TFC–AM and DFM schemes. Moreover, it does not compromise on weight and size indicators.

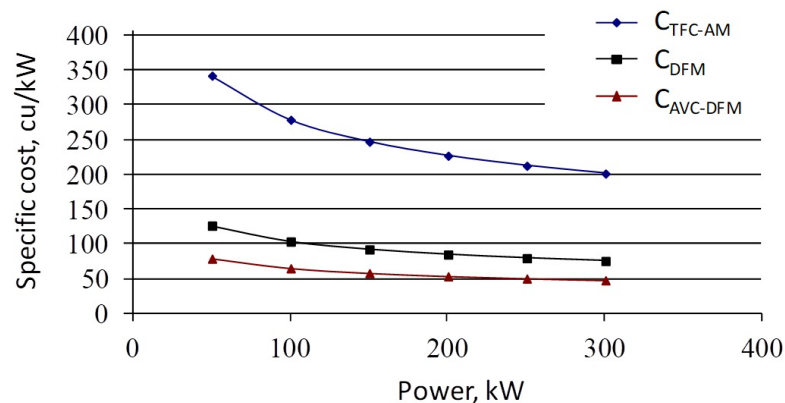


Figure 10. Dependence of the unit cost of an asynchronous machine on power at various rotation frequencies.

4. Conclusions

Therefore, employing a cascade circuit in a dual-motor electric drive, supplemented by an additional power source in the rectified rotor current circuit, enables the synchronized rotation of two motors. This synchronization can be achieved not only with identical nominal parameters but also with differing power and synchronous frequency of rotation.

The primary advantages of this approach to coordinated rotation in a twin-motor electric drive using a cascade scheme include the capacity to adjust the power factor of the machines. Moreover, it reduces the power transferred to the control circuit by the thyristor frequency converter, thus enhancing the reliability of the electric drive's power components. By regulating the rotation frequency of two AC motors, it becomes feasible to enhance energy efficiency [29,30].

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