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IMPROVING THE INDUCTION MOTOR STARTING MODE UNDER A VOLTAGE DROP CONDITIONS

Oleksandr Vovk[1], Serhii Halko[1], Andrii Sabo[1], Oleksandr Miroshnyk[2], Taras Shchur[3]

[1]Dmytro Motornyi Tavria State Agrotechnological University, Department of Electrical Engineering and Electromechanics Named after prof. V.V. Ovharov, Zaporizhia, Ukraine, [2]State Biotechnological University, Department of Electricity Supply and Energy Management, Kharkiv, Ukraine, [3]State Biotechnological University, Department of Agricultural Engineering, Kharkiv, Ukraine

Abstract. *Asynchronous motors are the most common electric motors used to drive work machines. This is due to their high structural reliability and other significant advantages. During operation, they are exposed to a variety of operational influences. One of the most frequent of these is a voltage dip. As a result of this influence, the performance of the electric motor deteriorates both in steady-state and starting modes. A voltage drop is especially dangerous when starting an electric motor, as it leads to an increase in starting time and a decrease in starting torque. The thermal effect of inrush currents during a voltage dip can lead to motor failure. Therefore, the article proposes to increase the voltage in one of the phases of an induction motor during the startup period under conditions of voltage dip. To assess this technical impact, a methodology has been developed for studying the starting torque and starting time of an induction motor under conditions of rated voltage, voltage dip, and voltage asymmetry. It takes into account the voltage reduction factor, the voltage ratios of the forward and reverse sequences, and the motor load factor. The evaluation criteria are the starting torque of the motor and its starting time. The paper compares these criteria according to the developed methodology in the following cases: nominal mains voltage, mains voltage dip, mains voltage dip with an artificial increase in voltage in one of the induction motor phases. The results of the comparison in these cases showed the effectiveness of artificial voltage asymmetry for the period of starting the motor during a voltage dip. To implement the proposed idea, a block diagram of a device for improving the starting mode of an induction motor under voltage dip conditions was drawn up.*

Keywords: asynchronous motor, reduced voltage, starting mode

POPRAWA TRYBU ROZRUCHU SILNIKA INDUKCYJNEGO W WARUNKACH SPADKU NAPIĘCIA

Streszczenie. *Silniki asynchroniczne są najczęściej stosowanymi silnikami elektrycznymi do napędzania maszyn roboczych. Wynika to z ich wysokiej niezawodności konstrukcyjnej i innych istotnych zalet. Podczas pracy są one narażone na różne wpływy operacyjne. Jednym z najczęstszych z nich są zapady napięcia. W wyniku tego wpływu wydajność silnika elektrycznego pogarsza się zarówno w stanie ustalonym, jak i podczas rozruchu. Spadek napięcia jest szczególnie niebezpieczny podczas rozruchu silnika elektrycznego, ponieważ prowadzi do wydłużenia czasu rozruchu i zmniejszenia momentu rozruchowego. Efekt termiczny prądów rozruchowych podczas spadku napięcia może prowadzić do awarii silnika. Dlatego w artykule zaproponowano zwiększenie napięcia w jednej z faz silnika indukcyjnego w okresie rozruchu w warunkach spadku napięcia. Aby ocenić ten wpływ techniczny, opracowano metodologię badania momentu rozruchowego i czasu rozruchu silnika indukcyjnego w warunkach napięcia znamionowego, spadku napięcia i asymetrii napięcia. Uwzględnia ona współczynnik redukcji napięcia, stosunki napięć sekwencji do przodu i do tyłu oraz współczynnik obciążenia silnika. Kryteriami oceny są moment rozruchowy silnika i jego czas rozruchu. W artykule porównano te kryteria zgodnie z opracowaną metodologią w następujących przypadkach: nominalne napięcie sieciowe, zanik napięcia sieciowego, zanik napięcia sieciowego ze sztucznym wzrostem napięcia w jednej z faz silnika indukcyjnego. Wyniki porównania w tych przypadkach wykazały skuteczność sztucznej asymetrii napięcia w okresie rozruchu silnika podczas zapadu napięcia. W celu realizacji proponowanego pomysłu opracowano schemat blokowy urządzenia do poprawy trybu rozruchu silnika indukcyjnego w warunkach zapadu napięcia.*

Słowa kluczowe: silnik asynchroniczny, obniżone napięcie, tryb rozruchu

Introduction

At the present stage of industrial development electrical energy is used in many technological processes. Its main consumers are electric motors, which account for about 52% of the consumed electricity [11, 29]. Among them, induction motors are the most widespread – about 90% of the total market share of low-voltage motors [36]. This is due to their low cost, high structural reliability and many other factors [2]. However, in practice, the operational reliability of induction motors is lower than the structural one [9, 20]. In some industries the number of motors that fail before the guaranteed term can reach 25% [34, 40]. One of the reasons for this is the influence from the electrical network as electric motors were not designed and manufactured for some unproper network parameters. These include voltage dips, overvoltages, voltage asymmetries, higher voltage harmonics, short circuits, etc. [1, 13]. Among these effects, voltage dips are most often observed, which lead to additional heating of induction motors and other negative effects [5, 21]. The causes of voltage dips are short circuits in the network, saturation of the power transformer, starting of a high-power electric motor, etc. [19]. Voltage dips are especially dangerous during the start-up of an induction motor with a load on the shaft, when the current consumed is several times higher than the nominal value [25]. When starting an electric motor under such conditions, the starting time, slip, and torque increase [14, 23]. At a certain voltage dip it may not even start, and its insulation will overheat and fail [22]. Economic losses due to the shutdown of electric motors due to voltage dips range on average from 8000 to 20000 dollars per dip according to various data [6, 27].

1. Literature review

Recently, developments to improve the starting mode of induction motors under voltage dips have been carried out in two directions mainly. According to the first direction, the improvement is carried out at the location of the power source, according to the second - at the location of the induction motor [30]. In [18] the authors propose to switch the electric motor to another feeder in the event of a voltage drop at the terminals of one power feeder. For this purpose coordination of local control of several VSDGs is used by feedback signals and subsequent gain control for the PI controller. It is shown that in low-voltage networks the proposed system can quickly restore the voltage without the need for any voltage regulation devices. However, the authors do not take into account the load on the source and the power transmission line for the performed switching. The authors of [35] propose to use an inverter to raise the voltage in the event of its drop, which is based on the principle of sequential voltage supply to the distribution network. An energy storage device is connected to its input terminals. The output terminals of the inverter are connected to the distribution feeders through an injection three-phase transformer. The system mitigates voltage dips, but does not take into account the power of the load connected to it and has a significant cost.

In [7] the authors propose a system for raising the voltage in the event of a voltage dip. It includes an intelligent inverter with a controller controlled by artificial intelligence and a photovoltaic panel is used as an additional voltage source [15]. Such a system allows you to quickly raise the voltage to the required level, but has a high cost of technical implementation and can be applied to large asynchronous motors of responsible mechanisms. In [16] it is proposed to smooth out voltage dips in the power supply system of electric motors using a superconducting magnetic energy storage device, the control strategy includes fuzzy logic. The system has a significant cost and is used for a group of high-power asynchronous motors. The authors of [30, 38] propose to compensate the symmetrical voltage drop in the network when electric motor starting with a buffer source of electricity. They propose to use a block of supercapacitors as such a source, for which an operating algorithm has been developed. The mentioned article has conducted simulation modeling and shown some good results. However, the authors did not take into account the possibility of ferroresonance in the "asynchronous motor – supercapacitor" system in the presented model. The authors of [28] propose the use of static reactive power compensators together with a combined controller to eliminate voltage dips when starting asynchronous motors. Such a system allows not only to increase the voltage and torque of the electric motor, but also the power factor. It is profitable to use it only for large motors. In [16], an approach is proposed to mitigate the voltage dip during the start of an electric motor using distributed generation with voltage support. It is proved that such a system restores the voltage level faster than conventional regulators. It is used for motors of significant power. The authors of [33] propose a strategy for compensating for voltage dips in power system networks with AC drives. Its technical basis is an additional source of constant voltage stabilizing the voltage in the network through a converter, filter and injection transformers. The disadvantages of this strategy include the significant cost of technical implementation. Another direction of development in combating voltage dips of asynchronous motors during start-up are various protection devices. The essence of these developments is to turn off the asynchronous motor when the voltage drop at its terminals is unacceptable [26, 32]. Thus, the current solutions for combating voltage dips of asynchronous motors during start-up require the presence of an additional energy source, which leads to significant cost of technical implementation, or to turn off the electric motor.

Based on the results of the analysis presented above, the paper hypothesizes that in the event of a voltage drop during the start-up of an asynchronous motor, a short-term voltage asymmetry at the terminals of the electric motor should be used to improve its starting mode. Its confirmation will allow the asynchronous motor not to be turned off during start-up under voltage drop conditions and will not require significant technical implementation costs.

2. Materials and methods

To verify the mentioned hypothesis, the process of starting an asynchronous motor at different load factors under the following conditions was considered: 1) nominal voltage at the terminals of the electric motor; 2) voltage drop at the terminals of the electric motor; 3) increase in voltage in one of the phases of the electric motor during a voltage drop. The starting torque and starting time were selected as parameters for whose value comparison in the three cases.

The starting torque was determined according to well-known dependencies [3, 10, 12]. In the case of nominal voltage or voltage drop as follows:

$$M_S = k_u^2 \cdot \mu_S \cdot M_N \tag{1}$$

where k_u is the electric motor voltage deviation coefficient; μ_S is the electric motor starting torque multiplicity; M_N is the electric motor torque at rated load and rated voltage, N·m;

$$k_u = U/U_N \tag{2}$$

where U, U_N – respectively the current and nominal voltage at the terminals of the electric motor, V.

At nominal voltage $k_u = 1$, at voltage failure $k_u < 1$.

In the case of asymmetrical voltage, the starting torque was determined as follows:

$$M_S = \left(k_{u1}^2 - k_{u2}^2\right) \cdot \mu_S \cdot M_N \tag{3}$$

where k_{u1}, k_{u2} – are the voltage coefficients of the forward and reverse sequences, respectively;

$$k_{u1} = U_1/U_N \text{ ; } k_{u2} = U_2/U_N \tag{4}$$

where U_1, U_2 are the forward and reverse sequence voltages at the terminals of the electric motor, V.

If in (3) we have

$$k_{u1}^2 - k_{u2}^2 = 1 \tag{5}$$

then the starting torque of the electric motor will be the same as at nominal voltage.

It is assumed that under a voltage drop during start-up the voltage modules in the phases of the electric motor decrease equally, and their phases remain unchanged. Then the artificial voltage asymmetry for the start-up period should be characterized by the forward and reverse sequence voltages, the equations of which after transformation are as follows:

$$U_1 = \frac{1}{3}\left(U_a + 2 \cdot k_u U_N\right) ; U_2 = \frac{1}{3}\left(U_a - k_u U_N\right) \tag{6}$$

After substituting (6) into (4) and (5) and proper transformations, the equation of the voltage on phase "a" of an asynchronous motor, which should be when creating artificial asymmetry for the starting period, so that the starting torque is the same as at the nominal voltage, is obtained:

$$U_a = \frac{3 - k_u^2}{2 \cdot k_u} \cdot U_N \tag{7}$$

A new calculation method was developed to determine the starting time of an asynchronous motor. This is due to the fact that existing methods for analytically determining the starting time of an asynchronous motor do not allow it to be calculated in the three modes specified above. In [8], a nonlinear equation for the starting time of an electric motor is proposed as a function of the parameters of the Thevenin equivalent circuit. Its solution is carried out by an iterative procedure based on the Lambert function. The specified method is rather cumbersome due to the iteration procedure, it does not take into account the load of the asynchronous motor, the dip and the asymmetry of the supply voltage. The authors of [24] propose to calculate the starting time of an electric motor using an algorithm obtained on the basis of the Kloss equation. However, the Kloss equation does not accurately reflect the change in the torque of the electric motor from the starting to the critical one, and the specified algorithm does not allow taking into account the dips, voltage asymmetry and the load value of the asynchronous motor. In addition, this calculation method shows that the starting time decreases with an increase in the moment of inertia of the system, which is not true. In [4] it is proposed to calculate the starting time of an electric motor based on its catalog information (starting torque, critical torque, rated torque, rated slip, parameters of the equivalent circuit), taking into account the voltage dip of the electric motor and its load at start-up. When determining the starting time, it is necessary to find the roots of the fourth-order equation, which introduces certain inconveniences. This calculation method gives satisfactory results compared to dynamic modeling, but these results, according to the author, differ significantly from the passport data of the electric motor. In addition, this calculation method does not take into account the asymmetry of the electric motor voltage at start-up [37, 39].

The mechanical characteristic of the electric motor in a linearized form shown in Fig. 1 is considered to obtain equations for the starting time of an asynchronous motor that would take into account its load as well as the voltage dip and its asymmetry.

Fig. 1 shows the mechanical characteristic of an asynchronous motor provided that it is powered by the rated voltage. It shows the points of the mechanical characteristic with their coordinates: M_S, M_{min}, M_C, M_N – respectively, the starting, minimum at starting, critical and nominal torques of the electric motor at the rated voltage, N·m; ω_{min}, ω_C, ω_N, ω_0 – respectively, the minimum, critical, nominal and synchronous angular velocities of the electric motor rad/s. It is assumed that the normal operation of the electric motor at start-up occurs sequentially in sections 1-2, 2-3 and 3-4.

The equations of the sections of the mechanical characteristic are as follows:

$$\begin{vmatrix} M_{12} & \omega_{12} & 1 \\ M_S & 0 & 1 \\ M_{min} & \omega_{min} & 1 \end{vmatrix} = 0; \quad \begin{vmatrix} M_{23} & \omega_{23} & 1 \\ M_{min} & \omega_{min} & 1 \\ M_C & \omega_C & 1 \end{vmatrix} = 0; \quad \begin{vmatrix} M_{34} & \omega_{34} & 1 \\ M_C & \omega_C & 1 \\ M_N & \omega_N & 1 \end{vmatrix} = 0 \quad (8)$$

where M_{12}, M_{23}, M_{34} – current torque of the electric motor at rated voltage, respectively, on sections 1-2, 2-3, 3-4 of the mechanical characteristic, N·m; ω_{12}, ω_{23}, ω_{34} – current angular velocity of the electric motor at rated voltage, respectively, on sections 1-2, 2-3, 3-4 of the mechanical characteristic, rad/s.

From (8) the current torques of the electric motor are expressed, they are substituted into the basic equation of the electric drive motion and solved for the time of the electric motor motion on separate sections of the mechanical characteristic. As a result, taking into account (1), (2), the equation of the start-up time of an asynchronous motor on separate sections in the case of rated voltage or voltage drop is obtained:

$$t_{12} = \frac{J \cdot \omega_{min}}{M_N \cdot k_u^2 \cdot (\mu_S - \mu_{min})} \cdot \ln \frac{k_u^2 \cdot \mu_S - k_L}{k_u^2 \cdot \mu_{min} - k_L} \quad (9)$$

$$t_{23} = \frac{J \cdot (\omega_{min} - \omega_C)}{M_N \cdot k_u^2 \cdot (\mu_C - \mu_{min})} \cdot \ln \frac{\omega_{min} - \omega_C \cdot \dfrac{k_u^2 \cdot \mu_{min} - k_L}{k_u^2 \cdot \mu_C - k_L}}{\omega_{min} - \omega_C} \quad (10)$$

$$t_{34} = \frac{J \cdot (\omega_C - \omega_N)}{M_N \cdot k_u^2 \cdot (1 - \mu_C)} \cdot \ln \frac{\omega_C - \omega_N \cdot \dfrac{k_u^2 \cdot \mu_C - k_L}{k_u^2 - k_L}}{\omega_C - \omega_N} \quad (11)$$

where J is the moment of inertia of the electric motor, kg·m^2; μ_{min}, μ_C are the multiplicity of the minimum starting and critical moments of the electric motor, respectively; k_L is the load factor of the electric motor.

Taking into account (3), (4), the equation of the starting time of an asynchronous motor in separate sections in the case of asymmetrical voltage is obtained:

$$t_{12} = \frac{J \cdot \omega_{min}}{M_N \left(k_{u1}^2 - k_{u2}^2\right)\left(\mu_S - \mu_{min}\right)} \cdot \ln \frac{\left(k_{u1}^2 - k_{u2}^2\right)\mu_S - k_L}{\left(k_{u1}^2 - k_{u2}^2\right)\mu_{min} - k_L} \quad (12)$$

$$t_{23} = \frac{J \cdot (\omega_{min} - \omega_C)}{M_N \left(k_{u1}^2 - k_{u2}^2\right)\left(\mu_C - \mu_{min}\right)} \cdot \ln \frac{\omega_{min} - \omega_C \dfrac{\left(k_{u1}^2 - k_{u2}^2\right)\mu_{min} - k_L}{\left(k_{u1}^2 - k_{u2}^2\right)\mu_C - k_L}}{\omega_{min} - \omega_C} \quad (13)$$

$$t_{34} = \frac{J \cdot (\omega_C - \omega_N)}{M_N \left(k_{u1}^2 - k_{u2}^2\right)\left(1 - \mu_C\right)} \cdot \ln \frac{\omega_C - \omega_N \dfrac{\left(k_{u1}^2 - k_{u2}^2\right)\mu_C - k_L}{k_{u1}^2 - k_{u2}^2 - k_L}}{\omega_C - \omega_N} \quad (14)$$

$$t_n = t_{12} + t_{23} + t_{34} \quad (15)$$

In order for the starting time at voltage drop to be the same as at nominal voltage, it is necessary to increase the voltage in phase "a" of the electric motor for the starting period according to (7).

In (9)–(15), unlike [8, 24], the widely known passport data of the electric motor are used for the calculation and its load, drop and asymmetry of the applied voltage are taken into account; and unlike [4], the asymmetry of the applied voltage is taken into account. Also, the proposed method for calculating the starting time differs from [4, 8, 24] in its simplicity and convenience and allows comparing the starting time of an asynchronous motor under different conditions: at nominal voltage, at voltage drop and with an increase in voltage in one of the phases of the electric motor in the event of a voltage drop.

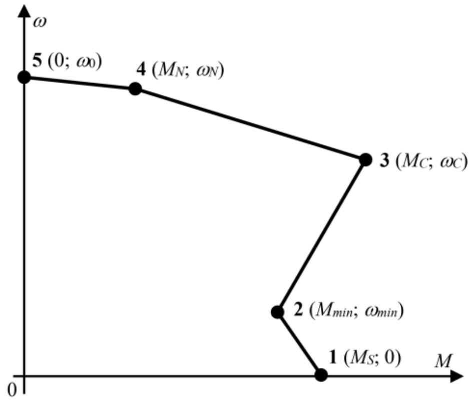

Fig. 1. Mechanical characteristics of an induction motor in linearized form

3. Research and discussion

An asynchronous motor of the AIR132M4 brand with a capacity of 11 kW was selected for the study. For this motor U_N = 220 V, J = 0.04 kg·m^2, ω_N = 152.6 rad/s, ω_C = 126.4 rad/s, ω_{min} = 39.2 rad/s, M_N = 72.1 N·m, μ_C = 3.0, μ_{min} = 1.7, μ_S = 2.2. The starting torque and starting time were determined for two sets of cases. The first set of cases: 1) at a nominal phase voltage of 220 V; 2) at a voltage drop of up to 90% of the nominal (k_u = 0.9); 3) when the voltage in phase "A" of the electric motor increases to 270 V in the case of k_u = 0.9 (k_{u1} = 1.01 and k_{u2} = 0.11). The second set of cases: 1) at the nominal phase voltage of 220 V; 2) when the voltage drops to 80% of the nominal (k_u = 0.8); 3) when the voltage in phase "A" of the electric motor increases to 330 V in the case of k_u = 0.8 (k_{u1} = 1.03 and k_{u2} = 0.24). The load factor of the electric motor in all cases was in the range $k_L \in [0; 1)$.

The results of determining the starting torque in the specified sets of cases are shown in Fig. 2 and 3.

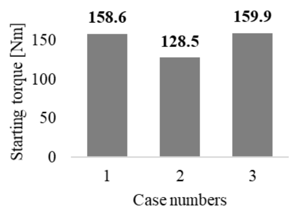

Fig. 2. Starting torque value for the first set of cases

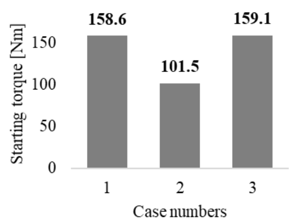

Fig. 3. Starting torque value for the second set of cases

From the obtained values of the starting torque (Fig. 2 and 3) it follows that an increase in the voltage in phase "a" of the electric motor by 50 V relative to the nominal value when starting under conditions of a voltage drop by 10% provides the level of its starting torque, as at the nominal voltage. A similar effect is observed when the voltage in phase "A" of the electric motor is increased by 110 V relative to the nominal value when starting under conditions of a voltage drop by 20%. Thus, an increase to a certain value of the voltage in one of the phases of the asynchronous motor during starting under voltage drop causes an increase in its starting torque to the desired level and ensures stable operation of the electric motor during starting over the entire range of normal load.

The verification of the proposed method for calculating the starting time was carried out for direct starting of an asynchronous motor under conditions of nominal voltage without load. In the passport information of the above-mentioned electric motor, this time is equal to 0.07 s. Calculation according to (9)–(11), (15) for the specified conditions gave the result 0.067 s; calculation result according to [8] – 0.061 s; calculation result according to [4] – 0.063 s. The difference between the result obtained by the proposed method and other results is not significant and does not exceed 9%, which indicates sufficient accuracy of the proposed method for calculating the starting time.

When studying the starting time of an asynchronous motor in the above-mentioned sets of cases, it was assumed that the moment of inertia of the system "asynchronous motor – working machine" is equal to 0.94 kg·m^2. The results of the study of the starting time are shown in Fig. 4–7.

From the results given (Fig. 4, 5) it follows: if the voltage is nominal, then the electric motor starts up to the nominal speed and operates normally (curve for k_u = 1 in Fig. 4). If the voltage at its terminals decreases to 90% of the nominal, then starting the electric motor to the nominal speed and its normal operation are possible only at k_L = 0,8; at the same time, the starting time under such a load increases from 2.85 s to 5.1 s (curve for k_u = 0.9 in Fig. 4 and curves for t_{12}, t_{23}, t_{34} in Fig. 5). At k_L = 0.9, the electric motor accelerates only to the critical speed (curves for t_{12}, t_{23} in Fig. 5), and at k_L > 0.9 – only to the minimum speed (curve for t_{12} in Fig. 5), which causes a sharp increase in the current consumed in the steady-state operation mode. If, at the specified voltage drop, the voltage in phase "a" of the asynchronous motor is increased to 270 V for the start-up period, this will cause it to start up to rated speed and stable operation over the entire range of normal load; in this case, the start-up time will be almost the same as at rated voltage (curve for k_u = 0.9 (U_a = 270 V) in Fig. 4).

From the results given (Fig. 6, 7) it follows: if the voltage is nominal, then the electric motor starts up to the nominal speed and operates normally (curve for k_u = 1 in Fig. 6). If the voltage at its terminals decreases to 80% of the nominal, then starting the electric motor to the nominal speed and its normal operation are possible only at k_L = 0.6; at the same time, the starting time under such a load increases from 2.31 s to 5.55 s (curve for k_u = 0.8 in Fig. 6 and curves for t_{12}, t_{23}, t_{34} in Fig. 7). At k_L = 0.7, the electric motor accelerates only to the critical speed (curves for t_{12}, t_{23} in Fig. 7), and at k_L > 0.7 – only to the minimum speed (curve for t_{12} in Fig. 7), which causes a sharp increase in the current consumed in the steady-state operation mode. If, at the specified voltage drop, the voltage in phase "a" of the asynchronous motor is increased to 330 V for the start-up period, this will cause it to start up to rated speed and normal operation over the entire load range; at the same time, the start-up time will be almost the same as at rated voltage (curve for k_u = 0.8 (U_a = 330 V) in Fig. 6).

From the obtained results (Fig. 2–7) it follows that increasing the voltage in one of the phases of the asynchronous motor to a certain value for the start-up period during a voltage drop provides the starting torque and start-up time of the electric motor, as at rated voltage. The block diagram of the device that improves the starting mode of an asynchronous motor under voltage drop conditions is shown in Fig. 8.

The diagram (Fig. 8) contains the following designations: 1 – power supply; 2.1, 2.2, 2.3 – primary measuring voltage converters; 3.1, 3.2, 3.3 – measured voltage converters; 4 – microprocessor; 5 – timer; 6 – actuator; 7 – step-up transformer. The primary measuring converters are connected to the linear power supply wires of the induction motor, the step-up transformer is connected to one of the linear power supply wires of the induction motor after the primary measuring converters.

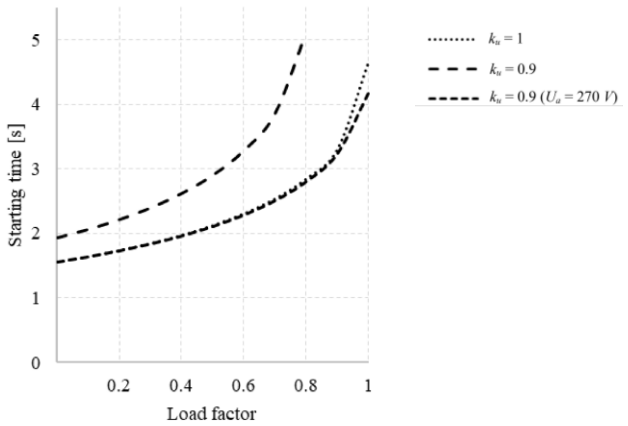

Fig. 4. Dependence of start-up time on load factor for the first set of case

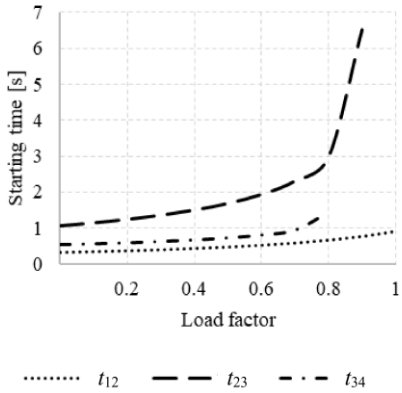

Fig. 5. Dependence of start-up time on individual areas of acceleration from load factor in case of voltage failure 0.9U_N

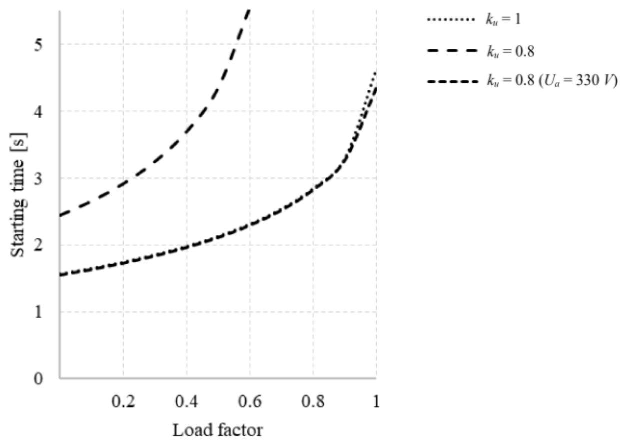

Fig. 6. Dependence of start-up time on load factor for the second set of cases

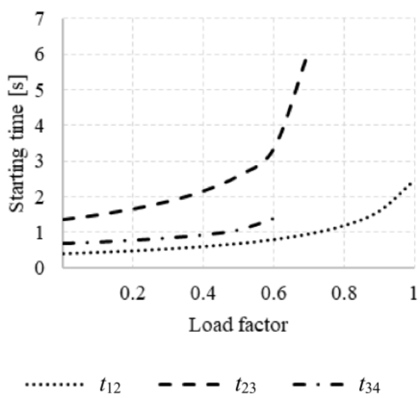

Fig. 7. Dependence of start-up time on individual areas of acceleration from load factor in case of voltage failure 0.8U_N

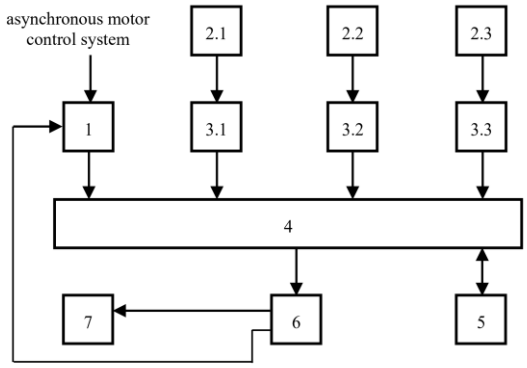

Fig. 8. Block diagram of a device for improving the starting mode of an asynchronous motor under voltage drop conditions

The device works as follows: before starting work, the necessary passport information about the electric motor and the working machine, specified above, as well as the expected load factor of the electric motor, is entered into it. The device is turned on together with the induction motor as a result of applying voltage to the power supply from the electric motor control system. After turning on the device and the electric motor, the signals from the primary measuring voltage converters 2.1, 2.2, 2.3 through the converters 3.1, 3.2, 3.3 are fed to the microprocessor 4. It calculates the root mean square value of the supply voltage of the asynchronous electric motor. Then, k_u is determined as the ratio of the root mean square value of the voltage to the nominal value. If $k_u < 1$, then (7) calculates the voltage value that must be set in the phase of the electric motor to create asymmetry for the start-up period. After that, the microprocessor sends a command to the actuator 6, which sets the required voltage value in the phase of the electric motor using the voltage-boosting transformer 7. Next, the start-up time of the electric motor is determined by (9) – (11), (15) at $k_u = 1$ and the timer for counting this time is turned on. Upon its completion, the microcontroller returns the step-up transformer to its original position through the actuator, turns off the power supply and the device stops working. Then the asynchronous motor, which has accelerated to the required speed, is powered directly from the network.

The proposed device for improving the starting mode of an asynchronous motor in conditions of voltage drop differs from existing technical solutions in its simplicity and does not involve switching to another line of the power grid as in [16, 18, 33, 35], the presence of an additional energy source as in [7, 17], connecting reactive power compensation devices as in [28, 30] or disconnecting the asynchronous motor in the event of an unacceptable voltage drop as in [26, 32].

4. Conclusion

The paper proposes to improve the starting mode of an asynchronous motor under voltage sag conditions by using voltage asymmetry at the motor terminals for the starting period. To prove this, a study of the asynchronous motor starting process at different load factors was conducted under the following conditions: 1) nominal voltage at the motor terminals; 2) voltage sag at the motor terminals; 3) voltage increase in one of the motor phases for the starting period during a voltage sag. The starting torque and starting time were selected as the parameters whose values were compared.

To study the starting torque a calculation method was developed based on well-known equations and uses widely available passport data of the motor and the applied voltage. To study the starting time a calculation method was obtained with the input data like passport data for the asynchronous motor and the working machine, as well as parameters of the starting mode based on the linearized mechanical characteristic of an asynchronous motor. The starting time is defined as the sum of the intervals of the electric motor operation time in its partial sections during starting. These intervals of time have partially logarithmic dependences on the electric motor passport data and the parameters of the starting mode. Comparison of this method with the electric motor passport data and other existing methods showed its sufficient accuracy.

An expression is proposed for calculating the voltage on one of the asynchronous motor phases, which should be set when creating artificial asymmetry for the start-up period under voltage dip conditions, so that the starting torque and starting time of the electric motor are the same as at nominal voltage. To implement the proposed idea a block diagram of a device for improving the starting mode of an asynchronous motor under voltage dip conditions has been developed, which differs from existing ones in simplicity and does not require additional energy sources, switching to other power supply lines or disconnecting the asynchronous motor.

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Ph.D.Eng. Oleksandr Vovk
e-mail: oleksandr.vovk@tsatu.edu.ua

Graduated from the Tavria State Agrotechnical Academy, Ukraine, with a degree in electrical engineering. The scientific degree of Candidate of Technical Sciences (specialty – electrical equipment and electrical technologies in the agro-industrial complex) was awarded at the Tavria State Agrotechnical Academy, Ukraine, in 2003. Currently he is an associate professor at the Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzha, Ukraine. Author of about 100 scientific publications and 11 inventions. His scientific interests are related to research in the field of resource and energy conservation in electromechanical systems.

https://orcid.org/0000-0003-0154-6972

Ph.D.Eng. Serhii Halko
e-mail: serhii.halko@tsatu.edu.ua

Graduated from Melitopol Institute of Mechanical Engineers of Agriculture, Ukraine, in 1994, and was qualified as an Electrical Engineer. He received his Ph.D. in electric engineering (power stations, systems and networks) from the Donetsk National Technical University, Ukraine, in 2003. Presently, he is an assistant professor of Dmytro Motornyi Tavria State Agrotechnological University and Dean of the Faculty of Energy and Computer Technologies, Melitopol, Ukraine. He is the authorof more than 100 scientific publications, 10 inventions, two monographs.
His research interests are related to researchin the field of renewable and alternative energy.

https://orcid.org/000-0001-7991-0311

Ph.D.Eng. Andrii Sabo
e-mail: andrii.sabo@tsatu.edu.ua

Graduated from the Melitopol Institute of Agricultural Mechanization, Ukraine, with a degree in electrical engineering. The scientific degree of Candidate of Technical Sciences (specialty – application of electrical technologies in agricultural production) was awarded at the Tavria State Agrotechnical Academy, Ukraine, in 2002. Currently he is an associate professor at the Dmytro Motornyi Tavria State Agrotechnological University, Zaporizhzha, Ukraine. Author of more than 70 scientific publications and 5 inventions.
His scientific interests are related to research in the field of modeling and development of control systems, energy conservation and resource conser-vation in electromechanical systems.

https://orcid.org/0000-0002-7948-6933

D.Sc. Eng. Oleksandr Miroshnyk
e-mail: omiroshnyk@btu.kharkiv.ua

Graduated from Kharkiv State Technical University of Agriculture, Kharkiv, Ukraine, in 2004, and was qualified as an electrical engineer. He received his Ph.D. in electric engineering (power stations, systems and networks) from the National Technical University "Kharkiv Politechnic Institute", Ukraine, in 2009 and Doctor of Technical Sciences degree in 2016.
His research interests include: smart grid and renewable energy.

https://orcid.org/0000-0002-6144-7573

Ph.D. Eng. Taras Shchur
e-mail: shchurtg@gmail.com

Graduated from Kharkiv State Technical University of Agriculture in 2004, and was qualified as mechanical engineer. He received his Ph.D. in mechanical engineering (machines and means of mechanization of agricultural production) from the Kharkiv State Technical University of Agriculture, in 2009.
His research interests include: smart grid and renewable energy.

https://orcid.org/0000-0003-0205-032X