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COMPARISON OF ADJUSTABLE HIGH-PHASE ORDER INDUCTION MOTORS' MERITS

Purpose. *Development of mathematical models of adjustable electrical drives with high-phase order induction motors for their merits analysis at static and dynamical modes.* ***Methodology.*** *At the mathematical modeling main kinds of physical processes taking place in the high-phase order induction motors are considered: electromagnetic, electromechanical, energetic, thermal, mechanical, vibroacoustic ones. Besides, functional as well as mass, frame and value indicators of frequency converters are taking into account which permits to consider technical and economical aspects of the adjustable induction electrical drives. Creation of high-phase order induction motors' modifications in possible on the base of a stock 3-phase motors of basic design. Polyphase supply of induction motors is guaranteed by a number of the adjustable electrical drives' power circuits.* ***Results.*** *Modelling of a number of adjustable electrical drives with induction motors of different phase number working on the same load by its character, value and required adjustment range is carried out. At the utilization of the family of characteristics including mechanical ones at different adjustment parameters on which loading mechanism's characteristics are superimposed regulation curves representing dependences of electrical, energetic, thermal, mechanical, vibroacoustic quantities on the motors' number of revolutions are obtained.* ***Originality.*** *The proposed complex models of adjustable electrical drives with high-phase order induction motors give a possibility to carry out the grounded choice of the drive's acceptable variant. Besides, they can be used as design models at the development of adjustable high-phase order induction motors.* ***Practical value.*** *The investigated change of vibroacoustic indicators at static and dynamical modes has been determined decrease of these indicators in the drives with number of phase exceeding 3.* References 10, tables 2, figures 4.

Key words: **adjustable high-order induction motor, semiconductor frequency converter, mathematical modelling, regulation curves, stator winding, vibroacoustic indicators.**

Обоснована возможность создания модификаций многофазных асинхронных двигателей на базе серийных трехфазных. Рассмотрен ряд силовых схем регулируемых электроприводов, в которых обеспечивается многофазное питание асинхронных двигателей. Анализируется работа приводов на определенную по величине и характеру нагрузку и заданным диапазоном регулирования. В результате математического моделирования определено, что температуры перегревов обмоток статоров рассматриваемых двигателей не превышают допустимых значений соответственно классу нагревостойкости изоляции. Выполнено сравнение технико-экономических показателей рассматриваемых схем и двигателей, дающее возможность осуществить приемлемый выбор варианта. Установлены закономерности изменения фазных токов многофазных двигателей в диапазоне регулирования. Исследовано изменение виброакустических показателей в статических и динамических режимах. Определено снижение этих показателей в двигателях с числом фаз, превышающим три. Библ. 10, табл. 2, рис. 4.

Ключевые слова: **многофазный регулируемый асинхронный двигатель, полупроводниковый преобразователь частоты, математическое моделирование, регулировочные характеристики, обмотка статора, виброакустические показатели.**

Introduction. Adjustable high-phase order induction motors (AIM) are used in medical and domestic equipment, electrical car industry, textile industry, boats' electrical propulsion systems [1, 2]. It is useful to use them in special ventilation systems and complexes where increased motor's reliability at low noise and vibration levels is required [3]. AIMs have decreased torque and speed pulsations at the motor's shaft as well as increased reliability at decreased noise and vibration levels. Besides, division of electrical power to phases makes AIM's regulation curves more critical to the asymmetry by the amplitude and phase of the supply voltage that at the increase of the number of phases (m) simplifies finally the control system and increases the reliability [4, 5]. Systems of electrical drive (ED) with high-phase order AIM are realized at using frequency converters with a few autonomous voltage inverters (AVI) which creates a symmetrical voltage system with a time shift which equals to the spatial phase shift of high-phase order motors (see Fig. 1).

High-phase order induction motors can be developed on the base of stock 3-phase ones of basic modification. In some cases it is realized at presence of a few parallel loops in the 3-phase network. Decreasing their number we obtain a polyphase modification (in two times – 6-phase one, in 3 time – 9-phase one, etc.). And here the active part's geometry, number of turns in the phase and winding wire's section are not changed. Besides, it is necessary to take into account number of slots per the pole and the phase.

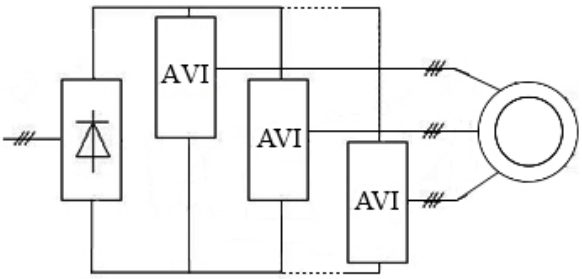

Fig. 1. Circuits of adjustable ED with high-phase order AIM

If such a problem solution is impossible it is necessary to change number of effective turns in the phase w_p and a wire's section d_w. Using an expression $w_p = \frac{Z_1}{2 \cdot m} \cdot \frac{U_c}{a}$ by variation of number of parallel loops (a), number of conductors in the slot (U_c) and number of turns they achieve the conservation of the value of magnetic flux. Here it is necessary to check the coefficient of the slot filling [6].

Problem definition. To build models of electrical drives with high-phase order AIMs it is necessary to input

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a few initial data which determine functional properties as well as indicators of mass, frame and value. Last ones give a possibility to consider economical aspects of various ED's variants. Indicators of mass, frame and value of multiphase frequency transducers increase approximately in 30 % at the transition from the 3-phase modification to the 6-phase one, in 60 % at the transition to the 9-phase one, etc. Increase of production expenses results in the change of high-phase order motors' value.

To compare the ED's variants it is necessary to use some indicators including the effectiveness averaged in the range [7] which reflects the AIM's energetic in all adjustment range given from n_1 to n_2 and is determined as equivalent one averaged for this range.

$$\eta_{atrIM} = \frac{1}{n_2 - n_1}\int_{n_1}^{n_2} \eta_{IM}(n)dn.$$

The generalized criterion of the adjusted present expenses (APE) takes into account production value and operation expenses. Expenses depend on the efficiency and the power ration, therefore the generalized criterion of the adjusted present expenses has different values in different points of the range, and it is expediently to determine the range value of this criterion, i.e. equivalent averaged value for all range.

It is necessary to note that at the AIM operation in modern variable-frequency electrical drives the drive's power ratio is near 1 and as a result from the expression for the electrical drive's APE the component corresponding the value of the reactive energy compensation can be excluded. So

$$APE_{ED} = ved\,[1 + T_n(k_d + k_s)] + C_{eED},$$

where *ved* is the total electrical drive's value which consists of the values of the AIM and the transducer, USD; $C_{eED} = C_{apl}P_{1ED}(1{,}04 - \eta_{atrED})$ is the value of the electrical energy losses during the year, USD; T_n is the normative term of the motor's cover of expenditure, years; k_d is the part of expenses for depreciation charges; k_s is the part of service expenses during the motor's operation; C_{apl} the coefficient taking into account the value of the active power losses representing the product of the value of the production of the 1 kW·h of electrical energy during the drive's service life (USD 0.1 for 1 kW·h), number of hours of the motor's operation during the year (2100), number of years of the operation till the major overhaul (5 years), and the coefficient of the relative motor's loading (accepted 1); P_{1ED} – active power consumed by the drive, kW, η_{artED} – the drive's effectiveness averaged in the range. For adjustable induction motors the values T_n = 5 years, k_d = 0.065, k_s = 0.069 are accepted the same as for general industrial IM [8].

Results of investigations. The modeling of adjustable electrical drives (AED) with coupled consideration of transducers, motors and loads [9] can be carried out by the code DimasDrive [10] developed at the Department for Electric Machines, Odessa Polytechnic University.

As a base motor the 4A200M6 3-phase motor working with the frequency transducer Altivar 58HD33N4 (USD 3650, 34 kg, η_{tr} = 0.94) is selected. Changing the winding data, the 6-phase (number of turns w_p = 114, number of parallel loops a = 2, the effective conductor's section q_{ef} = 1.76 mm^2, the insulated winding wire's diameter d_w = 1.585 mm) and the 12-phase (number of parallel loops a = 1, the rest of data are the same as for the 6-phase one) modifications have been carried out.

The frequency control low *U/f* = const has been considered. As a load the traction one has been used, P_{load} = 18 kW with maximal torque of 140 N·m. At the given constant value of the load, the required adjustment range (200-1600 RPM) in the AED systems can be guaranteed by the considered electric motors.

Regulation curves representing dependences of electrical, energetic, thermal, mechanical, vibroacoustic quantities on the number of revolutions can be obtained by using a family of characteristics including mechanical ones at different adjustment parameters on which loading mechanism's characteristics are superimposed. In Fig. 2 a family of the mechanical characteristics and given load corresponding the AED with the 3-phase AIM is presented. Families of the mechanical characteristics for the AED with the 6-phase and 12-phase motors have the same form.

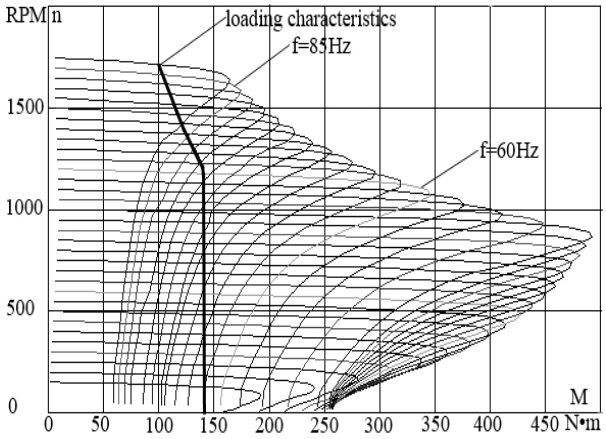


Fig. 2. A family of mechanical characteristics

At this composition of mechanical characteristics and loads the presence of three zones takes place. Within all of zones the monotonous change of mechanical characteristics and loading characteristics takes place. Temperatures of the considered motors stator windings do not exceed the values permitted by the class *F* of the thermal resistance at the selected load in the given adjustment range.

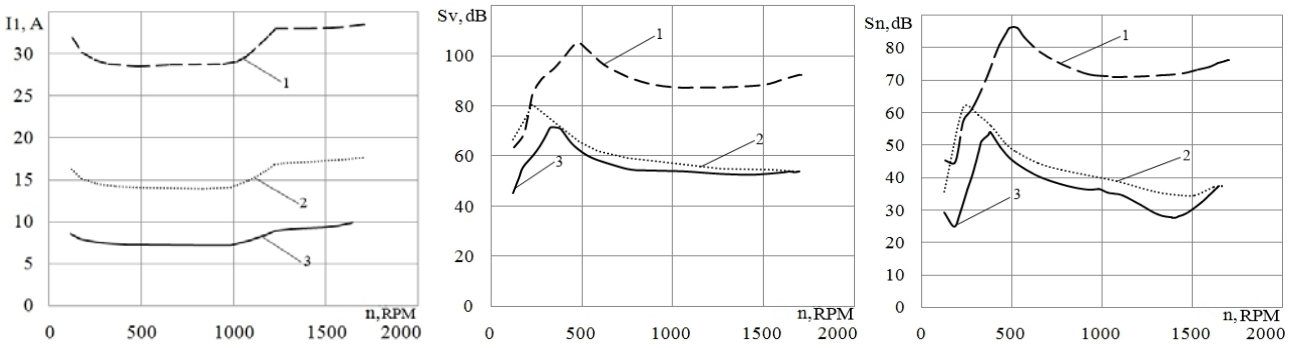
In Fig. 3 some regulation curves of the considered AED representing dependences of motors' consumption current and vibroacoustic indicators of electromagnetic nature on the number of revolutions are presented.

In Table 1 values of the considered AEDs' indicators including the effectiveness averaged in the range (η_{atr}) and adjusted present expenses (APE) as well as indicators of mass, frame and value for motors and drives are presented.

It is possible to carry out the calculation of the active energy losses value during the year.

$$C_a = V_a \cdot T_n \cdot K_l \cdot P_{mech} \cdot (1 + 0{,}04 - \eta_{AED}) / \eta_{AED},$$

where V_a = USD 0.1 is the value of the 1 kW·h; T_n = 2100 is number of hours of the AED's operation during the year; K_l is the coefficient of loading (accepted to be equal to 1.0); 0.04 is the relative value of losses in the customer's distribution network.



a *b* *c*

Fig. 3. Change of the consumption current (*a*), vibration speed (*b*) and noise of electromagnetic nature (*c*) in the adjustment range: 1 – AED with a stock 3-phase IM, 2 – AED with a 6-phase IM, 3– AED with a 12-phase IM

Table 1

Comparison of different AEDs' indicators

Indicators and parameters \ AED	With 3-phase AIM	With 6-phase AIM	With 12-phase AIM
η_{atr} of IM, %	82.97	82.41	81.70
η_{atr} of AED, %	81.34	80.79	80.10
APE of IM, USD	5729	5844	6034
APE of AED, USD	11991	13935	17779
Value of IM, USD	1994	2016	2069
Mass of IM, kg	254	254	254
Volume of IM, dm^3	19	19	19
Mass of AED, kg	288	298	318
Volume of IED, dm^3	56	101	275
Value of AED, USD	5644	6761	9004

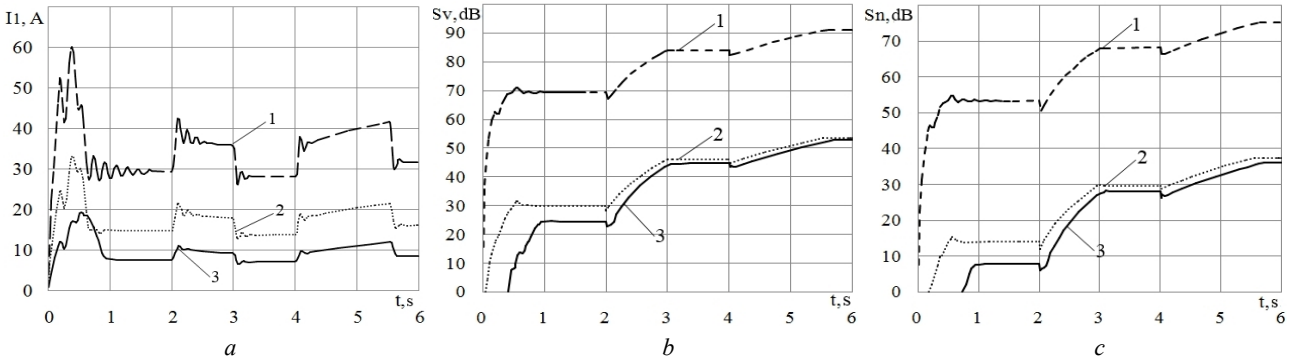
Comparison of the considered AED's variants by the active energy losses value during the year is carried out (see Table 2). Besides, modeling for each AED's circuit design at the operation on the given tachogram (2 s – 200 RPM, 2 s – 600 RPM, 2 s – 1200 RPM) taking into account transients is carried out.

Table 2

Comparison of the active energy losses value for various AED

Indicators and parameters \ AED	With 3-phase AIM	With 6-phase AIM	With 12-phase AIM
η_{atr} AED, %	81.34	80.79	80.10
Active energy losses value during the year, USD	1001	1036	1073

In Fig. 4 changes of currents, vibration speeds and noises of electromagnetic nature at the considered motors' operation on the given tachogram are presented.



a *b* *c*

Fig. 4. Change of the consumption current (a), vibration speed (b) and noise of electromagnetic nature (c) in the adjustment range: 1 – AED with a stock 3-phase IM, 2 – AED with a 6-phase IM, 3– AED with a 12-phase IM

Conclusions.

1. High-phase order AIMs' consumption current decreases in proportion to the number of phases in the comparison with the 3-phase motor's current.

2. Essential decrease of the vibroacoustic indicators of electromagnetic nature at the transition from the 3-phase AED to the high-phase order ones takes place. This decrease is irregular and minimal in the initial part of the range. Besides, resonant phenomena take place. In addition, for the considered AED the difference between these indicators for the 6-phase and 12-phase AIM is not so essential. Therefore, for this design problem the 6-phase AIM is preferable because the 12-phase one essentially is more expensive, has increased mass and volume at practically equal energetic indicators.

3. Comparison of the considered AEDs' the active energy losses value during the year permits to conclude that the AED with 3-phase IM has a little bit better indicators in the comparison with other considered variants.

4. Results of modeling of dynamical dependences of consumption current, vibration speed and noise of electromagnetic nature confirm lows elicited at static modes.

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