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Characteristics of Adjustable High-Phase Order Induction Motors and Their Optimal Design

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Abstract: The possibility of creating of modifications of high-phase asynchronous motors based on standard three-phase ones is justified. The authors considered a number of power circuits of controlled electrical drives in which high-phase power supply of induction motors is provided. The drives operation to certain by value and nature the load as well as the given adjustment range is analyzed. As a result of mathematical modeling it is determined that the overheating temperatures of stator windings of considered high-phase motors do not exceed the permissible values corresponding the heat resistance insulation class. Comparison of technical and economic parameters of the considered circuits and motors making it possible to realize an acceptable determination of options depending on reasonable selection criterion is carried out. The regularities of changes of the phase currents of high-phase motors in the adjustment range are determined. The change in the vibro-acoustic characteristics in static and dynamic modes is investigated. Reduction of these indicators in motors with the number of phases greater than three is determined. The authors considered a number of circuits of adjustable electric drives in which two-block rectifiers and high-phase induction motors are used. Automated optimal design of adjustable six-phase induction motors for three project tasks is carried out. Through parametric optimization acceptable values of variable parameters in two design criteria are found.

Keywords: adjustable high-phase order induction motor, semiconductor frequency converter, mathematical modelling, regulation curves, stator winding, vibroacoustic indicators, two-block rectifier, selection criteria, automated optimal design, design range criteria, varied parameters

1. Introduction

Adjustable high-phase order induction motors (AIM) are used in medical and domestic equipment, electrical car industry, textile industry, boats’ electrical propulsion systems. 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 [1-3]. 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 not so 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 [3-6]. Systems of electrical drive (ED) with high-phase order AIM are realized at using

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a high-phase frequency converter which creates a symmetrical voltage system with a time shift which equals to the spatial phase shift of high-phase order motors. Frequency converters used in ED used in adjustable electric drives (AED) may include one, two or more blocks of network rectifier connected accordingly. At several blocks three-winding transformers are used [7,8] and this technical solution makes it possible to reduce the pulsations on the DC side of the converter and compensate harmonic current components of certain orders on the AC side. As at one-block and at the multi-block rectification through the use of one or more autonomous inverters a multiphase symmetrical voltage system which feeds the multiphase AIM is created (Figure 1) [9-12].

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 the number of slots per the pole and the phase.

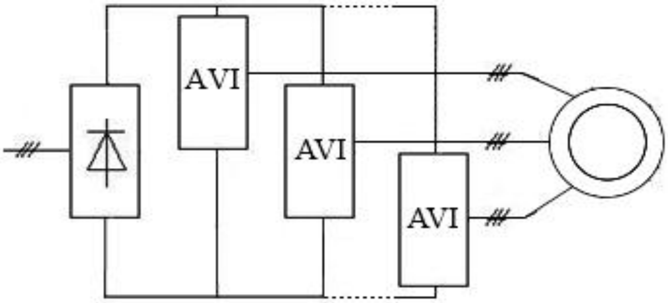


Figure 1. Circuits of adjustable ED with high-phase order AIM

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 [8,13].

2. Statement of problem

To build models of ED with high-phase order AIMs it is necessary to input 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 converters 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 [7].

To compare the ED's variants it is necessary to use some indicators including the effectiveness averaged in the range [14] 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.

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

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 ratio, 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.

$$APE_{atrAED} = \frac{1}{n_2 - n_1} \int_{n_1}^{n_2} APE_{AED}(n) \cdot dn. \tag{2}$$

It is necessary to note that at the AIM operation in modern variable-frequency ED 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[14,15]. So

$$APE_{ED} = ved\,[1 + T_n(k_d + k_s)] + C_{eED}, \tag{3}$$

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} is 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} is the active power consumed by the drive, kW; η_{artED} is 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 [4].

It is advisable to compare the performance of the AIM at various circuits of electric drives working at the same load in a certain adjustable range. Next, the following AED circuits are considered: 1 - with one-block rectifier and three-phase AIM; 2 - with two-block rectifier and six-phase AIM; 3 - with two-block rectifier and three-phase AIM; 4 - with two-block rectifier and six-phase AIM.

For the design of six-phase AIM a integrated ED model to be created including a six-phase frequency converter model of the with two autonomous voltage inverters (AVI), six-phase motor and load. Next, optimal design of the six-phase AIM is considered.

In the six-phase IM model provided the exclusion from consideration of spatial harmonics 5, 7 and multiple order is provided [12].

In the design of AIM for drives with semiconductor converters such criteria as weight, dimensions, motor's value or range criteria - the energy indicators of the motor and APE can be used. Design results vary with different criteria used or with their various components in the consolidated criterion, and also depend on the given importance ratios of these components [14].

Design of AIM should be performed taking into account the demands for operation in a certain rotation speed range and this determines the specificity of the optimality criterion [14,15]. Well-grounded is the selection of average range efficiency criteria that will minimize power loss in the whole adjustable range from n_1 to n_2.

However, this range efficiency criterion ignores the costs of manufacturing and operation of the motor and drive, the inflation rate and more. This account is carried out using range criteria of annual APE.

If you know the timing diagrams of operation loads, i.e. operation time at each rotation speed, the evaluation of the data of range power criteria of the motor and the drive must be made taking into account the duration of the operation of the motor at each point of the adjustable range

$$\eta_{atrIM} = \frac{\sum_i \left(\eta(n_i) \cdot t_{n_i} \right)}{\sum_i t_{n_i}}, \tag{4}$$

where t_{n_i} is the motor's operation time at the rotation speed n_i, i is the serial number of the tachogram area.

Accordingly, the average range APE are calculated

$$APE_{atrAED} = \frac{\sum_i \left(APE(n_i) \cdot t_{n_i} \right)}{\sum_i t_{n_i}}, \tag{5}$$

3. The results of investigation

The modeling of AED with coupled consideration of converters, motors and loads [16-18] can be carried out by the code DimasDrive [19] developed at the Department for Electric Machines, Odessa National Polytechnic University.

As a base motor the 4A200M6 3-phase motor working with the frequency transducer Altivar 58HD33N4 (USD 3650, 34 kg, $\eta_{tr} = 0.94$) 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 selected.

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, vibro-acoustic 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 [20]. In Figure 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.

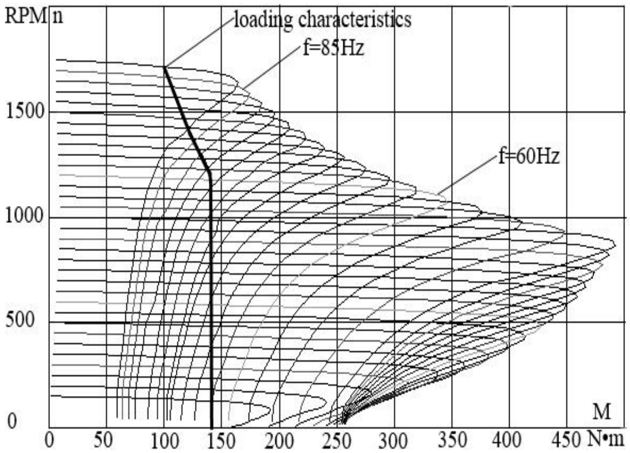
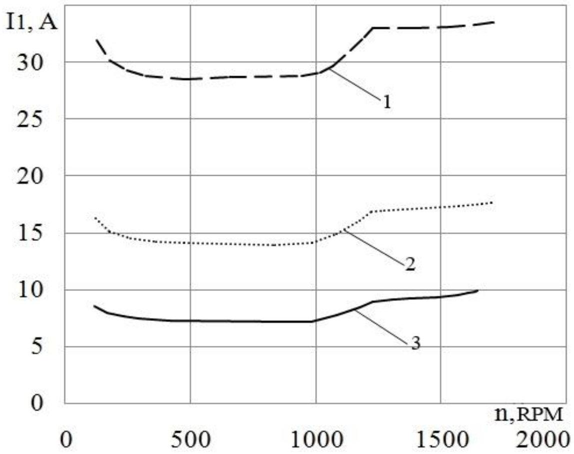


Figure 2. A family of mechanical characteristics

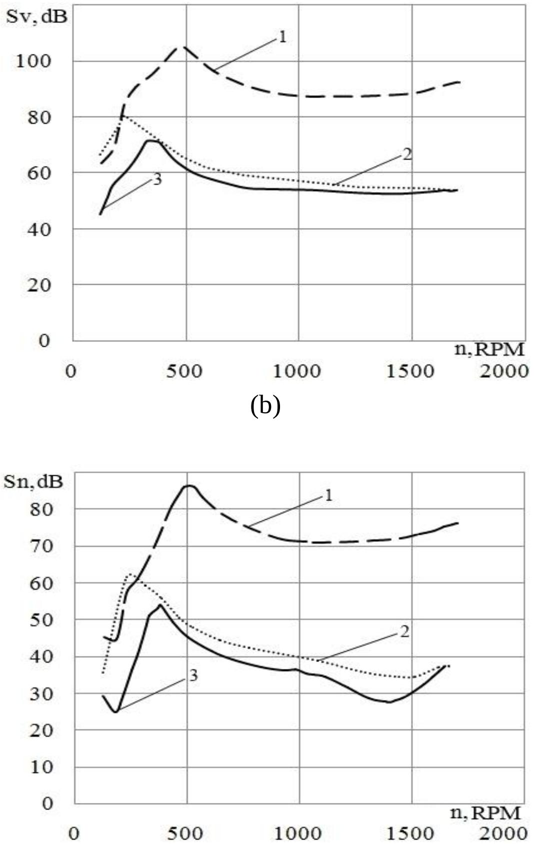
At this composition of mechanical characteristics and loads the presence of three zones takes place. Within all of zones the monotonous change of mechanical characteristics and loading characteristics takes place. Temperatures of the considered motors stator windings do not exceed the values permitted by the class F of the thermal resistance at the selected load in the given adjustment range [20,21].



(a)

In Figure 3 some regulation curves of the considered AED representing dependences of motors' consumption current and vibro-acoustic 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 (APE_{atr}) as well as indicators of mass, frame and value for motors and drives are presented.



(b)

(c)

Figure 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

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

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

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.

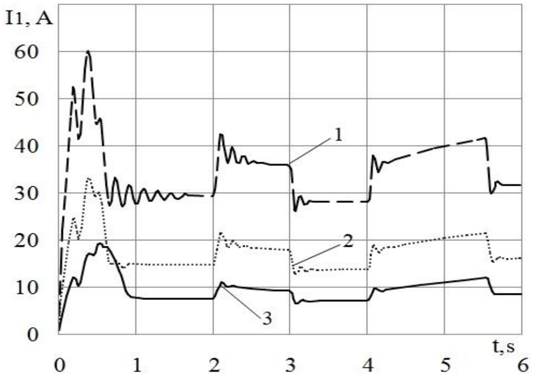
Table 1. Comparison of different AEDs' indicators

Indicators and parameters	AED With 3-phase AIM	AED With 6-phase AIM	AED 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_{atr} of IM, USD	5729	5844	6034
APE_{atr} 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).

Table 2. Comparison of the active energy losses value for various AED

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



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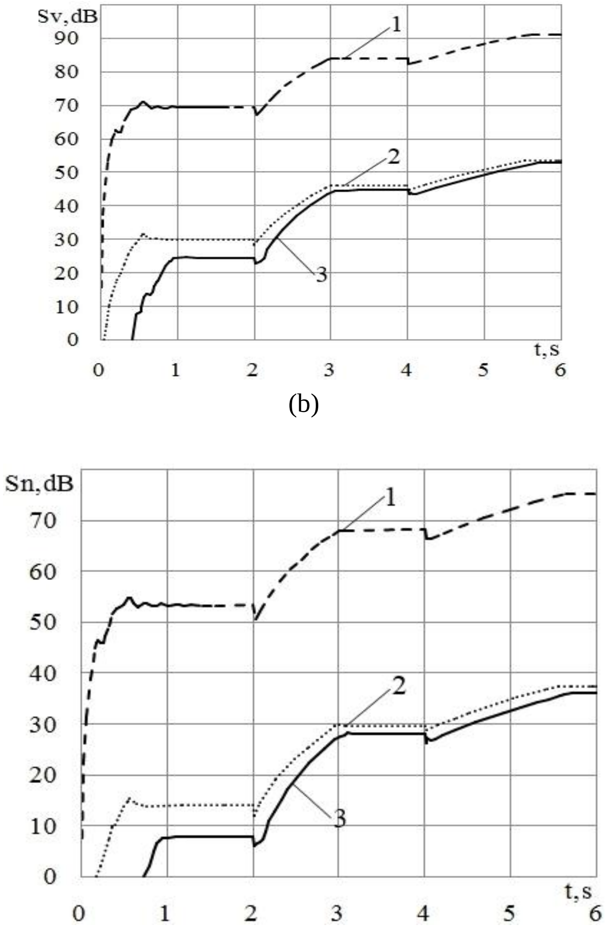


(b)

(c)

Figure 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

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 [22,23].

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

We consider the operation of AIM based on the serial motor 4A160S4. In the motors stator winding connection scheme "star" is used. At setting the initial data of six-phase motor the number of parallel branches is halved. When using two-block rectifiers connected in series, the phase voltage at the motor is twice as much than with a one-block rectifier. In this regard, motors for two-block circuits must have windings recalculated to new voltage. In the six-phase IM model the exclusion from consideration of spatial harmonics 5, 7 and multiple orders is provided as well as the distribution ratio which depends on the number of phases changes.

For the ED with one-block rectifier and AIM the frequency transducer Altivar 58 (28000 UAH, 15 kg, η_{tr}=0.94) is selected. Mass, frame and value indicators of six-phase converters are conditionally increased by 30%. Also, by 30% these figures increase by using two-block rectification circuits. By increasing the cost of production changes in the value of six-phase AIM compared to the three-phase ones is taken into account.

In all converters the frequency control law U/f = const has been considered. As the load the "elevator" load 75 N·m has been used. At this load the required adjustment range (300 – 1800 RPM) can be provided with all electric drives under consideration, as evidenced by the overheating temperature dependencies Θ_{oc} of the motors' stator windings (Figure 5). Dependencies are represented by numbering of circuits under consideration.

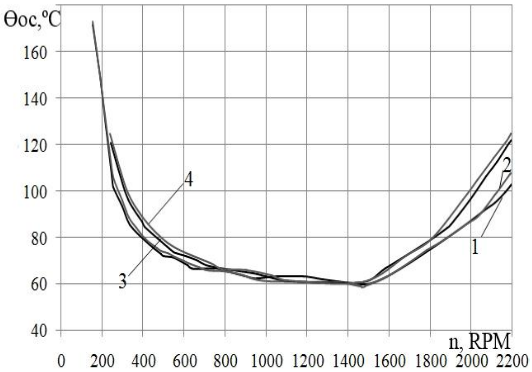
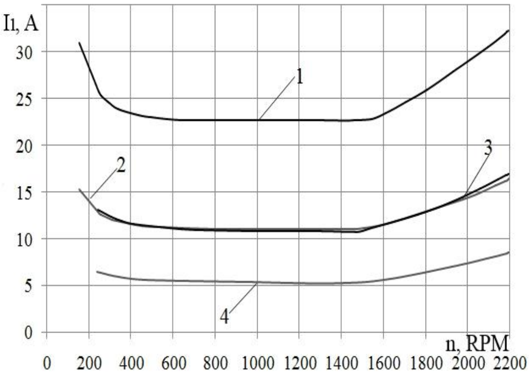


Figure 5. Motor's stator windings overheating temperatures changing in the adjustment range

Figure 6 shows adjustable curves of the considered AIM which are dependencies of changes in the motors' current consumption and efficiency on the motors' rotation speed.



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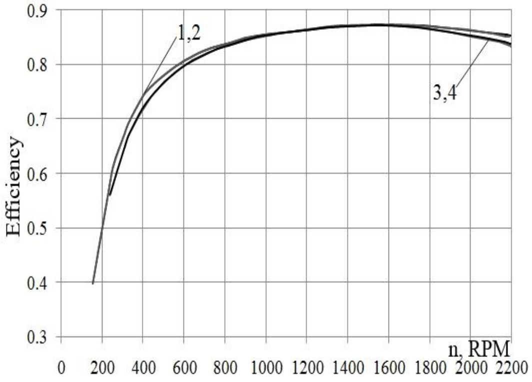

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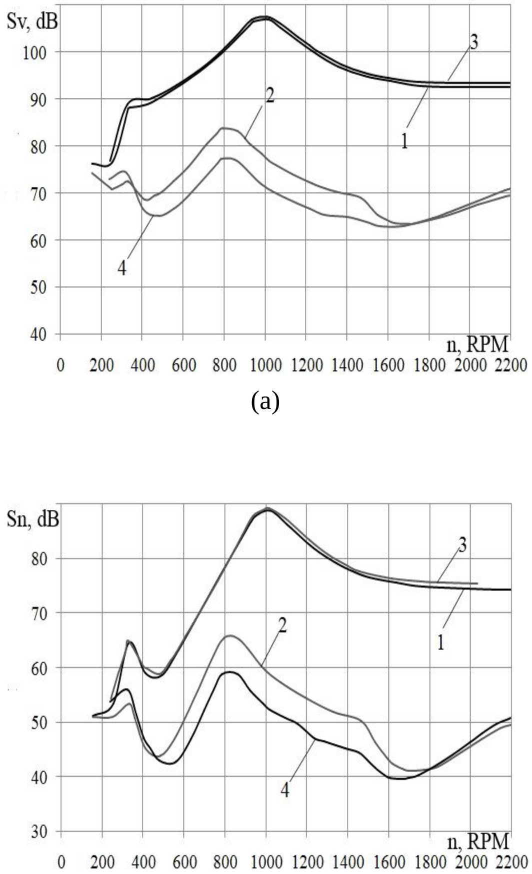
Figure 6. Change of the motor’s current consumption (a) and efficiency (b) in the adjustment range



(a)

(b)

Figure 7. Change of vibration speed (a) and magnetic noise (b) in the adjustment range

We considered also dependencies of change of vibro-acoustic indicators of electromagnetic nature (vibration speed S_v and magnetic noise S_n) on the rotation speed (Figure 7).
Table 3 represents the values of the indicators of considered AED which include averaged range efficiency (η_{atr}) and present expenses (APE_{atr}) as well as the mass, frame and value indicators of motors and drives.

A feature of the design of AIM is a need to use in the calculation design system of the complex mathematical model of the entire ED system, not only the motor model. The software DIMASDrive allows to carry out the design of AIM.

We consider operation of a serial induction three-phase motor 4A160S4 and developed on its basis a six-phase IM. In the six-phase motor the number of parallel branches is halved. The cost of six-phase IM more than the cost of the three-phase IM which is accounted by 5% increase in production costs. We consider the operation of the motor in the AED with frequency transducer (Altivar 58, 1500 USD, 15 kg, η_{tr}=0.94) at the frequency control law *U/f*=const. Conventionally, it is assumed that mass, frame and value indicators of six-phase converters more to 30% compared to the three-phase converters. As load the "elevator" load of 75 Nm is used. As variable parameters frequency for which the stator coil (SC) is designed and the length of the motor stator pack (*L*) are selected. Change of the frequency (*f*) involves the automatic change in the number of turns of the SC (w_p), effective section of the SC wire (q_{ef}), and the diameter of the winding wire (d_w) [4].

Table 3. Comparison of different AEDs' indicators

Indicators and parameters	AED One-block 3-phase	AED One-block 6-phase	AED Two-block 3-phase	AED Two-block 6-phase
η_{atr} of IM, %	80.78	80.88	79.69	79.59
$\cos\varphi_{atr}$ of IM	0.90	0.91	0.91	0.91
η_{atr} of AED, %	79.20	79.29	79.69	79.59
APE_{atr} of IM, thousand USD	39.13	39.05	41.22	41.39
APE_{atr} of AED, thousand USD	87.38	101.3	102.0	116.1
Mass of IM, kg	118	118	120	120
Value of IM, dm^3	9.62	9.62	9.62	9.62
Value of IM, UAH	10222	10237	10669	10684
Mass of AED, kg	133	138	139	144
Value of AED, UAH	38222	46637	47069	55484

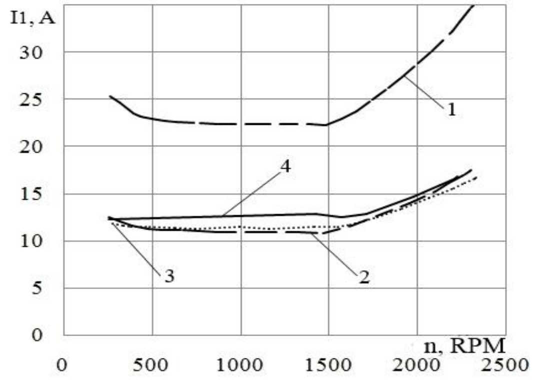
The first design task involves the AIM optimal design for a specific adjustment range. In this case, the range 300 – 1900 RPM is selected. Ranges of change of variable parameters are from 0.8 to 1.2 basic values.

Table 4 shows the values of design criteria and design changes of the six-phase induction motor using design criteria: η_{IM} (1) and APE_{AED} (2).

Table 4. Design criteria and design changes of the six-phase induction motor

Indicators and parameters	Motor Serial three-phase	Motor Base six-phase	Motor Optimized	
			by criterion 1	by criterion 2
η_{atr} of IM, %	83.87	84.05	85.89	84.10
APE$_{atr}$ of AED, thousand USD	5.162	5.928	5.968	5.882
η_{atr} of AED, %	82.23	82.40	84.21	82.45
L, mm	130	130	153.9	123.3
f, Hz	50	50	59.90	52.96
w_p	112	112	93	106
q_{ef}, mm^2	2.45	2.45	2.94	2.59
d_w, mm	1.33	1.33	1.43	1.33

Figure 8 illustrates the adjustable characteristics of considered AED for the first project task which are dependencies of changes in the electrical and vibro-acoustic values on the rotation speed.



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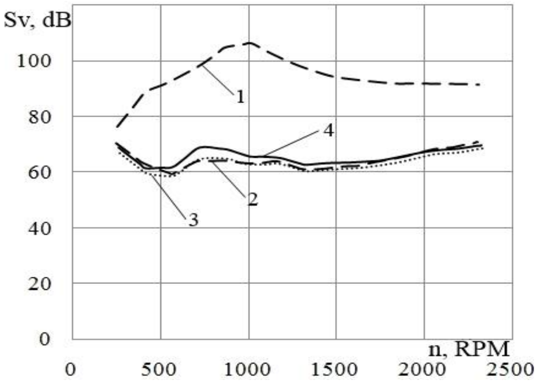

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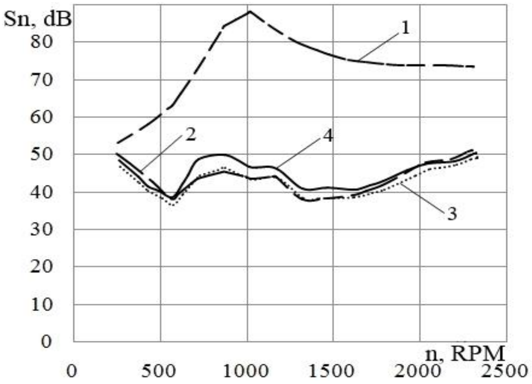


(c)

Figure 8. Changes of current consumption (a), vibration speed (b) and magnetic noise (c) in the adjustable range: 1 AED with serial three-phase IM, 2 AED with base six-phase IM, 3 AED with six-phase IM optimized by criterion 1, 4 AED with six-phase IM optimized by criterion 2

The second design task involves AIM optimal design for operation on a predetermined tachogram (100 s – 300 RPM, 100 s – 1900 RPM) and is solved excluding transients.

Table 5 shows the values of design criteria and design changes of the six-phase induction motor using design criteria: η_{IM} (1) and APE_{AED} (2).

Table 5. Design criteria and design changes of the six-phase induction motor in the second design task

Indicators and parameters	Motor Serial three-phase	Motor Base six-phase	Motor Optimized	
			by criterion 1	by criterion 2
η_{atr} of IM, %	76.12	76.12	80.76	79.04
APE_{atr} of AED, thousand USD	5.587	6.363	6.201	6.093
η_{atr} of AED, %	74.63	74.63	79.18	77.49
L, mm	130	130	148.4	116.3
f, Hz	50	50	59.83	57.13
w_p	112	112	94	98
q_{ef}, mm^2	2.45	2.45	2.937	2.80
d_w, mm	1.33	1.33	1.43	1.38

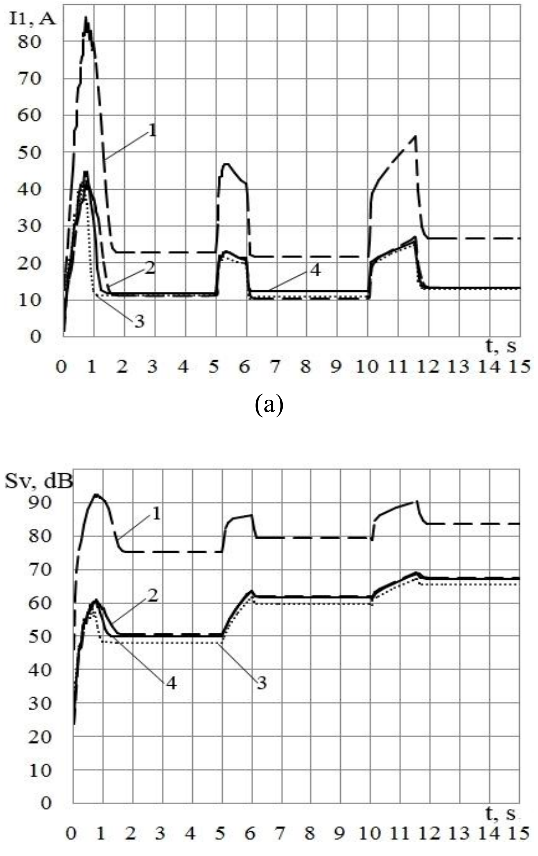
The third problem involves AIM optimal design for operation on the predetermined tachogram (5 s – 400 RPM, 5 s –1000 RPM, 5 s – 1900 RPM) and is solved taking into account transients [24,25]. In this experiment the rate of increase of frequency of 20 Hz/s and the moment of inertia of the motor with a load mechanism 1 kg·m^2 have been taken.

Table 6 shows the values of design criteria and design changes of the six-phase induction motor using two criteria: η_{IM} (1) and APE_{AED} (2).

Table 6. Design criteria and design changes of the six-phase induction motor in the third design task

Indicators and parameters	Motor Serial three-phase	Motor Base six-phase	Motor Optimized	
			by criterion 1	by criterion 2
η_{atr} of IM, %	90.13	90.38	92.48	90.72
$APE_{atr,}$ of AED, thousand USD	4.074	4.850	5.004	4.769
η_{atr} of AED, %	88.34	88.61	90.61	88.94
L, mm	130	130	154.1	117.3
f, Hz	50	50	59.51	51.89
w_p	112	112	94	108
q_{ef}, mm^2	2.45	2.45	2.92	2.54
d_w, mm	1.33	1.33	1.43	1.33

Figure 9 illustrates the changes in currents, vibration speeds and magnetic noises at operation of considered motors on the predetermined tachogram.



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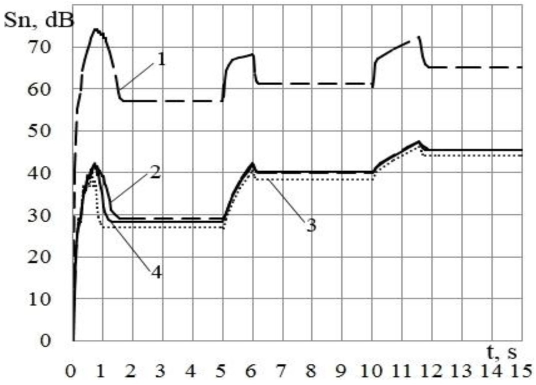

(c)

Figure 9. Changes of current consumption (a), vibration speed (b) and magnetic noise (c): 1 AED with serial three-phase IM, 2 AED with base six-phase IM, 3 AED with six-phase IM optimized by criterion 1, 4 AED with six-phase IM optimized by criterion 2

4. Conclusion

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

It is possible, by comparing the technical and economic indicators of the considered circuits, make a selection of an acceptable variant depending on the reasoned selection criteria.

Essential decrease of the vibroacoustic indicators of electromagnetic nature at the transition from the three-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 AIMs is not so essential. Therefore, for this design task the 6-phase AIM is preferable because the 12-phase one is essentially more expensive, has increased mass and volume at practically equal energetic indicators.

Comparison of the considered AEDs' annual active energy loss values permits to conclude that the AED with three-phase IM has a little bit better indicators in the comparison with other considered variants.

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

Results of optimal design vary depending on what which design criterion was selected. Due to the found varying variables extremes of the relevant criteria are provided.

Carrying out the optimal design with other criteria, the criteria significance factors, design tasks as well as a variety of variable parameters is possible.

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