DOI: https://doi.org/10.15407/techned2020.01.033

# EFFICIENT OPERATING CONDITIONS OF INDUCTION MOTORS FOR PISTON COMPRESSORS WITH FREQUENCY REGULATION

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*The influence of periodic load on pulsations of electromagnetic torque and rotational speed, the losses and the efficiency of frequency-controlled induction motors for single-cylinder piston compressors are investigated using computer modeling. The region of critical reduction of motor efficiency when changing the frequency and supply voltage and the loading degree are determined using the criterion of heavy quasi-static regimes.* References 16, figures 7, tables 2.

***Keywords:*** induction motors, frequency control, single-cylinder piston compressors, pulsations, efficiency.

**Introduction.** Induction motors (IMs) are the most common type of piston compressor (PC) motors for refrigeration machines of heat pumps and refrigerators. Three-phase IMs are more often used for open-type PCs. The single-phase IM with two-phase stator winding is used for hermetic PCs. The improvement of energy efficiency is a very topical task for these motors; this is due to their long work hours during the day. The article [1] shows the importance of designing the induction PC electric drives, taking into consideration their operation cycle features (periodically changing load torque). Such consideration can provide the efficiency increase up to 8–10%. This task is realized when complex designing of IM as a part of electromechanical PC system. At the same time, the quasi-static operation conditions of the motors are taken into account. The design studies under such repeated dynamic conditions are performed using the mathematical model of electromechanotronic systems in [2, 3]. This model takes into account the features of both operating conditions and construction of IM.

The complex design of PC induction motors is effective with changing the load torque. However, the efficiency depends on standard sizes and construction of IM. The ratio for heavy quasi-static conditions $k_1$ is proposed for selection of such uncontrolled IMs for which this method of improving the energy efficiency gives an appreciable effect [3]. The value of $k_1$ is calculated as a ratio of the mechanical $T_{MK}$ to electromagnetic $T_E$ time constants of IM. In this case, the ratio of the mechanical and electromagnetic energies of IM is taken into account. The efficiency of quasi-static regimes depends on the ratio of these time constants. The resonance phenomena occur for disadvantageous cases. This leads to windings overheating, increased vibrations and IM breakdown. The resonance non-availability is provided when $k_1 = T_{MK} / T_E > 2$ [1]. This can be achieved by choosing the moment of inertia, the number of pole pairs, critical torque and the rotor impedance of electric drive. That affects the critical slip according to the following expression:

$$k_1 = \frac{J \cdot (\omega_0 \cdot s_\kappa)^2}{2pM_\kappa}, \tag{1}$$

where $J$ is the moment of inertia of electric drive; $\omega_0$ is the angular speed of the field in the air gap of IM; $s_K$ and $M_K$ are the critical slip and critical torque; $p$ is the number of pole pairs.

The effect of complex design decreases with increase of rotor kinetic energy. However, there are such standard sizes of IM for the design is not effective under in-controlled conditions, but effective at frequency control (taking into account that the kinetic energy decreases in proportion to the square of speed). Moreover, the consideration of periodically changing load torque can significantly increase the energy efficiency. The use of controlled electric drives (induction motors with frequency converters (FC), etc.) for refrigeration compressors is an efficient way to increase their energy efficiency [4–10]. Therefore, the task of complex designing of their IM taking into account the periodic change in the load torque is a topical one. At the same time, the determination of dynamic parameters and criteria for effective controlled IM with PC is of

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importance. This is confirmed by the analysis of equivalent time constants of the stator and rotor, electromechanical time constants of a number of modern domestic and foreign frequency-controlled electric drives in [11]. The analysis is performed for specifying their dynamic parameters as applied to regimes of IM. In this paper, the criterion of heavy quasi-static regimes of IMs with PC is proposed to estimate the possibility to increase the efficiency of their operating conditions.

**The purpose of the paper** is to define the effect of periodic load on the characteristics of the operating conditions: efficiency and pulsations of the electromagnetic torque and the angular rotor speed of the induction motors for single-cylinder piston compressors under frequency-controlled conditions, and to develop the criterion of efficient quasi-static operating conditions.

**Materials and results.** The object of study is a three-phase two-pole 550 W IM of frequency-controlled drive of piston single-cylinder compressor. The complex study of the operating condition of the IM of drive compressor with periodically changing load torque depending on the angle of rotor rotation uses the mathematical model under dynamic conditions. Such model for simulation (Fig. 1) is developed similarly to [2, 3] with added blocks for: periodic load "Mc_1"; voltage changes with changing supply frequency *"u (f)"* (for consideration of given IM is assumed that $U = Un*(1+(50-f)/175)*f/50$, where $Un$ is the rated voltage; $f$ is the supply frequency); analysis of quasi-static regimes "quasi" (for determining the relative pulsations $\Delta u = 100\%\ (u_{min} - u_{max})/u_{cp}$, where $u_{min}$, $u_{max}$ and $u_{cp}$ are the minimum, maximum and average signal values over a period of load change).

The electromagnetic parameters are determined taking into account the changes in the magnetic field saturation as a function of the total magneto-motive force (MMF) of the motor similarly to [3]. The simulated results of the design condition as compared to the catalog data (with determination of relative deviation Δ) for 4A63V2U3-typed motor are given in table 1. The calculation was performed according to [12] with a space factor of core package of 0.963; specific losses in steel $p_{1.5.50}$ = 5.6 W/kg; coefficient of increase in steel losses – 2.5; calculated working temperature is 75° C.

**Table 1**

| Source of data | Rated data of 4A63V2U3-typed motor | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $M_2$ | $P_2$ | $I_1$ | η | cos φ | $s$ | $P_{гр.}$ | $B_\delta$ |
| | N·м | W | A | % | relative units | | W | T |
| Reference book [12] | 1,913 | 550 | 1,327 | 73,0 | 0,86 | 0,085 | – | 0,7 |
| Mathematical model | 1,913 | 549,0 | 1,309 | 72,54 | 0,876 | 0,0868 | 189,7 | 0,663 |
| Δ, % | – | 0,02 | 1,36 | 63,0 | 1,86 | 2,12 | – | 5,29 |

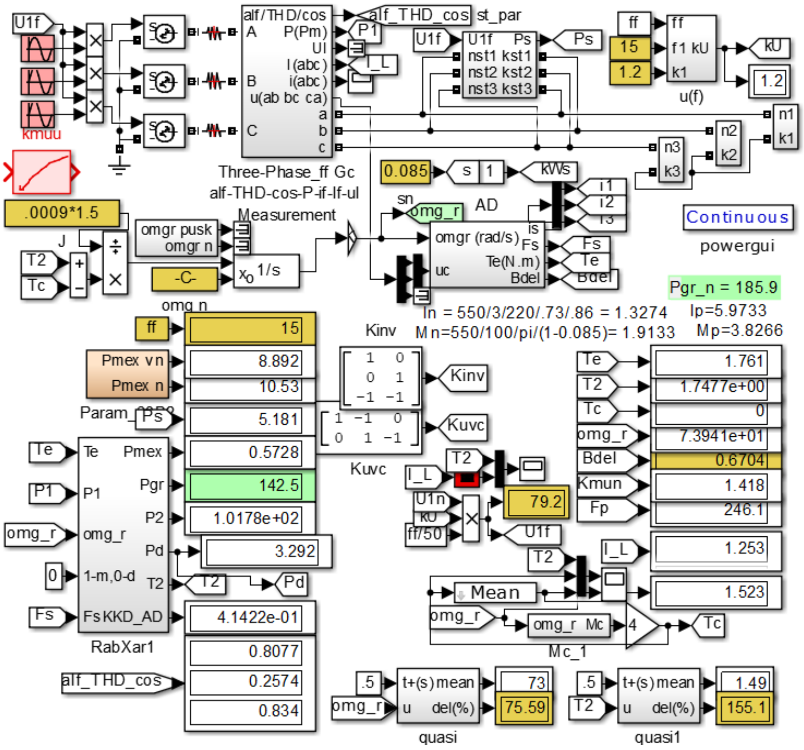

**Fig. 1**

The calculated results for the dependences of torque output and root-mean-square [rms] current in the stator of IM on the rotor angular speed using the indicated parameters are shown in Fig. 2. The electromagnetic parameters are corrected according to the field analysis [13] for refined calculations, especially for large slips.

The influence of the periodic load on the characteristics of the operating conditions of IM of piston single-cylinder compressors under the conditions of frequency-controlled speed is studied. It is possible to carry out their detail analysis and determine the conditions for the expedient application of additional ways to increase the efficiency. The following criteria are selected: 1) relative torque pulsations on the motor shaft (Δ*M*); 2) relative pulsations of the rotor angular speed ($\delta\omega_r$); 3) the deviation of the average efficiency of the quasi-static regime of the periodic load from the efficiency of regime with constant torque on the motor shaft, which is equal to the average load torque under quasi-static condition ($\Delta\eta$).

The numerical experiment is realized with moment of inertia $J$ = 0.00135 N·m$^2$ when varying the dependence of the maximum load torque of the single-cylinder piston compressors on the rotation angle of shaft $\gamma$: $M_c = f(\gamma)$ and supply frequency (within the range of 15–50 Hz) and at voltage changing according to the above ratio. The experimental results are summarized in table 2.

**Table 2**

| Maximum of $M_c = f(\gamma)$ | $f$ | $U$ | $\omega^{\gamma}_{r\,cep} = \omega^{c}_{r}$ | $\delta\omega_r$ | $M^{\gamma}_{2cep} = M^{c}_{2}$ | $\Delta M$ | $\eta^{\gamma}$ | $\eta^{c}$ | $\Delta\eta$ | $P^{\gamma}_{t}$ | $B_{\delta}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N·м | Hz | V | s$^{-1}$ | % | N·м | % | % | % | % | W | T |
| 2 | 50 | 220 | 305,5 | 1,9 | 0,688 | 18 | 68,7 | 68,71 | 0,01 | 83,37 | 0,711 |
| | 40 | 186,1 | 243,5 | 3,08 | 0,6883 | 29,4 | 64,55 | 64,62 | 0,07 | 85,19 | 0,745 |
| | 30 | 147,1 | 181,4 | 5,51 | 0,6893 | 47,1 | 57,91 | 58,09 | 0,18 | 87,4 | 0,774 |
| | 25 | 125,7 | 150,2 | 8,26 | 0,6909 | 61,8 | 53,49 | 53,86 | 0,37 | 87,59 | 0,784 |
| | 23 | 116,8 | 137,7 | 9,86 | 0,6921 | 71,04 | 51,56 | 52 | 0,44 | 87,2 | 0,786 |
| | 20 | 103,1 | 118,8 | 13,3 | 0,6949 | 87 | 48,44 | 49,12 | 0,68 | 85,82 | 0,788 |
| | 18 | 93,68 | 106,3 | 16,9 | 0,6986 | 102,4 | 46,16 | 47,17 | 1,01 | 84,16 | 0,786 |
| | 15 | 79,2 | 87,1 | 25,3 | 0,7092 | 131,4 | 42,52 | 44,39 | 1,87 | 80,39 | 0,778 |
| 3 | 50 | 220 | 300,9 | 2,92 | 1,032 | 17,44 | 73,59 | 73,64 | 0,05 | 99,5 | 0698 |
| | 40 | 186,1 | 239,4 | 4,68 | 1,033 | 27,21 | 70,22 | 70,34 | 0,12 | 98,23 | 0,731 |
| | 30 | 147,1 | 177,4 | 8,7 | 1,035 | 45,25 | 64,6 | 64,9 | 0,3 | 97,3 | 0,756 |
| | 25 | 125,7 | 146,2 | 13 | 1,039 | 60,9 | 60,57 | 61,2 | 0,63 | 96,2 | 0,762 |
| | 23 | 116,8 | 133,6 | 15,67 | 1,041 | 69,41 | 58,7 | 59,55 | 0,85 | 95,5 | 0,763 |
| | 20 | 103,1 | 114,7 | 21,5 | 1,049 | 85,6 | 55,4 | 56,85 | 1,45 | 94,08 | 0,761 |
| | 18 | 93,68 | 102,1 | 27,47 | 1,058 | 99,56 | 52,8 | 54,92 | 2,12 | 93,01 | 0,756 |
| | 15 | 79,2 | 82,25 | 42,5 | 1,085 | 129,1 | 47,58 | 51,74 | 4,16 | 93,04 | 0,74 |
| 4 | 50 | 220 | 296 | 4,03 | 1,376 | 17,05 | 74,92 | 74,99 | 0,07 | 124,9 | 0,685 |
| | 40 | 186,1 | 234,8 | 6,48 | 1,378 | 26,59 | 71,88 | 72,04 | 0,16 | 120,2 | 0,715 |
| | 30 | 147,1 | 173 | 12,18 | 1,382 | 44,14 | 66,56 | 67,06 | 0,5 | 116,6 | 0,736 |
| | 25 | 125,7 | 141,6 | 18,43 | 1,388 | 59,38 | 62,47 | 63,48 | 1,01 | 115,2 | 0,739 |
| | 23 | 116,8 | 128,9 | 22,37 | 1,394 | 67,59 | 60,39 | 61,76 | 1,37 | 114,9 | 0,737 |
| | 20 | 103,1 | 109,4 | 31,25 | 1,406 | 83,86 | 56,4 | 58,76 | 2,36 | 115,6 | 0,73 |
| | 18 | 93,68 | 96,1 | 40,65 | 1,426 | 98,69 | 52,7 | 56,32 | 3,62 | 118,3 | 0,721 |
| | **15** | **79,2** | **75,78** | **75,59** | **1,49** | **155,1** | **41,58** | **51,05** | **9,47** | **143,2** | **0,685** |
| 5 | 50 | 220 | 290,7 | 5,217 | 1,721 | 16,68 | 74,41 | 74,49 | 0,08 | 161 | 0,671 |
| | 40 | 186,1 | 229,8 | 8,46 | 1,722 | 26,05 | 71,39 | 71,6 | 0,21 | 152,5 | 0,699 |
| | 30 | 147,1 | 168 | 16,4 | 1,729 | 43,28 | 65,8 | 66,5 | 0,7 | 147,4 | 0,714 |
| | 25 | 125,7 | 136,1 | 24,8 | 1,74 | 58,48 | 61,07 | 62,51 | 1,44 | 147,6 | 0,713 |
| | 23 | 116,8 | 123,5 | 30,49 | 1,752 | 67,04 | 58,42 | 60,43 | 1,85 | 149,4 | 0,708 |
| | 20 | 103,1 | 103 | 43,9 | 1,78 | 85,23 | 52,6 | 56,4 | 3,8 | 159,1 | 0,694 |
| | 18 | 93,68 | 63,6 | 72,7 | 1,75 | 119 | 26,2 | 53,5 | 27,3 | 333 | 0,607 |
| | 15 | 79,2 | /68,08 | - | /1,78 | - | - | 45,56 | - | /144,2 | /0,64 |
| 5,5 | 50 | 220 | 287,8 | 5,85 | 1,893 | 16,47 | 73,7 | 73,79 | 0,09 | 183,7 | 0,664 |
| | 40 | 186,1 | 226,9 | 9,53 | 1,895 | 25,77 | 70,6 | 70,84 | 0,24 | 173,2 | 0,69 |
| | 30 | 147,1 | 165,2 | 18,36 | 1,904 | 42,98 | 64,7 | 65,48 | 0,78 | 167,9 | 0,702 |
| | 25 | 125,7 | 133 | 28,57 | 1,917 | 58,48 | 59,4 | 61,13 | 1,73 | 170,8 | 0,697 |
| | 23 | 116,8 | 120,2 | 35,4 | 1,93 | 67,5 | 56,21 | 58,76 | 2,55 | 175,7 | 0,688 |
| | 20 | 103,1 | 78 | 65 | 2,1 | 119,9 | 27,9 | 51,42 | 23,52 | 385/190 | 0,59 |
| | 18 | 93,68 | 68,8 | 121,3 | 2,1 | 123,6 | 25 | 46,4 | 21,4 | 354/196 | 0,61 |
| | 15 | 79,2 | /53,4 | - | /2,1 | - | - | 32,3 | - | /234 | /0,56 |

The sequence of numerical experiment is as follows: 1) the differential equations of the electric balance of IM and the mechanical equilibrium of the periodic load are calculated for each selected values of supply frequency and maximum $M_c = f(\gamma)$; 2) the criteria Δ*M*, $\delta\omega_r$, average efficiency $\eta^{\gamma}$, torque on the shaft (equal to average load torque $M_{2\text{сер}}^{\gamma}$), induction in the air gap $B_{\delta}$ and heating losses in IM $P_t^{\gamma}$ (to control the thermal state in comparison with design condition are determined upon reaching the quasi-static conditions), Table 1; 3) the steady-state operating condition is calculated at constant shaft torque $M_2^c = M_{2\text{сер}}^{\gamma}$ and the corresponding efficiency $\eta^c$ is determined; 4) the difference between the efficiency $\Delta\eta$ for static and periodic loads is determined. The partially filled rows correspond to non-available sustainable solution due to insufficient torque on the induction motor shaft (the information in the row corresponds to result for static load).

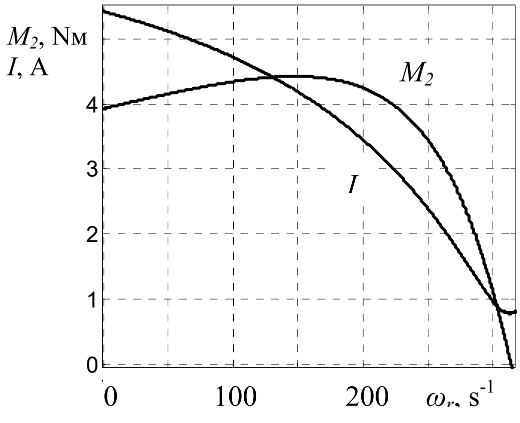

**Fig. 2**

The upper index $\gamma$ indicates the condition with periodically changing load torque, and the upper index *c* indicates the static torque.

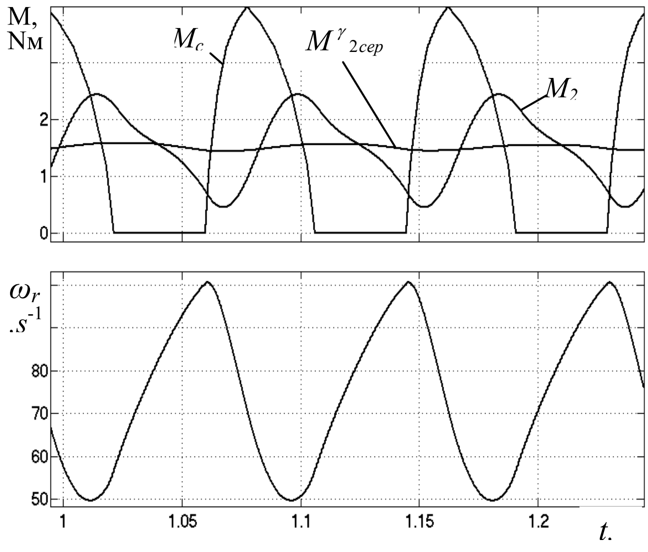

**Fig. 3**

The example of the dynamic characteristics for 4A63V2U3-typed quasi-static motor at 15 Hz supply frequency with the load similar to single-cylinder piston compressor with a maximum load torque of 4 N·m is shown in Fig. 3. The corresponding row in table 2 is marked by bold type. In addition, the calculated results for such operating conditions are presented in Fig. 1.

Fig. 3 shows the time dependences of instantaneous values of the angular rotor speed, load torque ($M_c$), torque on the shaft ($M_2^{\gamma}$) and its average value ($M^{\gamma}{}_{2cep}$), according to which the conditions with constant torque are calculated. The plots in Fig. 3 show that the decrease of rotor speed when the load torque exceeds the motor torque. It is on the contrary for speed. The motor torque increases with decreasing speed, and decreases otherwise. The pulsation values are given in table. 2.

The considered operating conditions at supply frequency of 15 Hz are characterized by 155.1% relative value of torque pulsations and 76% angular rotor speed. This leads to an increasing losses and decreasing efficiency by 9.47%. It should be noted that according to (1) the ratio for heavy quasi-static conditions of 4A63V2U3-typed IM at 50 Hz frequency is $k_1 = T_{MK} / T_E = 3.9$. It shows (in accordance with $k_1 > 2$ by [1]) no-resonance within the frequency motor characteristics (when the amplitude of the electromagnetic torque $M_2^{\gamma}$ exceeds the shaft torque amplitude $M_2^c$). The calculation of ratio (1) at changing supply frequency (for the values of Table 2) is carried out taking into account the varying critical slip and torque. These values are obtained by determination of the speed-torque characteristics (Fig. 4) for frequencies of 50, 40, 30, 25, 23, 20, 18, 15 Hz, which are indicated in the figure.

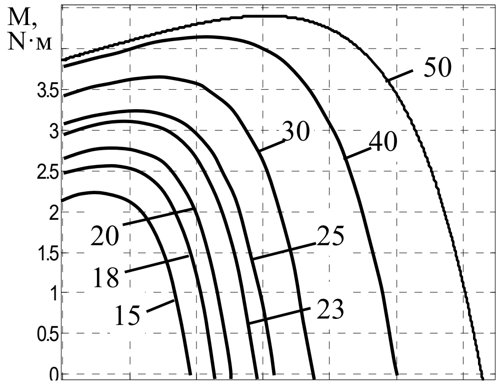

**Fig. 4**

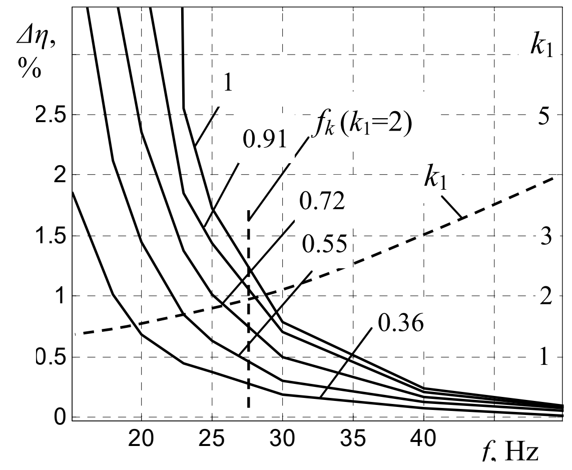

**Fig. 5**

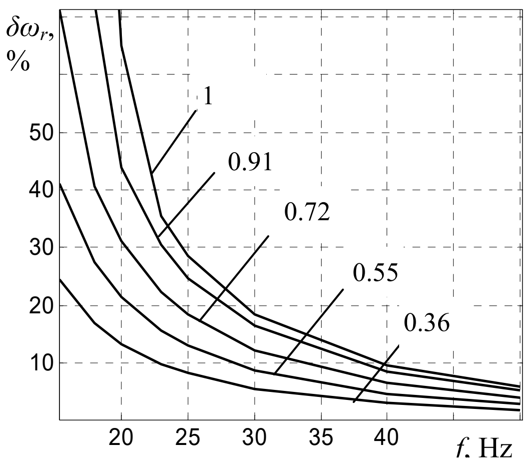

**Fig. 6**

The graphic dependence of the changing ratio $k_1$ on the supply frequency is shown in Fig. 5 along with a set of dependencies $\Delta\eta$. As seen, when the frequency is less than the critical value $f_k$ = 28 Hz, the ratio for heavy quasi-static conditions $k_1 = T_{MK} / T_E$ becomes less than the critical value which is equal to 2.0 [1]. This correlates with strong reduction of efficiency under operating conditions (Fig. 5, Table 2). It can be seen that the line of the critical frequency passes approximately through the inflection of curves $\Delta\eta$ (*f*) for different loading degrees $k_з$. This confirms proposed criterion to be used for controlled IMs with periodic load concerning increase of their energy efficiency under quasi-static conditions.

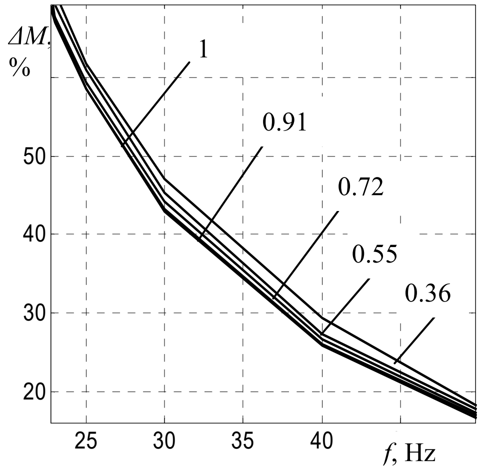

**Fig. 7**

The graphic dependencies of $\Delta\eta$, $\delta\omega_r$, $\Delta M$ as functions of supply frequency for various loading degrees $k_з = M^{\gamma}_{2\text{сер}} / M_{2\text{Н}}$ (calculated according to data in Tables 1, 2 and used to mark the plots) are shown in Figs. 5–7. As seen, at increasing loading degree, the decreasing efficiency and speed pulsations reach the critical level within the smaller range of supply frequency, and the pulsation of torque depends little on the loading degree.

The calculated results show the possibility to determine the characteristics of IM with frequency converters (with limited speed pulsations for IM of the single-cylinder compressors – at the level of 20% [14]). For example, these characteristics are realized within the range of 1:3.5 for loading degree of 0.36 (which corresponds to the maximum 2 N·m shaft torque) and within the range of 1:1.8 – for 1.0 loading degree (maximum 5.5 N·m). The maximum difference of efficiency for constant and periodic loads (27.3%) is calculated. This value corresponds to the operating conditions with $k_з$ = 0.91 and *f* = 18 Hz.

The efficiency of quasi-static regimes should be determined taking into account the influence of the current-shape distortion on the power factor due to the periodic load. The values on the displays in Fig. 1 show that for quasi-static regime THD$_i$ = 0.2574. Such current-shape distortion reduces the power factor in comparison with cos$\varphi_1$ = 0.834 that determined by the first harmonic. So, the power factor according to the following expression [15], which takes into account non-sinusoidality and asymmetry, is equal to $\alpha = P_1 / U / \sqrt{I_A^2 + I_B^2 + I_C^2}$ = 0.8077, where $P_1$, $U$ and $I$ are the power consumption, the effective values of the line voltage and currents respectively. The similar value of the power factor can be calculated by expression [16]: $\alpha = \cos\varphi_1 \big/ \sqrt{1 + THD_i^2}$ = 0.8077 at the symmetry of the processes that are representative for model of Fig. 1.

## Conclusions

1. The effect of supply frequency on the power and operational efficiency of frequency-controlled drive of IM for piston compressor is determined by complex modeling taking into account the varying load torque, nonlinear electromagnetic parameters, asymmetry and non-sinusoidality of processes. The region of critical reduction of the efficiency is revealed**.**
2. The criterion for heavy quasi-static regimes is proposed for IM piston compressor with frequency regulation. The criterion is used to determine the need for consideration of periodically varying load torque when developing the proposition to improve the efficiency.
3. For 4A63V2U3-typed 550 W motor, the region of critical reduction of efficiency (the reduction of efficiency exceeds 10% at the boundaries of the region) is found under conditions of the periodic load for single-cylinder piston compressor, the varying frequency, supply voltage and loading degree. The permissible ranges of speed regulation are defined for different loading degrees of IM at 20% regulated speed pulsation level.
4. The complex design work should be carried out taking into account the changing range for speed control, loading degree, moment of inertia, the varying voltage and frequency, the structure of frequency-controlled system in order to develop the effective technical solutions for frequency-controlled induction motor drive for piston compressors. Without such complex designing the power efficiency can be decreased by more than 10%.

*The work was carried out according to governmental project «Scientific bases and tools for complex design synthesis of induction machines of energy-efficient and resource-saving electromechanical systems» (state registration number 0117U007715).*

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УДК 621.313

## ЕФЕКТИВНІСТЬ РОБОЧИХ РЕЖИМІВ АСИНХРОННИХ ДВИГУНІВ ПОРШНЕВИХ КОМПРЕСОРІВ ПРИ ЧАСТОТНОМУ РЕГУЛЮВАННІ

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*Досліджено вплив періодичного навантаження на пульсації електромагнітного моменту й частоти обертання ротора, втрати і коефіцієнт корисної дії частотно-регульованого асинхронного двигуна поршневого одноциліндрового компресора з застосуванням імітаційного моделювання. З використанням критерію інтенсивних квазісталих режимів визначено області критичного зниження ефективності двигуна за зміни частоти і напруги живлення та ступеня його завантаження.* Бібл. 16, рис. 7, табл. 2.

***Ключові слова***: асинхронні двигуни, частотне регулювання, поршневі одноциліндрові компресори, пульсації, коефіцієнт корисної дії.

УДК 621.313

## ЭФФЕКТИВНОСТЬ РАБОЧИХ РЕЖИМОВ АСИНХРОННЫХ ДВИГАТЕЛЕЙ ПОРШНЕВЫХ КОМПРЕССОРОВ ПРИ ЧАСТОТНОМ РЕГУЛИРОВАНИИ

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*Исследовано влияние периодической нагрузки на пульсации электромагнитного момента и частоты вращения ротора, потери и коэффициент полезного действия частотно-регулируемого асинхронного двигателя поршневого одноцилиндрового компрессора с помощью имитационного моделирования. С использованием критерия интенсивных квазиустановившихся режимов определены области критического снижения эффективности двигателя при изменении частоты и напряжения питания и степени его загрузки.* Библ. 16, рис. 7, табл. 2

***Ключевые слова:*** асинхронные двигатели, частотное регулирование, поршневые одноцилиндровые компрессоры, пульсации, коэффициент полезного действия.

Надійшла 27.09.2019
Остаточний варіант 05.11.2019