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METHOD FOR OPTIMIZATION OF SWITCHING FREQUENCY IN FREQUENCY CONVERTERS

Purpose. To present a methodology for determining the optimal switching frequency in frequency converters and autonomous voltage inverters, the load of which is an asynchronous electric motor. The methodology is based on determining the dependences of static and dynamic power losses in the power switches of the inverter on the switching frequency and the dependence of power losses in the windings of an induction motor on the higher harmonics of currents, which also depend on the switching frequency.

Methodology. Polynomial approximation of the energy characteristics of power transistors. General provisions of the theory of electrical circuits. The determination of additional power losses in the windings of an induction motor from higher harmonics is based on analytical calculation and simulation in the Matlab/Simulink software environment and a specialized program from the manufacturer of power switches Mitsubishi – MelcoSim 5.1.

Findings. A method for optimizing the frequency of pulse-width modulation in frequency converters, the load of which is an asynchronous motor, is presented according to the criterion of the minimum total power losses in the power transistors of the inverter and the resistance of the motor windings. The proposed calculation technique allows determining the dependence of static and dynamic losses in power IGBT-transistors with a sufficiently high accuracy while being in the MelcoSim software environment. To calculate the losses in the motor, it is shown that the switching frequency of the power switches affects the harmonic distortion factor and the average value of the phase current of the induction motor. Provided that only the first harmonic of the current performs the useful action in an asynchronous motor, the dependence of additional power losses on the switching frequency is given.

Originality. A method for optimizing the frequency of pulse-width modulation by the criterion of minimum additional power losses in the resistance of the motor windings from higher harmonics of the current and static and dynamic losses in the power transistors of the inverter is presented. An analytical dependence of additional power losses in the active resistance of the windings of induction motors as a function of the harmonic distortion factor of the phase current of an autonomous voltage inverter is presented.

Practical value. The presented technique makes it possible to determine the optimal modulation frequency in frequency converters with asynchronous motors and to ensure the minimum total power losses and the maximum value of efficiency in the "autonomous voltage inverter – asynchronous motor" system.

Keywords: *switching frequency, higher current harmonics, power losses, coefficient of harmonic distortion, simulation modeling, frequency converter, asynchronous motor*

Introduction. Asynchronous electric motors are widely used in various industries and transport – from rolling mills to rail transport [1, 2]. Frequency converters that work with sinusoidal or spatial-vector PWM are most often used to regulate the speed and torque of induction motors [3, 4].

Improving the energy efficiency of asynchronous electric drive is an important area of development of electrical engineering and electromechanics.

Ways to increase the energy efficiency of an asynchronous electric drive. The increase in the efficiency of induction motors (AD) is associated with an increase in the poles of the AD, a decrease in the resistance of the windings of the AD and an increase in power factor. In addition, to ensure the maximum efficiency of the induction motor, it is rational to use a BP with full (nominal) load [5, 6] (Fig. 1).

It is also important to increase the efficiency of frequency converters in an asynchronous electric drive. Types of power losses in power switches, possible methods for reducing these losses are given in Table 1. Reduction of power losses and, accordingly, increase in efficiency in the "frequency converter – induction motor" system, in addition to design methods, can be achieved by algorithmic methods, i. e. features of the algorithm of control systems, or mode of operation.

Literature review. In publications [7, 8] the study on power loss optimization in the "autonomous voltage inverter – induction motor" system by the parameter of the modulation coefficient M, which is defined as the ratio of the amplitude of the sinusoidal signal of the PWM $A_{\sin}$ to the amplitude of the reference sawtooth signal A_{op}

$$M = \frac{A_{\sin}}{A_{op}}.$$

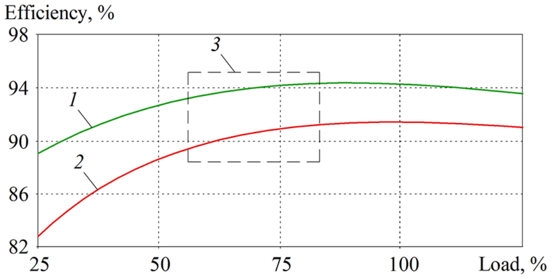


Fig. 1. Efficiency at full and partial loading of the motor:
1 – high efficiency; 2 – low efficiency; 3 – normal speed zone

The disadvantage of optimizing power losses in the "autonomous inverter – asynchronous motor" system by the parameter of the modulation factor is that at a given value of the motor torque it cannot be changed, as reducing M will reduce the phase current of the motor and therefore reduce torque. In addition, the disadvantage of these publications is that it is not clear how the dynamic power losses in the power switches were determined and how the power losses in the induction motor were determined [9, 10].

In [11], a study on the optimization of the switching frequency of power transistors of a single-phase half-bridge two-level voltage inverter with an output LC filter by the criterion of minimizing the mass and dimensions of the system. The disadvantage of the publication is the inaccuracy of the formulas used, as well as the lack of attention to the fact that the efficiency of the converter will be significantly reduced. According to this work, "with increasing frequency there is a noticeable decrease in mass and dimensions due to their reduction for reactive elements", thus high enough frequencies are selected as "optimal" at which in power switches there will be quite high power losses and, as a result, overheating. There is a violation of the logic of the statement, because it is indicated that for power transistors of class S with a switching frequency of 1 kHz, the optimal switching frequency by mass of the system is a frequency of 12.2 kHz, which is physically impossible.

In [12] it was shown that the efficiency of an induction motor type 4AA50V4U3 with a power of 90 W when powered by "pure" sinusoidal voltage is 3–7 % higher than when powered by a real frequency converter with voltage distortion. The disadvantage of this publication is the lack of data on the PWM frequency used in the experiment, as well as the lack of dependences on the efficiency of power losses on the switching frequency of the keys, or on the parameter of the harmonic distortion of the phase current.

In [13], a study on methods for optimizing the efficiency of the vector control system of an induction motor according to the criterion $I_d = I_q$ is presented. The disadvantage of this study is the lack of accounting for the impact of losses in the inverter keys on the overall efficiency of the drive.

In [14], a study was presented to reduce the coefficient of harmonic distortion of the output current of the AVI and minimize the equivalent frequency of switching power switches by remodulation.

Based on the review, it can be concluded that the task of optimizing the frequency of switching power switches in the "AVI–AD" system by the criterion of minimum losses is relevant.

Purpose. Minimization of power losses in the "autonomous voltage inverter – asynchronous motor" system by optimizing the frequency of pulse-width modulation.

Optimization of pulse-width modulation frequency in frequency converters by the criterion of minimum power losses in the AVI–AD system. Most common frequency converters (such as Siemens, OWEN, Danfoss and others) have the ability to configure and set the modulation frequency. The switching frequency affects the following factors. As the modulation frequency increases, the power losses in the power switches of the stand-alone inverter increase.

At the same time, as the switching frequency increases, the sinusoidality of the inverter phase current improves, as a result of which additional power losses in the windings of induction motors from higher harmonics are reduced. One of the ways to improve the energy efficiency of an asynchronous electric drive with a frequency converter is to optimize the switching frequency of power switches.

There is a dilemma: the higher the switching frequency of the transistors is, the greater the power loss in the power switches is, yet the higher the sinusoidal current of the induction motor is and, accordingly, the smaller the power loss in the induction motor from higher harmonics becomes.

Thus, a switching frequency is theoretically possible at which the total power losses in the motor and inverter will be minimal.

Next, we give analytical dependences that describe the dependences of power losses in power switches on the switching frequency.

Analysis of the dependence of power losses in the power switches of the inverter on the switching frequency. Power losses in power MOSFET or IGBT modules consist of power losses in the transistors themselves and power losses in the reverse diode [15, 16].

In this case, power losses are conventionally divided into static power losses – losses in the conductive state, and dynamic power losses – losses when turning on and off the transistor

$$E_{loss.module} = E_{loss.VT} + E_{loss.VD};$$

$$E_{loss.VT} = E_{VT.DC} + E_{VT.SW};$$

$$E_{loss.VD} = E_{VD.DC} + E_{VD.SW},$$

where $E_{VT.DC}$ is the static loss energy in MOSFET-transistors; $E_{VT.SW}$ is the energy of dynamic losses in MOSFET-transistors; $E_{VD.DC}$ is the energy of static losses in parallel diodes; $E_{VD.DC}$ is the energy of dynamic losses in parallel diodes.

The approximate process of switching current and voltage in power transistors and the distribution of static and dynamic losses is shown in Fig. 2.

Table 1

Structural and circuit methods for reducing power losses in the power switches of the inverter

Type of losses	Components of losses	Causes of losses	Possible methods to reduce losses	Disadvantages
Static	- losses in the leading state; - leakage currents	- depending on the amount of current and voltage on the device	- change of an internal design of a power key for decrease in voltage drop	- high cost of keys based on silicon carbide
Dynamic	- losses on the transistor; - losses on switching off the transistor; - diode recovery losses; - losses in drivers	- the amount of current and voltage during switching; - duration of switching; - the number of switches	- soft switching methods; - improved driver designs; - reducing the switching frequency	- complications of the circuitry of the device; - increase in cost; - reducing the quality of the output current of the inverter

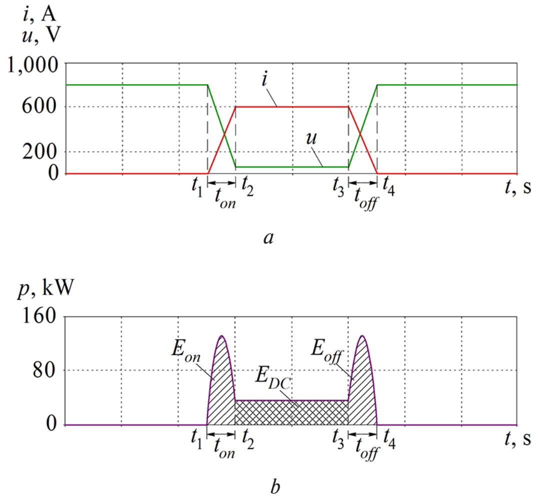


Fig. 2. Switching process in MOSFET or IGBT-switches:
a – current and voltage transients; b – transients of power losses

The energy of static power losses in transistors can be defined as the integral of the power function over time and are determined from the expression

$$E_{VT.DC}=\int_{t_2}^{t_3}(i_c\cdot u_{ce})dt,$$

where i_c is the collector current; $u_{ce}(i_c)$ is the voltage between the collector and the emitter, which depends on the magnitude of the collector current.

Similarly, the energy of dynamic losses can be defined as the power integral at the on and off intervals

$$E_{VT.SW}=\int_{t_1}^{t_2}P_{on}(I_c)\cdot dt+\int_{t_3}^{t_4}P_{off}(I_c)\cdot dt,$$

where $P_{on}(I_c)$ is the power loss in the transistor when it is turned on, depending on the value of the collector current; $P_{off}(I_c)$ is the power loss in the transistor when it is turned off, depending on the value of the collector current.

Static losses in reverse diodes are determined from the expression

$$E_{VD.DC}=\int_{t_i}^{t_{i+1}}(u_{fwd}\cdot i_{vd})\cdot dt,$$

where u_{fwd} is the voltage drop across the reverse diode; *ivd* is the reverse diode current.

Dynamic losses in reverse diodes are determined from the expression

$$E_{VD.SW}=\int_{t_i}^{t_{i+1}}P_{rec}(i_{vd})\cdot dt,$$

where P_{rec} is the reverse diode reduction energy.

The change in switching frequency has almost no effect on static losses and directly affects the dynamic power loss [17].

Determination of power losses in the power switches of the inverter can be determined, for example, by calculation in specialized programs from manufacturers of power transistors, namely programs MelcoSim, SemiSel and the like.

Determination of additional power losses in the resistance of windings of induction motors as a function of the coefficient of harmonic distortion of the phase current. A method for determining additional heat losses in the windings of electric motors of alternating current from higher harmonics, which are uniquely determined based on the resulting value of the coefficient of harmonic distortion of the motor current. This method can be used in the case when the effect of the skin effect on the resistance of the windings of motors with a limited range of higher harmonics of the current is insignificant. In this case, additional losses in the windings from higher harmonics can be calculated based on the increase in the root mean square value (*RMS*) of the current relative to the value of the first harmonic, and, consequently, the increase in square losses depending on the *RMS* value of the current [18].

As is known, the harmonic distortion coefficients for alternating current THD_{AC} are defined as

$$THD_{AC}=\frac{\sqrt{\sum_{m=2}^{m=\infty}I_m^2}}{I_1},$$

where I_m is the root-mean-square value of the m^{th} harmonic.

For further formulas, the *THD* values are given in relative values, i. e. from 0 to 1.

As is known, the effective value (also the root-mean-square value – *RMS*) of alternating (or constant pulsating) current is equal to the value of such direct current, which for a time equal to one period of alternating current, will do the same work (thermal or electrodynamic effect) as the alternating current considered.

$$I_{RMS}=\sqrt{\frac{1}{T}\cdot\int_0^T i^2(t)dt}.$$

The *RMS* value of alternating current can also be expressed through the spectrum of higher harmonics

$$I_{RMS\_AC}=\sqrt{I_1^2+\sum_{m=2}^{m=\infty}I_m^2}.$$

Then the *RMS* value of direct and alternating currents can be represented as

$$I_{RMS\_AC}=I_{AC}\cdot\sqrt{\left(1+THD_{AC}^2\right)}.$$

The relative increase in power loss in the active phase resistance of the motor R_s caused by higher harmonics can be expressed as

$$\Delta P=\frac{I_{RMS}^2\cdot R_s}{I_1^2\cdot R_s}=\frac{I_1^2\cdot R_s\cdot\left(1+THD^2\right)}{I_1^2\cdot R_s}=1+THD_2^2.$$

Thus, a clear relationship between the coefficient of harmonic distortion of current consumption and the percentage of additional power losses is established.

The dependence of the relative value of additional power losses on the value of the harmonic distortion coefficient is shown in Fig. 3, which is 100 % assumed losses caused by the fundamental harmonic of the phase current of the motor.

Shown in Fig. 3 ratios allow determining the additional losses in the active resistance of the motor windings from the value of the coefficient of harmonic distortion THD_I load current. Fig. 4 shows that the distortion of the phase current with

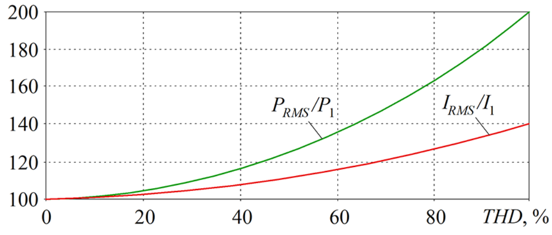


Fig. 3. Dependence of the relative value of the RMS value of current and power relative to the current and voltage of the first harmonic on the coefficient of harmonic distortion

a harmonic distortion coefficient of 50 % causes an increase in power losses in the electrical network by approximately 25 %.

Further determination of the dependence of the harmonic distortion coefficient of the phase current of the motor on the modulation frequency of the inverter can be performed by simulation.

Determination of additional power losses from higher harmonics in the steel of induction motors. Additional power losses from higher harmonics in the steel of induction motors are due to the presence of hysteresis losses and eddy current losses.

In the study [19] determination of power losses due to hysteresis and eddy currents was performed by the expression

$$p_o = p_g + p_{in} = B_e^2 \cdot \left(K_g \cdot f + K_{in} \cdot f^2\right) \cdot \left(m_{a1} + m_{z1}\right),$$

where p_o is the main losses in steel; *pg* is the loss of hysteresis; p_{in} is the losses on eddy currents; K_g is the loss factor for hysteresis; K_{in} is the coefficient of losses on eddy currents; B_e is the equivalent value of magnetic induction, averaged over the mass of the teeth and the yoke of the stator core; *f* is the frequency; m_{a1} is the mass of the yoke; m_{z1} is the mass of the teeth of the stator core.

The equivalent average value of magnetic induction can be determined from the expression

$$p_o = p_{a1} + p_{z1} = \left(B_{a1}^2 \cdot m_{a1} + B_{z1}^2 \cdot m_{z1}\right) \cdot \left(K_g \cdot f + K_{in} \cdot f^2\right). \quad (1)$$

From expression (1) we obtain

$$B_e = \sqrt{\frac{B_{a1}^2 \cdot m_{a1} + B_{z1}^2 \cdot m_{z1}}{m_{a1} + m_{z1}}},$$

where p_{a1} is the losses in the steel yoke; p_{z1} is the losses in the steel of the stator teeth; B_{a1} is the magnetic induction in the yoke; B_{z1} is the magnetic induction in the teeth of the stator.

In [20] the method for determining additional power losses of a frequency-controlled induction motor from higher voltage harmonics is given.

Higher voltage harmonics create magnetic fields, which cause additional losses in the magnetic circuit. Since the sliding of the rotor in relation to these fields will be approximately one, the magnetic losses will take place in the rotor.

$$P_{mv} = P_{m\alpha} \cdot \left(\frac{B_v}{B_1}\right)^2 \cdot \left(\frac{f_v}{f_{1N} \cdot \alpha}\right) \cdot \frac{m_c + m_p}{m_c},$$

where $P_{m\alpha}$ is the main magnetic losses at $f_1 = f_{1N} \cdot \alpha$; B_v is the induction from the flow of higher harmonics; B_1 is the induction from the main harmonic flow; f_v is the frequency of the higher harmonic voltage; f_1 is the frequency of the fundamental harmonic voltage; m_c is the mass of stator steel; m_p is the mass of rotor steel.

In the first approximation

$$B_v = \frac{U_v}{f_v} = \frac{U_1}{f_1} \cdot \frac{1}{v^2} = B_1 \cdot \frac{1}{v^2}.$$

Summing up the losses from all harmonics, we get

$$P_{mv} = P_{m\alpha} \cdot \frac{m_c + m_p}{m_c} \cdot \sum_{v=6K\pm1}^{\infty} v^{-(4-n)}. \quad (2)$$

Additional magnetic losses from the higher harmonics of the magnetic flux at different control laws and values of the control coefficient α are carried out in accordance with (2).

Losses on eddy currents in the core of the rotor from the action of higher harmonics can be determined according to [21] by the expression

$$\eth_{in2} = \sum_{v=5}^{\infty} \eth_{in2v} = k_{in} \cdot m_{z2} \cdot \sum_{v=5}^{\infty} B_{z2v}^2 \cdot \left(f_1 \cdot v\right)^2 \cdot \xi_v,$$

where m_{z2} is the mass of the teeth of the rotor core.

Losses on the hysteresis in the core of the rotor from the harmonics of the order v_{PWM} are

$$p_{gc2} = k_{gc} \cdot m_{z2} \cdot f_1 \cdot s \cdot B_{z2(1)}^2 \cdot \left(1 + \frac{k}{B_{z2(1)}} \cdot B_{z2vPWM} \cdot \left(v_{PWM} - 1\right)\right),$$

where $B_{z2(1)}$ is the amplitude of the fundamental harmonic of the magnetic induction in the teeth of the rotor.

The coefficient of increase in losses in steel of the induction motor at food from the frequency converter with PWM is

$$K_{cm} = \frac{p_{in1} \cdot K_{in} + p_{gc1} \cdot K_{gc} + p_d + p_{in2} + p_{gc2}}{p_o + p_d},$$

where p_d is the additional losses in the steel of an induction motor during sinusoidal power supply.

In the model of accounting for losses in the frequency domain

$$P = \sum_{n=1}^{N} \left(K_h \cdot (n \cdot f) \cdot B_n^2 + K_c \cdot \left(n \cdot f \cdot B_n\right)^2 + K_e \cdot \left(n \cdot f \cdot B_n\right)^{1.5}\right),$$

where *n* is the harmonic number, the Fourier transform is used for the time domain simulation results in each grid element.

When using Perseval's theorem, average losses on eddy currents for the model in the time domain should be equivalent to the losses on eddy currents for the model in the frequency domain [22]

$$P_c = \sum_{n=1}^{N} \left(K_c \cdot \left(n \cdot f \cdot B_n\right)^2\right) = \frac{1}{T} \cdot \frac{2}{2\pi^2} \cdot \int_0^T K_c \left(\frac{dB}{dt}\right)^2 dt.$$

The extraction of coefficients for the model in the frequency domain is carried out by the same method as for the model in the time domain. Analytical calculation of power losses in the stator of an induction motor is complicated by the uncertainty of the corresponding coefficients, which in practice are determined empirically, i. e. in the course of physical experiments.

A very effective method for determining power losses in the steel of induction motors is 3D modeling of power losses in programs such as Ansys and Solid Works.

Results of calculations and modeling for optimization. As an example of the described method, we will optimize the modulation frequency for a stand-alone voltage inverter on power transistors type RS21A79 and a typical asynchronous motor with a motor power of 3.7 kW.

The main parameters of the studied induction motor are given in Table 2.

The simulation model of an autonomous voltage inverter with an induction motor in the Matlab/Simulink software environment is shown in Fig. 4.

Table 2

The main parameters of an induction motor

Parameter	Value
Rated power, kW	3.73
Active resistance of stator windings, Ohm	1.115
Active resistance of rotor windings, Ohm	1.083
The inductance of the stator windings, mH	5.974
Inductance of rotor windings, mH	5.974
Rated voltage in a direct current circuit, V	460
The number of pole pairs	2
Rated frequency, Hz	60
Nominal speed, rpm	1750

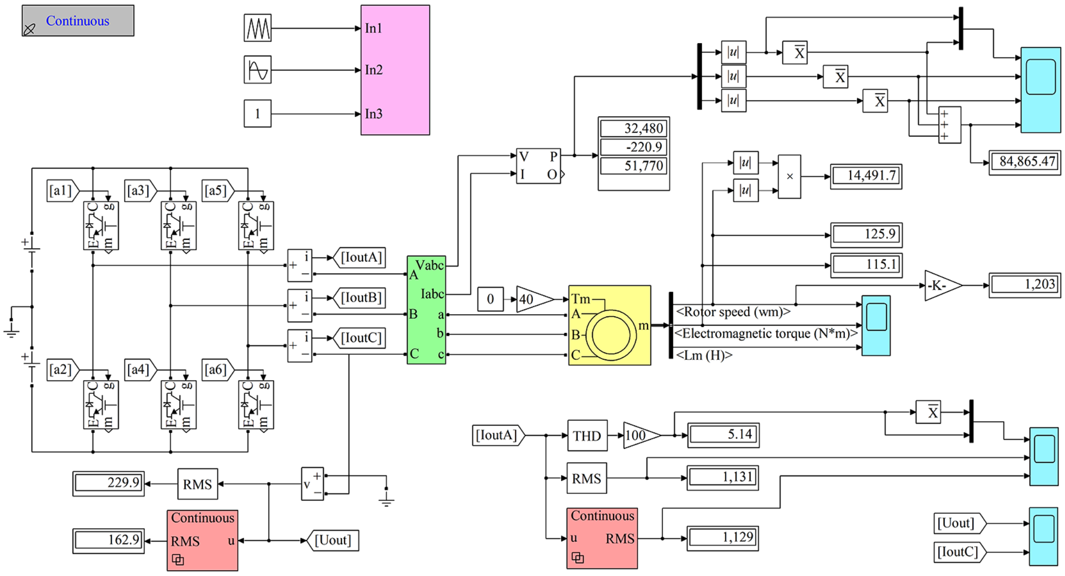


Fig. 4. Simulation model of a stand-alone voltage inverter with an induction motor

Simulation of the AVI-AD system was performed at the nominal load of the engine (nominal constant torque and nominal speed). During the experiments, only the PWM modulation frequency and, accordingly, the switching frequency of the power switches changed. According to the simulation results, the value of the first harmonic of the output voltage and output current does not change due to the change in modulation frequency, but the content of higher harmonics decreases with increasing PWM frequency, as a result of which the *RMS* value of phase current decreases. The simulation results are given in Table 3.

The dependence of the THD phase current of the inverter on the modulation frequency is shown in Fig. 5.

The dependence of power losses in the stator windings of the induction motor on the modulation frequency is shown in Fig. 6.

Power losses in the power keys are determined using the Melcosim program from the power key manufacturer Mitsubishi. Fig. 7 shows the interface of the program MelcoSim 5.1, which was used to calculate power losses in power transistors under appropriate conditions of simulation Matlab (namely, the calculation of power losses in the inverter PS22A79 at phase current 9.8 A, modulation frequency 4 kHz, frequency of the first harmonic output current 60 Hz, inverter supply voltage 460 V).

The results of calculations of total power losses in power switches from the modulation frequency are performed in the MelcoSim software environment and are shown in Fig. 8 and in Table 3.

The final result of analytical calculations and modeling in Matlab, namely the dependence of the total power losses in

Table 3

The results of modeling and calculation of the AVI-AD system at full load

PWM frequency, kHz	THD_I phase current, %	I_{RMS}, A	I_1, A	Loss in the three phases of the stator from full current, W	Losses in the three phases of the stator from the first harmonic, W	Additional power losses in the windings from current harmonics, W	Total losses in power switches, W	Total losses of AVI and AD, W
0.5	38.22	10.491	9.8	368.18	321.25	46.93	33.48	401.66
0.6	29.484	10.217	9.8	349.18	321.25	27.93	34.14	383.32
0.7	22.68	10.049	9.8	337.78	321.25	16.52	34.74	372.52
0.8	19.726	9.989	9.8	333.75	321.25	12.50	35.34	369.09
0.9	17.318	9.946	9.8	330.89	321.25	9.63	35.94	366.83
1	15.386	9.915	9.8	328.86	321.25	7.61	36.6	365.46
1.2	12.8926	9.881	9.8	326.59	321.25	5.34	37.86	364.45
1.4	11.228	9.862	9.8	325.30	321.25	4.05	39.18	364.48
1.6	9.674	9.846	9.8	324.26	321.25	3.01	40.38	364.64
1.8	8.6268	9.836	9.8	323.64	321.25	2.39	41.64	365.28
2	7.84	9.830	9.8	323.23	321.25	1.97	42.95	366.18
2.5	6.426	9.820	9.8	322.58	321.25	1.33	46.08	368.66
3	5.32	9.814	9.8	322.16	321.25	0.91	49.26	371.42
3.5	5.04	9.812	9.8	322.07	321.25	0.82	52.38	374.45
4	4.62	9.810	9.8	321.94	321.25	0.69	55.56	377.50

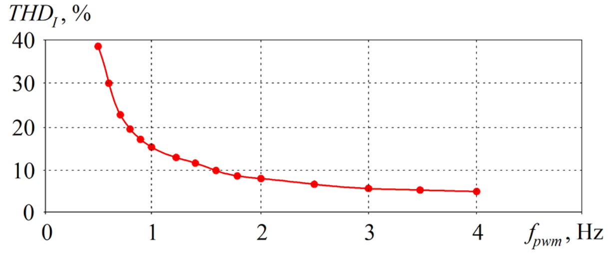


Fig. 5. Dependence of THD phase current of the inverter on the modulation frequency of the AVI

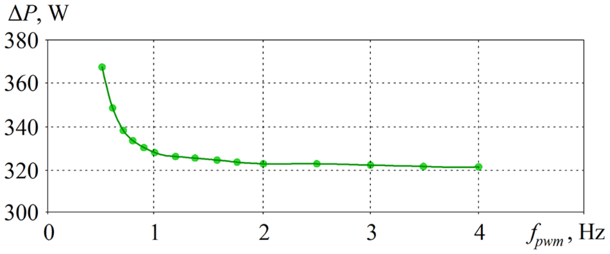


Fig. 6. Dependence of power losses in the resistance of the stator windings of an induction motor on the modulation frequency of the AVI

power transistors and losses in the motor windings on the modulation frequency is shown in Fig. 9.

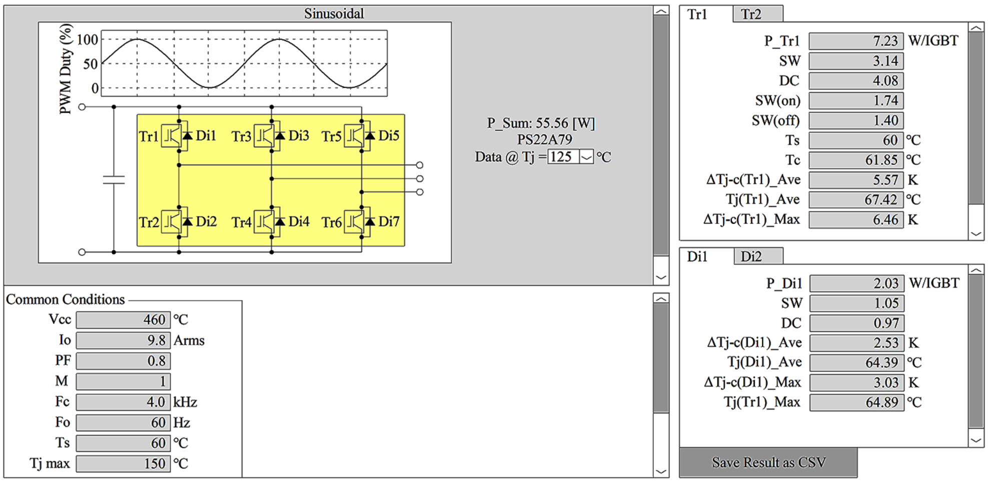
Based on the studies on a stand-alone voltage inverter on power transistors type RS21A79 and a typical asynchronous motor with a capacity of 3.7 kW, the optimal modulation frequency in PWM is 1.200 Hz. It should be noted that in the frequency range from 1 to 2 kHz, the total power loss does not increase significantly. In the frequency bands below 1 and above 2 kHz, power losses increase.

Conclusions. The frequency of pulse-width modulation increases and, accordingly, the frequency of switching power switches in an autonomous voltage inverter, the total static and dynamic power losses increase linearly. The value of the first harmonic of the output voltage and the output current of the inverter does not change, but the content of the higher harmonics of the output current of the inverter decreases. As a result, additional power losses in the induction motor from higher harmonics are reduced. A method is presented for optimizing the frequency of pulse-width modulation in the control system of frequency converters, the load of which is induction motors, by the criterion of minimum total power losses in the power transistors of the inverter and losses in the resistance of the motor windings.

Determination of the dependence of power losses in the power transistors of the inverter is performed using specialized programs MelcoSim. In the specialized program Matlab/Simulink the “autonomous voltage inverter – asynchronous motor” model was developed, in which the dependence of the harmonic distortion coefficient of the output current of the inverter (phase current AD) on the modulation frequency in PWM is obtained. Analytical expressions are presented that determine the dependences of additional power losses in the active resistance of the motor windings on the value of the coefficient of harmonic distortion of the phase current of the inverter.

The presented method for optimizing the modulation frequency is universal and can be used for different power classes in systems of frequency-controlled asynchronous electric drive.

To increase the accuracy of modulation frequency optimization in inverters with low-power induction motors, it is necessary to additionally take into account the dependence of motor steel losses (eddy current losses and hysteresis) on the harmonic output voltage spectrum, which in turn depends on PWM modulation frequency.



P_Sum: 55.56 [W]
PS22A79
Data @ Tj = 125 °C

Common Conditions
Vcc 460 °C
Io 9.8 Arms
PF 0.8
M 1
Fc 4.0 kHz
Fo 60 Hz
Ts 60 °C
Tj max 150 °C

P_Tr1 7.23 W/IGBT
SW 3.14
DC 4.08
SW(on) 1.74
SW(off) 1.40
Ts 60 °C
Tc 61.85 °C
ΔTj-c(Tr1)_Ave 5.57 K
Tj(Tr1)_Ave 67.42 °C
ΔTj-c(Tr1)_Max 6.46 K

P_Di1 2.03 W/IGBT
SW 1.05
DC 0.97
ΔTj-c(Di1)_Ave 2.53 K
Tj(Di1)_Ave 64.39 °C
ΔTj-c(Di1)_Max 3.03 K
Tj(Tr1)_Max 64.89 °C

Fig. 7. Power loss calculation interface in the software environment MelcoSim 5.1

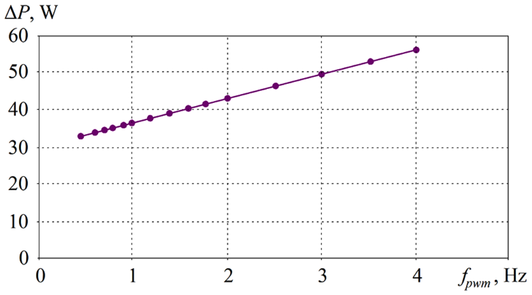


Fig. 8. Dependence of power losses in AVI power switches on the frequency of AVI modulation

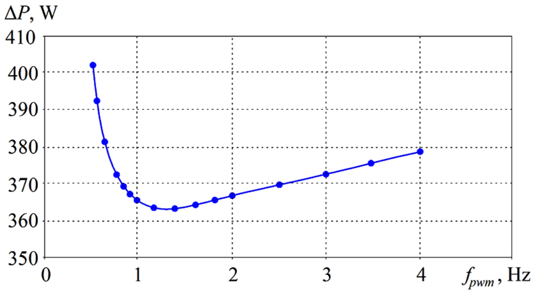


Fig. 9. Dependence of total power losses in transistor switches and losses in motor windings on AVI modulation frequency

The article presents well-known analytical expressions describing the losses in the steel of induction motors from the higher harmonics of the inverter, but in practice their application is quite difficult due to the uncertainty of the calculated coefficients for different motor designs. It is possible to more precisely determine the dependence of steel losses on the higher harmonics of the inverter with the help of the Ansys-Maxwell software environment, which will be the subject of the next stage of research and, consequently, subsequent scientific publications. In addition, in the future it is necessary to determine the optimal switching frequency of power transistors at different values of load torque and motor speed.

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Методика оптимізації частоти комутації в перетворювачах частоти

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Мета. Представити методику визначення оптимальної частоти комутації в перетворювачах частоти та автономних інверторах напруги, навантаженням яких є асинхронний електродвигун. Методика базується на визначенні залежностей статичних і динамічних втрат потужності в силових ключах інвертора від частоти комутації та залежності втрат потужності в обмотках асинхронного двигуна від вищих гармонік струмів, що також залежать від частоти комутації.

Методика. Поліноміальна апроксимація енергетичних характеристик силових транзисторів. Загальні положення теорії електричних кіл. Визначення додаткових втрат потужності в обмотках асинхронного двигуна від вищих гармонік виконано на базі аналітичного розрахунку та імітаційного моделювання у програмному середовищі Matlab/Simulink і спеціалізованої програми від виробника силових ключів Mitsubishi – MelcoSim 5.1.

Результати. Представлена методика оптимізації частоти широтно-імпульсної модуляції в перетворювачах частоти, навантаженням яких є асинхронний двигун, за критерієм мінімуму сумарних втрат потужності в силових транзисторах інвертора та опорі обмоток двигуна. Запропонована методика розрахунку дозволяє у програмному середовищі MelcoSim із досить високою точністю визначати залежність статичних і динамічних втрат в силових IGBT-транзисторах. Для розрахунку втрат у двигуні показано, що частота комутації силових ключів впливає на коефіцієнт гармонічних спотворень і середньоквадратичне значення фазного струму асинхронного двигуна. За умови, що корисну дію в асинхронному двигуні виконує лише перша гармоніка струму, приведена залежність додаткових втрат потужності від частоти комутації.

Наукова новизна. Представлена методика оптимізації частоти широтно-імпульсної модуляції за критерієм мінімуму додаткових втрат потужності в опорі обмоток двигуна від вищих гармонік струму та статичних і динамічних втрат у силових транзисторах інвертора. Представлена аналітична залежність додаткових втрат потужності в активному опорі обмоток асинхронних двигунів у функції коефіцієнта гармонічних спотворень фазного струму автономного інвертора напруги.

Практична значимість. Представлена методика дозволяє визначити оптимальну частоту модуляції в перетворювачах частоти з асинхронними двигунами й забезпечити мінімальні сумарні втрати потужності й максимальне значення ККД у системі «автономний інвертор напруги – асинхронний двигун».

Ключові слова: *частота комутації, вищі гармоніки струму, втрати потужності, коефіцієнт гармонічних спотворень, імітаційне моделювання, перетворювач частоти, асинхронний двигун*

Методика оптимизации частоты коммутации в преобразователях частоты

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Цель. Представить методику определения оптимальной частоты коммутации в преобразователях частоты и автономных инверторах напряжения, нагрузкой которых является асинхронный электродвигатель. Методика базируется на определении зависимостей статических и динамических потерь мощности в силовых ключах инвертора от частоты коммутации и зависимости потерь мощности в обмотках асинхронного двигателя от высших гармоник токов, которые также зависят от частоты коммутации.

Методика. Полиномиальная аппроксимация энергетических характеристик силовых транзисторов. Общие положения теории электрических цепей. Определение дополнительных потерь мощности в обмотках асинхронного двигателя от высших гармоник выполнено на базе аналитического расчёта и имитационного моделирования в программной среде Matlab/Simulink и специализированной программы от производителя силовых ключей Mitsubishi – MelcoSim 5.1.

Результаты. Представлена методика оптимизации частоты широтно-импульсной модуляции в преобразователях частоты, нагрузкой которых является асинхронный двигатель, по критерию минимума суммарных потерь мощности в силовых транзисторах инвертора и сопротивлении обмоток двигателя. Предложенная методика расчёта позволяет в программной среде MelcoSim с достаточно высокой точностью определять зависимость статических и динамических потерь в силовых IGBT-транзисторах. Для расчёта потерь в двигателе показано, что частота коммутации силовых ключей влияет на коэффициент гармонических искажений и среднее значение фазного тока асинхронного двигателя. При условии, что полезное действие в асинхронном двигателе выполняет только первая гармоника тока, приведена зависимость дополнительных потерь мощности от частоты коммутации.

Научная новизна. Представлена методика оптимизации частоты широтно-импульсной модуляции по критерию минимума дополнительных потерь мощности в сопротивлении обмоток двигателя от высших гармоник тока и статических и динамических потерь в силовых транзисторах инвертора. Представлена аналитическая зависимость дополнительных потерь мощности в активном сопротивлении обмоток асинхронных двигателей в функции коэффициента гармонических искажений фазного тока автономного инвертора напряжения.

Практическая значимость. Представленная методика позволяет определить оптимальную частоту модуляции в преобразователях частоты с асинхронными двигателями и обеспечить минимальные суммарные потери мощности и максимальное значение КПД в системе «автономный инвертор напряжения – асинхронный двигатель».

Ключевые слова: *частота коммутации, высшие гармоники тока, потери мощности, коэффициент гармонических искажений, имитационное моделирование, преобразователь частоты, асинхронный двигатель*

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