UDC 621.316.71

FEATURES OF MINIMIZING TOTAL ELECTRICAL LOSSES IN HIGH-VOLTAGE ELECTROMECHANICAL SYSTEMS FOR STATIONARY INDUSTRIAL FAN INSTALLATIONS

SYNETSKYI A.V. postgraduate student of the Department of Electrical Machines, National University “Zaporizhzhia Polytechnic”, Zaporizhzhia, Ukraine, e-mail: xibi-tur@ukr.net, ORCID: https://orcid.org/0009-0005-1859-4171;

KOTSUR I.M. Ph.D in Engineering, Associate Professor, Associate Professor of the Department of Electrical Machines, National University “Zaporizhzhia Polytechnic”, Zaporizhzhia, Ukraine, e-mail: igor.m.kotsur@gmail.com, ORCID: https://orcid.org/0000-0001-6394-7849;

Purpose. *Conduct a study of commutation processes and develop a methodology for determining the switching frequency of semiconductor elements in the converter for high-voltage electromechanical systems to minimize electrical losses during their operation with fan loads.*

Methodology. *Methods of multi-criteria and single-criteria optimization for finding the optimal values of electrical losses in an electromechanical system, methods for solving first-order differential equation systems, and analytical methods.*

Findings. *To improve the energy efficiency of a high-voltage electromechanical system for stationary industrial fan installations without modifying their structural design, the level of total losses has been assessed. A target function has been constructed to represent the dependence of total losses in the electric drive on the switching frequency of power switches and the harmonic distortion coefficients of the stator and rotor currents in a high-voltage wound-rotor asynchronous motor. Through approximation, a generating dependence of the switching frequency of the converter’s power switches on the harmonic distortion coefficient of the stator and rotor currents of the asynchronous motor has been established. The target function, initially dependent on three variables, has been transformed into a function of a single variable. Simulation modeling of electromagnetic and energy processes in the high-voltage electromechanical system has been conducted to evaluate total loss levels. A comparative analysis has been performed, confirming the adequacy of the obtained analytical expression for determining the optimal switching frequency of the converter’s power elements under the condition of minimizing losses in the high-voltage electromechanical system, with results validated through simulation.*

Originality. *A study of commutation processes in the power elements of the converter, which is part of the high-voltage electromechanical system, has been conducted. More precise analytical dependencies have been obtained, allowing for the determination of the main and commutation losses in the power elements of the converter for the high-voltage electromechanical system.*

Practical value. *A methodology for determining the optimal switching frequency of the semiconductor elements in the converter, which is part of the high-voltage electromechanical system, has been proposed. The calculation error of the optimal switching frequency of the semiconductor elements, obtained analytically, does not exceed 3.5% compared to the results obtained through simulation. The proposed methodology can be applied to minimizing losses in high-voltage electromechanical drive systems for both AC and DC applications used in various industrial mechanisms.*

Keywords: switching frequency, optimization, losses, energy efficiency, converter, high-voltage electromechanical system.

I. INTRODUTION

Ventilation of mines using main ventilation fans (MVF) is one of the most energy-intensive technological processes. Almost all mines use non-regulated electric drive systems for MVF [1]. To improve the efficiency of many MVF systems, it is possible to transition to a lower rotor speed by implementing energy-efficient electric drive control systems, such as frequency converters (FC), inductive-capacitive converters (ICC), and converters based on the asynchronous-thyristor cascade (ATC) scheme. These systems allow independent control of the speed and torque of both asynchronous and synchronous motors [2]-[4].

However, FCs and ICCs have high installed power, comparable to the power of the MVF motor. In addition, their application is limited in high-voltage MVF electric drives due to the voltage class of the converter’s semiconductor elements. Therefore, speed regulation remains feasible on the rotor side of the motor, where the rotor voltage is significantly lower than the stator voltage. For this purpose, an ATC can be used, and such an electric drive system must ensure a high level of energy

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DOI https://doi.org/10.15588/1607-6761-2025-1-2

efficiency.

It is known that increasing the switching frequency of power switches reduces the content of higher harmonics in the stator and rotor currents of an induction motor (IM), thereby decreasing AM losses. However, a higher switching frequency also increases both fundamental and commutation losses in the converter's power switches. Consequently, it is necessary to determine the optimal switching frequency for power switches in this type of electric drive system [5].

II. ANALYSIS OF LAST RESEARCHES

The analysis of studies [6]-[8] has shown that the development of contactless control systems for induction motors has led to reduced capital costs for equipment and increased energy efficiency in industrial mechanisms. The implementation of existing control systems enables smooth regulation of drive motors, maintaining constant torque in the sub-synchronous speed range while keeping the efficiency and power factor of the electric drive at a high level [8].

However, for such electric drive systems, the issue of determining the optimal switching frequency of power switches that ensures minimal losses in the motor-converter system has not been investigated [9], [10]. A comparative analysis has shown that the most energy-efficient control system, particularly for high-voltage electric drives, is the frequency-current asynchronous-thyristor cascade [11], [12].

According to [8], the frequency-current asynchronous-thyristor cascade combines the advantages of classical pulse regulation systems and asynchronous-thyristor cascades. A distinctive feature of this system is the presence of a pulse regulator in the rectified rotor current circuit, represented as a step-up voltage pulse converter (SUPC). The presence of a capacitor (C) ensures a specified level of overvoltage in the rotor winding, caused by the frequent switching of the key (K). The diode (VD) prevents the reverse current flow from the capacitor when the switch is closed.

When the switch is opened, the stored energy in the rotor winding, along with part of the slip energy (depending on the ratio of rotor EMF to inverter EMF), is recovered into the network at a constant inverter commutation angle in the low-power inverter. This minimizes the consumption of reactive power from the network and in-creases the power factor of the drive across the entire rotor speed range [5]-[8].

Thus, to improve the energy efficiency of the electric drive system, using the example of the frequency-current asynchronous-thyristor cascade, without altering the structural features of the circuit, it is necessary to evaluate the total loss level in the motor-converter system. A target function needs to be constructed to represent the dependence of total losses in the electric drive on the switching frequency of the power switches and the harmonic distortion coefficients of the stator and rotor cur-rents in the asynchronous motor [11]- [12]. Using approximation, the generating dependence of the switching frequency of the converter's power switches on the harmonic distortion coefficient of the stator and rotor currents in the drive motor should be established. The target function, initially dependent on three variables, must be reduced to a function of a single variable. Simulation modeling of the electromagnetic and energy processes in the considered electric drive system should be conducted to assess the total loss level. A comparative analysis should be performed to determine the adequacy of the obtained analytical expression for determining the optimal switching frequency of the converter's power elements, ensuring minimal losses in the electric drive, with the results obtained through simulation.

III. FORMULATION OF THE WORK PURPOSE

Conduct a study of commutation processes and develop a methodology for determining the switching frequency of semiconductor elements in the converter for high-voltage electromechanical systems to minimize electrical losses during their operation with fan loads.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

To determine the optimal switching frequency of the power switches in the converter based on the frequency-current asynchronous-thyristor cascade scheme, it is advisable to evaluate the amount of constant and variable losses in the induction motor (IM). As the switching frequency of the keys increases, these losses decrease relative to the growing fundamental and commutation losses in the converter's power switches.

The total losses in the IM, according to [13], can be determined using the following expression:

$$\Delta P = \frac{P_{rated} \cdot (1-\eta)}{\eta}, \tag{1}$$

where: P_{rated} is the rated power of the induction motor; η is the efficiency coefficient of the induction motor.

The constant losses, considering the presence of higher harmonics in the stator and rotor currents, can be determined with sufficient accuracy using the following relation [14]:

$$P_{const} = \lambda_1 \cdot \Delta P - M_{rated} \cdot \omega \cdot s_{rated} \cdot \left(1 + \frac{r_1}{r'_2}\right), \tag{2}$$

$$\lambda_1 = \frac{I_1}{\sqrt{\sum_{k=2}^{n} \cdot I_k^2}}, \tag{3}$$

where λ_1 is a coefficient that accounts for harmonic distortions in the current; s_{rated} is the nominal slip of the rotor of the asynchronous motor; M_{rated} is the nominal torque of the motor; I_k is the amplitude of the n-th harmonic of the current.

The variable losses in the stator and rotor windings of an induction motor can be determined using the following expression [15]:

$$P_{el} = 3 \cdot I_s^2 \cdot {\lambda_{Is}}^2 \cdot r_1 + 3 \cdot I_r^2 \cdot {\lambda_{Ir}}^2 \cdot r_2 \qquad (4)$$

The additional and ventilation losses in high-voltage asynchronous motors typically do not exceed 2% [15] and will increase or decrease proportionally with the change in the switching frequency of the key. Therefore, these losses can be neglected.

Thus, the target function for total losses in the induction motor as a function of the current distortion coefficient can be written as:

$$\Delta P_{IM}(\lambda_{Is}, \lambda_{Ir}) = 3 \cdot I_s^2 \cdot {\lambda_{Is}}^2 \cdot r_1 + 3 \cdot I_r^2 \cdot {\lambda_{Ir}}^2 \cdot r_2 + \ldots$$

$$\ldots + \lambda_{Is} \cdot \Delta P - M_{rated} \cdot \omega \cdot s_{rated} \cdot \left(1 + \frac{r_1}{r_2} \right) \qquad (5)$$

Let's consider the losses occurring in the DC circuit of the converter during periodic commutations of the valves, specifically in the power switch, the blocking diode, as well as in the rectifying-inverting groups.

The total losses in the power transistor have several components:

$$P_{tr} = P_{main} + P_{on} + P_{off} + P_{lc} + P_{cc} \qquad (6)$$

where P_{main} are the main losses created by the collector current in the on state of the transistor; P_{on} are losses when the transistor is turned on; P_{off} are losses when the transistor is turned off; P_{lc} are losses from leakage currents; P_{cc} are losses in the control circuit.

In most cases, losses from leakage currents and in the control circuit can be neglected.

Calculation of losses in the on state of IGBT type transistor can be done in the same way as it is done for thyristor (volt-ampere characteristics of devices in the on state are similar) [15]:

$$P_{main} = U_o \cdot I_a \left(1 + k_f^2 \frac{I_a R_\partial}{U_o} \right), \qquad (7)$$

where U_o, R_∂ are threshold voltage and dynamic resistance, respectively; $I_a = I_{c\_av}$ is the average value of the collector current of the power key; k_f is the coefficient of the collector current shape.

The parameters of the volt-ampere characteristic of the IGBT in the on state can be determined from the corresponding characteristics given in the IGBT data sheet [13].

The average value of collector current I_{c_av} is determined by the ratio:

$$I_{c\_av} = I_{in} \cdot \gamma, \qquad (8)$$

where I_{in} is the average value of the input current of the converters; $\gamma = \frac{t_i}{T}$ is fill factor, equal to the ratio of the duration of the on state of the transistor to the repetition period.

Since the input current of the converter can have significant ripple, the curves of the collector current of the transistor and the anode current of the diode can have a rather complex shape. To calculate the effective value of the collector current, it is possible to make an assumption about the linear law of change of this current on the interval of the on state of the power switch. In this case, the rate of increase of the input current is equal to:

$$\frac{di}{dt} = \frac{U_{in}}{L_1}, \qquad (9)$$

where L_1 is the inductance of the windings of the induction motor.

For calculating the losses in the transistor during turn-on, as shown in [15], it is convenient to assume a linear law for the collector voltage drop during the turn-on interval:

$$u_k = U_{k\,max}\left(1 - \frac{t}{t_{cn}}\right) \approx U_{out}\left(1 - \frac{t}{t_r}\right), \qquad (10)$$

where u_k is instantaneous value of collector voltage; $U_{k\,max} = U_{out}$ is collector voltage before switching on; $t_{cn} = t_r$ is duration of collector voltage decay, approximately equal to the duration of collector current rise when the transistor is turned on.

Equation (8) is valid assuming for $0 \le t \le t_{cn}$ that the beginning of time counting coincides with the beginning of collector voltage decay.

As the collector voltage decreases and the collector current increases, the voltage drop in the rotor winding of the induction motor increases, and accordingly, the current through the diode decreases. Since the stator and rotor windings have inductance L_1, the collector current during transistor turn-on increases according to a quadratic law:

$$i_k = \frac{U_{k\,max}}{2 \cdot L_1} \cdot \frac{t^2}{t_r} = \frac{U_{out}}{2 \cdot L_1} \cdot t_{cn} \cdot \frac{t^2}{t_r^2}. \qquad (11)$$

Let us introduce the value of I_{kp}, defined by the ratio:

$$I_{kp} = \frac{U_{out}}{2 \cdot L_1} \cdot t_r . \qquad (12)$$

The value of collector current, by (11) is the value of collector current at the moment of voltage drop between collector and emitter to zero. This current value is used as a design value in the equation for calculating turn-on losses [15]:

$$P_{on} = \frac{1}{T} \int_0^{t_{cn}} u_k i_k dt = \frac{1}{12} U_{out} I_{kp} \frac{t_r}{T} .$$

If we assume that $I_{kp} = I_{in}$, then the equation with regard to (12) can be rewritten in the form:

$$P_{on} = \frac{1}{12} U_{out} I_{in} \frac{t_r}{T} = \frac{1}{12} U_{out} \cdot I_{in} \cdot t_r \cdot f_k , \qquad (13)$$

Similar considerations can be used to calculate the losses in the transistor at turn-off. In this case, it is convenient to assume a linear law of collector current decay:

$$i_k = I_{k\,max} (1 - \frac{t}{t_f}) \approx I_{in} (1 - \frac{t}{t_f}) , \qquad (14)$$

where t_f is the duration of collector current drop at turn-off.

Similar can be made about the linear law of collector voltage rise by a quadratic law on the off interval:

$$u_k = u_{cs} = \frac{I_{in}}{2 \cdot C_s} \cdot \frac{t^2}{t_f} = \frac{I_{in} \cdot t_f}{2 \cdot C_s} \cdot \frac{t^2}{t_f^2} , \qquad (15)$$

$$C_s = \frac{I_{in} \cdot t_f}{2 \cdot U_{out}} .$$

where C_s is the capacitance of the thyristor protection circuit capacitor.

Accordingly, the losses when the transistor is turned off are determined by the ratio:

$$P_{off} = \frac{1}{T} \int_0^{t_f} u_k i_k dt = \frac{1}{12} \cdot U_{out} I_{in} \frac{t_f}{T} =$$

$$= \cdot U_{out} I_{in} \frac{t_f}{T} = \frac{1}{12} U_{out} I_{in} \cdot t_f \cdot f_k . \qquad (16)$$

Losses in the diode from reverse current VD, according to [8], have also several components, the most significant of which are losses from direct current (main) and losses at diode switching off. The forward current losses can be calculated using expression (7).

According to [13], [15] the diode turn-off loss powers can be determined from the following expression:

$$P_{off} = \frac{I_{bm} \cdot U_{bm}}{T_k} \cdot \frac{\tau}{2} = \frac{1}{2} I_{bm} U_{bm} \tau \ f_k , \qquad (17)$$

where I_{bm}, U_{bm} is amplitude of reverse current and voltage, respectively; T_k is period of switching frequency; f_k is switching frequency; τ is duration of the diode reverse current decay, the value of which is determined from [15].

Thus, the total losses in the limiting diode:

$$P_{vd} = U_o \cdot I_d \left(1 + k_f^2 \frac{I_d R_\partial}{U_o} \right) + \frac{I_{bm} \cdot U_{bm}}{T_k} \cdot \left(\frac{\tau_{ib}^2}{\tau_{ib} + \tau_{ub}} \right) + \ldots$$

$$\ldots + \frac{1}{2} I_{bm} U_{bm} \tau_{ib} f_k \qquad (18)$$

Losses in the rectifier-inverter group can be determined quite accurately as in the power transistor (diode) according to expression (6). Also, as in the case of the transistor, losses from leakage currents and in the control circuit can be neglected. In this case we can also neglect the losses during switching on and off of the thyristor (diode). Thus, the total losses in the thyristor of the rectifier will correspond to the main losses:

$$P_t = P_{main} = U_0 I_{av} \left(1 + k_f^2 \frac{I_{av} R_t}{U_0} \right), \qquad (19)$$

where U_0, R_t are threshold voltage and dynamic resistance of thyristor (diode), respectively; I_{av} is the average value of anode current of thyristor (diode); k_f is thyristor (diode) current waveform coefficient.

Average value of the thyristor anode current for a three-phase bridge circuit:

$$I_{av} = \frac{I_d}{3} , \qquad (20)$$

The total rectifier losses will be determined by the number of valve arms in the circuit:

$$P_{rect} = n \cdot P_{main} . \qquad (21)$$

For the three-phase bridge circuit $n = 6$.

According to equations (6), (18) and (21), we can finally write the function on the switching frequency of all losses in the convertors in the following form:

$$P_{\sum conv} (f_k) = U_o \cdot I_a \left(1 + k_f^2 \frac{I_a R_t}{U_o} \right) + ..$$

$$\ldots + \frac{1}{12} U_{out} \cdot I_{in} \cdot t_r \cdot f_k + \frac{1}{12} U_{out} I_{in} \cdot t_f \cdot f_k + \ldots$$

$$\ldots + U_o \cdot I_d \left(1 + k_f^2 \frac{I_d R_t}{U_o}\right) + \frac{I_{bm} \cdot U_{bm}}{T_k} \cdot \left(\frac{\tau_{ib}}{2}\right) + \ldots$$

$$\ldots + \frac{1}{2} I_{bm} U_{bm} \tau_{ib} f_k + 6 \cdot U_0 I_{av} \left(1 + k_f^2 \frac{I_{av} R_t}{U_0}\right) + \ldots$$

$$\ldots + 6 \cdot U_0 I_{inv} \left(1 + k_f^2 \frac{I_{inv} R_t}{U_0}\right) \qquad (22)$$

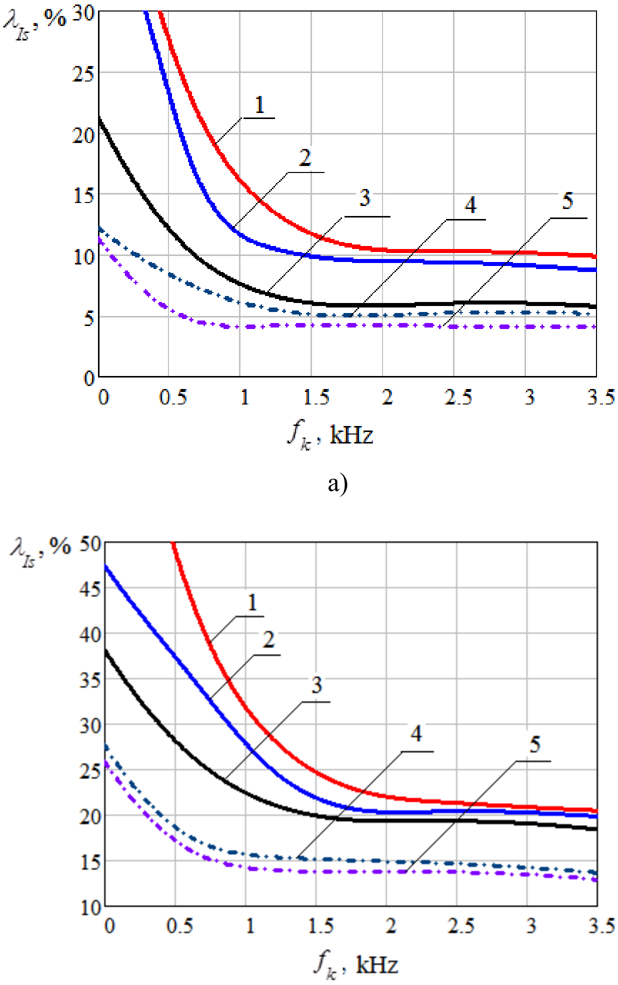
Using expressions (5) and (22), the overall loss function of the electromechanical system can be expressed:

$$P_{\sum sys}(f_k, \lambda_{Is}, \lambda_{Ir}) = P_{\sum conv}(f_k) + P_{motor}(\lambda_{Is}, \lambda_{Ir}) \qquad (23)$$

It follows from (23) that to determine the optimal switching frequency of the power switch it is necessary to set the optimization problem for three variables: the distortion coefficients of the stator currents λ_{Is}, rotor currents λ_{Ir} and from the switching frequency of the switch f_k. The solution of the problem is rather complex and cumbersome and requires the determination of the coefficients λ_{Is}, and λ_{Ir}, depending on the switching frequency of the switch f_k. Therefore, it is necessary to reduce the target function to the form from one variable, i.e. from f_k.

Fig. 1 shows the dependences of harmonic distortion coefficients for the stator and rotor currents of AK-4 type induction motor of 1000 kW power on the switching frequency of the converter switch elements, obtained by simulation modelling when the electromechanical system is operated with a fan load in the range of operating slip $s = 0{,}5 \div 0{,}1$.

During modelling and calculation of all losses in the converter we used power elements for bridge rectifier diodes of W1074Y#320 series, reverse current diode of M0768S/RX250 series, IGBT transistor of T0850VB25E series and inverter group thyristors of N0606YS250 series of Westcode manufacturer, the passport data of which are given in [16]. It is also possible to determine the harmonic distortion coefficients in practice in the process of converter adjustment, using modern measuring instruments that can perform spectral analysis of currents or voltages, and independently calculate the harmonic distortion coefficient.



a)

b)

Figure 1. Dependences of stator (a) and rotor (b) current harmonic distortion coefficients of AK-4 type induction motor with power of 1000 kW on the frequency of commutation of the converter switching elements: 1 - s=0,5; 2 - s=0,4; 3 - s=0,3; 4 - s=0,2; 5 - s=0,1.

The equation describing the dependence of the harmonic distortion coefficient on the switching frequency for the stator current of the induction motor is as follows:

$$\lambda_{Is}(f_k) = 0{,}529 - 0{,}701 \cdot f_k + 0{,}445 \cdot f_k^{\,2} - \ldots$$

$$\ldots - 0{,}126 \cdot f_k^{\,3} + 0{,}013 \cdot f_k^{\,4} \qquad (24)$$

and for rotor current of the induction motor:

$$\lambda_{Ir}(f_k) = 0{,}857 - 0{,}999 \cdot f_k + 0{,}614 \cdot f_k^{\,2} - \ldots$$

$$\ldots - 0{,}172 \cdot f_k^{\,3} + 0{,}018 \cdot f_k^{\,4} \qquad (25)$$

Dependence (23), taking into account (24) and (25), can be reduced to the form from one variable. Consequently, to determine the optimal switching frequency of the switching elements of converter at which the minimization of losses in the electromechanical system is performed, it is necessary to reduce the target function to the form:

$$\frac{d}{df_k}P_{\sum}\left(f_k\right)=0\,.$$

The final expression for determining the optimal switching frequency is as follows:

$$\begin{gathered}\left(1{,}35\cdot 10^{-3}\cdot I_s^2\cdot r_1+2{,}6\cdot 10^{-3}\cdot I_r^2\cdot r_2\right)\cdot f_k^7-\ldots\\ \ldots-\left(22{,}\cdot 94^{-3}\cdot I_s^2\cdot r_1+43{,}34\cdot 10^{-3}\cdot I_r^2\cdot r_2\right)\cdot f_k^6+\ldots\\ \ldots+\left(0{,}165\cdot I_s^2\cdot r_1+0{,}31\cdot I_r^2\cdot r_2\right)\cdot f_k^5-\ldots\\ \ldots-\left(0{,}652\cdot I_s^2\cdot r_1+1{,}236\cdot I_r^2\cdot r_2\right)\cdot f_k^4+\ldots\\ \ldots+\left(1{,}554\cdot I_s^2\cdot r_1+3{,}006\cdot I_r^2\cdot r_2\right)\cdot f_k^3-\ldots\\ \ldots-\left(2{,}271\cdot I_s^2\cdot r_1+4{,}565\cdot I_r^2\cdot r_2\right)\cdot f_k^2+\ldots\\ \ldots+\left(1{,}924\cdot I_s^2\cdot r_1+4{,}101\cdot I_r^2\cdot r_2\right)\cdot f_k-\ldots\\ \ldots-\left(0{,}742\cdot I_s^2\cdot r_1+1{,}712\cdot I_r^2\cdot r_2\right)+\Delta P+\ldots\\ \ldots+\frac{1}{12}U_{out}\cdot I_{in}\cdot t_r+\frac{1}{12}U_{out}I_{in}\cdot t_f+\ldots\\ \ldots+\frac{1}{2}I_{bm}U_{bm}\tau_{ib}=0\end{gathered}\qquad(26)$$

Expression (26) is not difficult to solve with the help of mathematical packages.

For AK-4 type of induction motor with rated power of 630 kW, working with fan character of load on working slip s=0,5, has power on shaft $P_{s=0.5}$ =204 kW, stator current $I_{s\_s=0.5}$ =118 A; stator winding resistance r_1 =0,295 Ohm; rotor current I_r =192 A; rotor winding resistance r_2 =0,028 Ohm, according to (26) the optimum value of switching frequency of switching elements of convertor under condition of minimisation of losses in electromechanical system f_k^{opt} =0,626 kHz is obtained.

Thus, the obtained analytical expression (26) can be used in determining the effective switching frequency of power switches of the convertors, which provides the minimum level of losses in the electromechanical system. To calculate the effective switching frequency for other values of operating slip and other power of induction motor, it is necessary to give approximating expressions (24) and (25) for eigenvalues of harmonic distortion coefficients of induction motor stator and rotor currents.

To confirm the adequacy of the above method of determining the effective switching frequency of the converter switchers, according to [8], a simulation model was developed, which includes a block of electromagnetic submodel, taking into account the nonlinearities of the induction motor [11], and the block of calculating the energy performance of the drive.

Fig. 2 shows the calculated dependences of total losses in the electromechanical system on the frequency of commutation of the converter switchers, respectively, for AK-4 type induction motors with rated power P_{rated} =630 kW, P_{rated} =800 kW, P_{rated} =1000 kW at operating slip s=0.5, obtained by simulation modeling.

The analysis of dependencies shows that minimization of total losses in the electromechanical system is performed at switching frequencies for induction motor: P_{rated} =630 kW - f_k = 0.643 kHz; for P_{rated} =800 kW - f_k = 0.698 kHz; for P_{rated} =1000 kW - f_k = 0.704 kHz. It should be noted, that for induction motor with different rated powers in the electromechanical system, the optimal value of the switching frequency practically does not change.

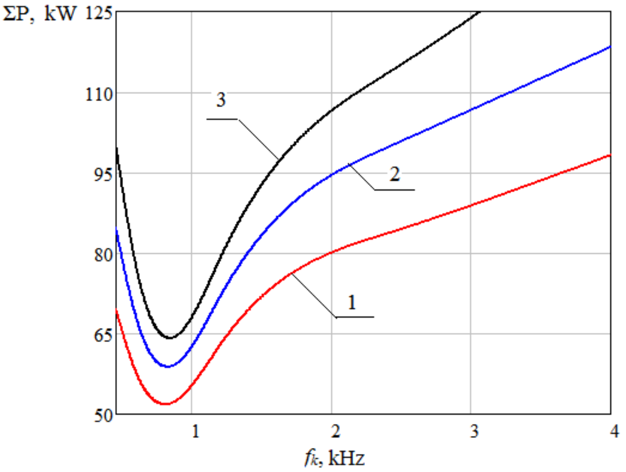


Figure 2. Calculated dependences of the total losses in the electromechanical system on the switching frequency for the operating slip of induction motor s=0.5: 1 - at P_{rated} =630 kW; 2 - at P_{rated} =800 kW; 3 - at P_{rated} =1000 kW.

As a result of the conducted research, the method of determining the optimal switching frequency of the converter power switchers is proposed, which consists in the formation of the target function of the dependence of the total losses in the electromechanical system on the switching frequency of the converter power switchers. For induction motor with P_{rated} =630 kW the optimal switching frequency calculated by means of analytical expression is f_k^{opt} =0,626 kHz, by means of simulation modeling - f_k = 0,621 kHz. Thus, the calculation error does not exceed 3.5%.

The obtained analytical expression (26) has an acceptable error in determining the effective switching frequency of the power switchers, which provides the minimum level of losses in the electromechanical system. However, the proposed method requires the determination of harmonic distortion coefficients for the stator and rotor currents of the induction motor, the values of which depend both on its operating slip and on the operating mode of the electromechanical system. Therefore, for each case it is necessary to give approximating expressions (24) and (25) for the eigenvalues of harmonic distortion coefficients of the induction motor stator and rotor currents. The proposed methodology for determining the optimal switching frequency of the power switch can be applied in engineering design, as well as in the adjustment work of converters depending on the class and mode of operation of the electromechanical system.

V. CONCLUSION

Investigations of switching processes in power elements of the converter are carried out. More accurate expressions allowing to estimate the main and switching losses in power elements of the converter have been obtained.

The method of determination of the optimum frequency of switching of the power switchers on the example of the converter is offered. The calculation error of the optimum switching frequency of the power switchers of the converter, which is obtained by the analytical method in comparison with the results obtained by means of modeling, does not exceed 3.5%.

The proposed methodology for determining the optimal switching frequency of the converter power switchers can be used in the problems of minimizing losses in AC and DC electromechanical systems, which are used in different areas of intermediate mechanisms.

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Received 18.02.2025;
Accepted 05.03.2025;
Published 30.04.2025;

ОСОБЛИВОСТІ МІНІМІЗАЦІЯ СУМАРНИХ ЕЛЕКТРИЧНИХ ВТРАТ ВИСОКОВОЛЬТНИХ ЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМ ДЛЯ СТАЦІОНАРНИХ УСТАНОВОК ПРОМИСЛОВИХ ВЕНТИЛЯТОРІВ

СИНЕЦЬКИЙ А.В. *аспірант кафедри електричних машин Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, e-mail: xibi-tur@ukr.net, ORCID: https://orcid.org/0009-0005-1859-4171;*

КОЦУР І.М. *канд. техн. наук, доцент, доцент кафедри електричних машин Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, e-mail: igor.m.kotsur@gmail.com, ORCID: https://orcid.org/0000-0001-6394-7849.*

Мета роботи. *Провести дослідження комутаційних процесів та розробити методику для визначення частоти комутації полупровідникових елементів перетворювача для високовольтних електромеханічних систем з метою мінімізації електричних втрат при їх роботі з вентиляторним навантаженням.*

Методи дослідження. *Методи багатокритеріальної та однокритеріальної оптимізації для пошуку оптимальних значень електричних втрат електромеханічної системи, методи рішення системи диференційних рівнянь першого порядку, аналітичні методи.*

Отримані результати. *Для підвищення рівня енергоефективності високовольтної електромеханічної системи для стаціонарних установок промислових вентиляторів без зміни їх конструктивних особливостей схеми оцінено рівень сумарних втрат. Побудовано цільову функцію залежності сумарних втрат в електроприводі від частоти комутації силових ключів та коефіцієнтів гармонічних спотворень струмів статора та ротора високовольтного асинхронного двигуна з фазним ротором. За допомогою апроксимації встановлено генеруючу залежність частоти ко-мутації силових ключів перетворювача від величини коефіцієнта спотворення гармонік струмів статора і приводного ротора асинхронного двигуна. Цільову функцію від трьох змінних приведено до виду функції від однієї змінної. Проведено імітаційне моделювання електромагнітних і енергетичних процесів в високовольтній електромеханічній системі з метою оцінки рівня сумарних втрат. Проведено порівняльний аналіз та визначена адекватність отриманого аналітичного виразу щодо визначення оптимальної частоти комутації силових елементів перетворювача при виконанні умови мінімізації втрат в високовольтній електромеханічній системі з результатами моделювання.*

Наукова новизна. *Проведено дослідження комутаційних процесів у силових елементах перетворювача що входить до структури високовольтної електромеханічної системи. Отримано більш точні аналітичні залежності, що дозволяють визначити основні та комутаційні втрати в силових елементах перетворювача для високовольтної електромеханічної системи.*

Практична цінність. *Запропоновано методику визначення оптимальної частоти комутації напівпровідникових елементів перетворювача що входить до структури високовольтної електромеханічної системи. Похибка розрахунку оптимальної частоти комутації напівпровідникових елементів перетворювача, що отримана аналітичним способом порівняно з результатами, отриманими за допомогою моделювання, не перевищує 3,5%. Запропонована мето-дика може бути використана в задачах мінімізації втрат в високовольтних електромеханічних системах електроприводу змінного та постійного струму, що застосовуються в різних областях промислових механізмів.*

Ключові слова: частота комутації, оптимізація, втрати, енергоефективність, перетворювач, високовольтна електромеханічна система