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CONVERTER FOR FREQUENCY-CURRENT SLIP-POWER RECOVERY SCHEME

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ПЕРЕТВОРЮВАЧ ЗА СХЕМОЮ ЧАСТОТНО-СТРУМОВОГО АСИНХРОННО-ВЕНТИЛЬНОГО КАСКАДУ

Purpose. Development of analytical expressions which allow determining the relation between the parameters and voltage amplification factor of the converter for impulse frequency-current slip-power recovery scheme.

Methodology. Solution of a set of second order linear differential equations based on the analysis of transients under switching of power gates in the converter for impulse frequency-current slip-power recovery scheme.

Findings. A system of electric drive for impulse frequency-current slip-power recovery scheme is proposed. It combines positive features of classic system for impulse control and slip-power recovery scheme with improved performances of power efficiency. The calculation procedure for amplification factor and parameters of the frequency-current slip-power recovery drive is developed. At desired voltage amplification factor, it allows finding transformation ratio for matching transformer. The expression is obtained which allows determining the minimum value of the time delay of the inverter of the converter, at which a stable operation during start-up is provided. The dependence of voltage amplification factor on equivalent resistance of the converter for frequency-current slip-power recovery scheme is found.

Originality. The relation between voltage amplification factor and equivalent resistance value of the converter for frequency-current slip-power recovery scheme which allows determining its best level of energy efficiency is established.

Practical value. The procedure for preliminary determination of the parameters of the converter for frequency-current slip-power recovery scheme is developed. It allows selecting the value of voltage amplification factor of the converter rationally and finding transformation ratio for matching transformer. The expression is obtained which allows determining the minimum value of the time delay of the inverter of the converter, at which a stable operation during start-up is provided. These findings can be used in engineering design of the converter for frequency-current slip-power recovery scheme both for high-voltage electric drives applied in stationary fan installations for the main lines of mine ventilation and low-voltage drives for materials-handling machines.

Keywords: *converter, amplification factor, motor, power-efficiency, switching, frequency*

Introduction. Application of automated controlled electric drive is considered as the most topical and effective means of power saving [1, 2]. The main losses (up to 90 %) account for power-consumption area, and just here, the main efforts into rational power-consumption must be concentrated [3, 4]. So, electric drives in all developed countries consume as much as 70 % of all generated electrical energy. The most essential economy of it can be achieved by application of controlled electric drives in combination with automation of production technologies [5]. For example, one of the most power-intensive electric drives is fans for the main ventilation

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of coal mines. The average installed capacity of fan drives is in the range of 1000 to 1600 kWt, but for the most powerful installations, it comprises as much as 4000 kWt. In such systems the wound-rotor induction motors (WRIM) are used as driving motor [6]. That is why nowadays electric drive systems with WRIM are of essential interest; they also find wide application in materials-handling machines and conveying systems. Use of modulating regulation in modern electric drives significantly reduces power consumption and mechanical loads, wear of mechanism components that substantially enhance reliability of the systems.

Analysis of the recent research. There are a number of engineering solutions that allow forming the characteristics with invariable torque of the drives based on WRIM and providing soft starting with constant acceleration. These most commonly used systems include classical slip-power recovery schemes (SPRS) [6], inductive-capacitive converters (ICC) [7] as well as current pulse control systems for WRIM rotor. The shortcomings of such systems are all-known. Among the main disadvantages of ICC there can be denoted the absence of possibility to change the current value and, consequently, torque of driving WRIM. SPRSs have a low power factor as well as increased inductance of matching reactor. The pulse control system provides low efficiency and also leads to overvoltage of the rotor winding in the process of gate switching in rectified WRIM rotor current.

In [8] the system of pulse frequency-current control for slip-power recovery scheme is proposed. It combines positive control characteristics of pulse control with possibility to regenerate power into the power network. Compared to ICC, the proposed system allows maintaining constant current in the rotor, irrespective of changing WRIM parameters in subsynchronous range of the rotor rotation [9]. This system shows itself to advantage in electric drives for materials-handling machines and can be effectively used in powerful high-voltage electric drives for ventilating installations, where application of high-voltage frequency converters leads to significant increase in their cost. Available current (torque) source in converter rotor for control by fan loads enables, at predetermined air head, to automatically select working point of discharge-head characteristic of the object to be ventilated or hydro supply at variable discharge value. The converter also allows enhancing operating efficiency as well as power efficiency of the electric drive for installations and mechanisms of different industries [9].

Unsolved aspects of the problem. The distinctive feature of the converter for pulse frequency current slip-power recovery scheme is available pulse regulator in the rectified rotor current circuit represented as pulse converter for stepping-up voltage. It is known that increasing output voltage in a converter under changing pulse ratio is limited by the losses in the converter. Furthermore, increase in output voltage is possible when decreasing the current load. In the process, the converter efficiency increases. Thus, it is necessary to find optimal value of the converter amplification factor providing its high efficiency as well as to determine relationship between its value and installed power of the converter circuit components.

Objectives of the article. The purpose of this work is investigation of electromagnetic processes in the pulse frequency-current control system of slip-power recovery scheme aimed to develop analytical expressions which allow determining the relation between the parameters and voltage amplification factor of the converter for pulse frequency-current slip-power recovery scheme.

Presentation of the main research. Fig. 1 represents the pulse frequency-current control system for slip-power recovery scheme.

The distinctive feature of this system involves available pulse regulator in rectified rotor current circuit represented as a pulse converter of stepping-up voltage (PCSUV). A capacitor (*C*) allows eliminating overvoltage across rotor winding caused by frequent switching of a chopper (*K*). Diode (*VD*) precludes appearance of reverse current from the capacitor, when the chopper is closed. As the chopper is closed, the energy stored in the rotor winding as well as part of slip energy, according to relationship between electromotive forces of the rotor and invertor (*I*), is regenerated into the electrical network at a constant inversion angle of the low power inverter that provides minimal consumption of reactive power from the electrical network and allows increasing power factor of the drive over all range of the rotor rotational speed. Matching of electromotive forces of the rotor and inverter can be performed with the help of transformer or autotransformer. The transformation ratio is determined by output voltage of PCSUV.

Simplified circuit of PCSUV is shown in Fig. 2. The load in the circuit is represented as resistance R_{load} that, for the converter being investigated, characterizes amount of energy being regenerated into the electrical network. As it is known from [10], the transfer ratio of

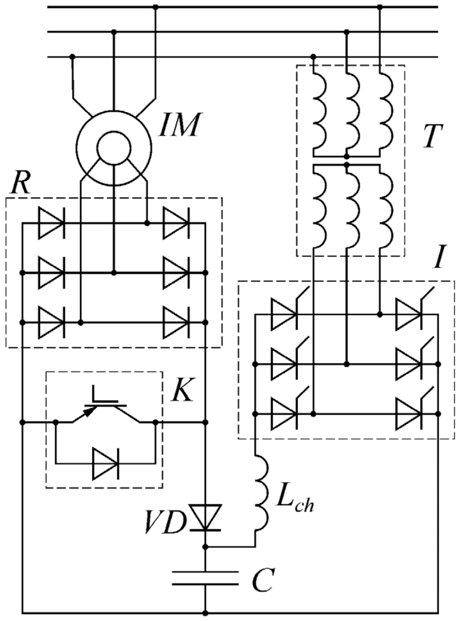

Fig. 1. Converter for pulse frequency-current slip-power recovery scheme

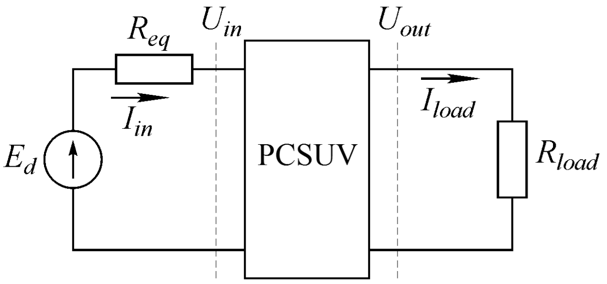

Fig. 2. Simplified model of pulse converter of stepping-up type

ideal PCSUV is described by the following relationship

$$K=\frac{U_{out}}{U_{in}}=\frac{1}{1-\gamma};$$

$$K=\frac{I_{in}}{I_{out}},$$

where I_{out}, U_{out} are average values of the PCSUV output current and voltage, respectively; I_{in}, U_{in} are average values of the PCSUV input current and voltage, respectively; $\gamma = t_i/T$ is the pulse ratio equal to relation of the on-state duration t_i to repetition cycle T.

From Fig. 2 it follows that PCSUV input voltage is found as follows

$$U_{in}=E_d-I_{in}\cdot R_{eq},$$

where I_{in} is the average value of the input current; R_{eq} is equivalent resistance of the converter; E_d is the average value of the motor rotor electromagnetic force (e.m.f.).

Output voltage of the converter is

$$U_{out}=K\cdot E_d-K^2\cdot I_{load}\cdot R_{eq}, \tag{1}$$

where I_{load} is the average value of the load current.

At variable value of e.m.f. the motor energy that is regenerated into the electrical network depends on the rotor slip, then it is reasonable to write expression (1) as follows

$$U_n=K\cdot E_{d0}\cdot s-K^2\cdot\frac{P_n\cdot s}{U_{out}}\cdot R_{eq}; \tag{2}$$

$$I_n=\frac{P_n\cdot s}{U_n}, \tag{3}$$

where P_n is nominal power on the motor shaft; s is the motor slip; U_d is rectified voltage in DC circuit of the motor rotor circuit.

Equation (2) can be written in relative units

$$U_n^*=K\cdot s-\frac{K^2\cdot R_{eq}^*}{K_E}; \tag{4}$$

$$R_{eq}^*=\frac{R_{eq}}{R_{load}}; \tag{5}$$

$$R_{load}=\frac{E_{d0}^2}{P_n}; \tag{6}$$

$$K_E=\frac{U_d}{E_{d0}}. \tag{7}$$

Maximal transfer ratio of the converter can be found from the following expression

$$K_{\max}=\frac{K_E}{2\cdot R_{eq}^*}.$$

Accordingly, maximal amplification ratio does not depend on the slip. As seen from (2–3) and (4–7) equivalent resistance R_{eq} imposes principle limitation on the reachable level of the PCSUV output voltage. Therefore, in order to select optimal value of the amplification factor, the circuit parameters should be selected correctly, i. e. the value of R_{eq} should be determined.

Fig. 3 shows equivalent circuit for the rectified rotor current subcircuit (PCSUV block) of the converter for frequency-current slip-power recovery scheme.

Let us determine the equivalent circuit parameters

$$R_2=r_{ch}+2\cdot r_T+\frac{3\cdot x_T\cdot s}{\pi};$$

$$R_1=2\cdot(r_s'+r_m)\cdot s+2\cdot r_r+\frac{3\cdot x_r\cdot s}{\pi};$$

$$L_1=2\cdot L_r;$$

$$L_2=L_{ch}+2\cdot L_T,$$

where r_{ir} is resistance of the invertor reactor; L_r is leakage inductance per one phase of the motor rotor; L_{ir} is the inductance of the invertor reactor; r_r is resistance per one phase of the motor rotor; r_s' is resistance per one phase of the stator reduced to the rotor winding; r_m is the reluctance of the motor magnetic circuit; r_T is equivalent resistance per one phase of the transformer; $\frac{3\cdot x_r\cdot s}{\pi}$ is the equivalent resistance resulted from switching of the rectifier valves; $\frac{3\cdot x_{2T}\cdot s}{\pi}$ is the equivalent resistance resulted from switching of the invertor valves; x_T the equivalent inductive reactance per one phase of the transformer.

Leakage reactance per one phase of the motor is

$$x_M=x_s'+x_r=2\cdot\pi\cdot f\cdot(L_s'+L_r),$$

where L_s' is total inductance per one phase of the stator reduced to the rotor; L_r is total inductance per one phase of the rotor.

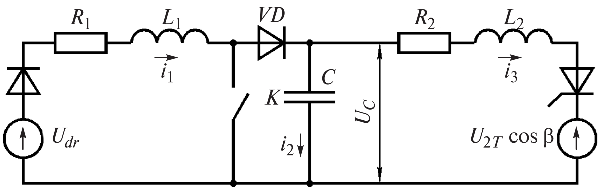

Fig. 3. Equivalent circuit for the rectified rotor current subcircuit of the converter

In accordance with a switching feature of the power chopper (K), the main stages of the circuit operation should be outlined. A certain equation of switching transients will correspond to each stage.

The main stages of the converter operation are represented in Fig. 4. The first (initial) stage of the converter operation is characterized by charging the capacitor (C) up to the value of voltage $U_C = U_{2T} \cdot \cos\beta$, when the chopper (K) is in open position, during the time span equal to $t = t_1 - t_0$. The charging circuit of the capacitor for this time span is $C \rightarrow R_2 \rightarrow L_2 \rightarrow C$. In the process, the gates of the invertor (I) will be applied by control signals to avoid change of state of the invertor at the moment when it is triggered. At this instant, the process of slip-power regeneration is impossible (here $U_C \prec U_{2T} \cdot \cos\beta$).

According to Fig. 3 at the first stage of the circuit operation the charging current through the capacitor and the voltage across it will vary according to the periodical law

$$u_C(t) = U_{2T(0)} \cos\beta \cdot e^{-\delta t} \sin(\omega_0 t);$$

$$i_2(t) = C \cdot \frac{d}{dt} u_C(t), \tag{8}$$

where

$$\delta = \frac{R_2}{2 \cdot L_2};$$

$$\omega_0 = \sqrt{\frac{1}{2 \cdot L_2 \cdot C} - \left(\frac{R_2}{2 \cdot L_2}\right)^2}.$$

To make the converter come into the second stage of its operation, it is necessary to find delay time of the inverter triggering, after lapse of which the condition of regeneration $U_C \geq U_{2T} \cdot \cos\beta$ will be fulfilled.

The minimal value of the converter triggering delay time is defined by the charging time of the capacitor. Since during the charging of the capacitor the charging current decreases, to find its charging time, equation (8) should be set to zero. Hence, the minimal value of the converter triggering delay time is evaluated according to the following expression

$$t_1 = \frac{2 \cdot \mathrm{arctg}\left(\frac{\delta + \sqrt{\omega_0^2 + \delta^2}}{\omega_0}\right)}{\omega_0} \cdot 2 \cdot \mathrm{arctg}\left(\frac{\delta - \sqrt{\omega_0^2 + \delta^2}}{\omega_0}\right). \tag{9}$$

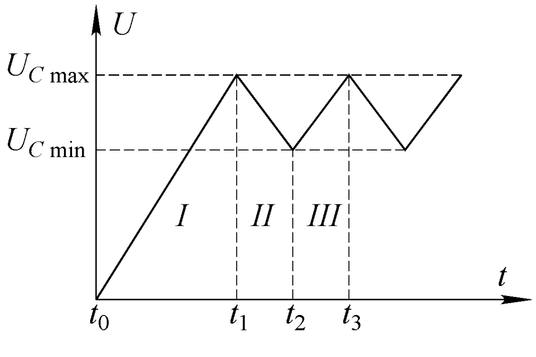

Fig. 4. Operation stages of the converter

At the second stage, the converter comes into the main operating duty. The second stage of the converter operation is characterized by charging of capacitor (C), when chopper (K) is in closed position, during the time span equal to $t = t_2 - t_1$. The energy that was dropped by the capacitor is regenerated into the electrical network via the gate of invertor. This time span will be corresponded by the circuits $R_1 \rightarrow L_1 \rightarrow K \rightarrow R_1$ and $C \rightarrow \rightarrow R_2 \rightarrow L_2 \rightarrow C$ (Fig. 3).

Set of the differential equations for this state of the circuit is

$$R_1 \cdot i_1 + L_1 \cdot \frac{di_1}{dt} = 1.35 \cdot U_{dr} \cdot s; \tag{10}$$

$$U_{C(t=t_1)} - U_{2T} \cdot \cos(\beta) = R_2 \cdot i_3 + L_2 \cdot \frac{di_3}{dt}. \tag{11}$$

Let us consider the third stage of the converter operation during the time span equal to $t = t_3 - t_2$, when power chopper (K) is in open position. In the process, a part of slip-power, namely, trapped in the rotor winding caused by sharp change of the rectified current, is released to the capacitor (circuit $R_1 \rightarrow L_1 \rightarrow C \rightarrow R_1$). The remainder of the slip-energy is regenerated into electrical network via the reactor and invertor (circuit $R_1 \rightarrow \rightarrow L_1 \rightarrow VD \rightarrow R_2 \rightarrow L_2 \rightarrow R_1$).

Differential equations for this state of the circuit are as follows

$$R_1 \cdot i_1 + L_1 \cdot \frac{di_1}{dt} + \frac{1}{C} \int i_2 dt = 1.35 \cdot U_{dr} \cdot s; \tag{12}$$

$$R_1 \cdot i_1 + L_1 \frac{di_1}{dt} + L_2 \frac{di_3}{dt} + R_2 \cdot i_3 = 1.35 \cdot U_{dr} \cdot s + U_{2T} \cdot \cos\beta; \tag{13}$$

$$i_1 = i_2 + i_3. \tag{14}$$

Differential equations (10–14) can be reduced to a set of linear algebraic equations that enable to determine the main parameters of the converter.

Resistance of the invertor reactor can be found from the following expression

$$r_{ir} = \frac{\gamma \cdot \left(U_{2T} \cos\beta - E_d\right) - I_{dav} \cdot R_1}{I_d} - 2 \cdot r_1 - \frac{3 \cdot x_T \cdot s}{\pi}, \tag{15}$$

where

$$I_{dav} = \frac{\gamma \cdot \left(U_{2T} \cos\beta - E_d\right)}{R_1 + R_2}; \tag{16}$$

$$E_d = 1.35 \cdot U_{dr} \cdot s, \tag{17}$$

where I_{dav} is average value of the motor rotor rectified current; γ is the pulse-duration ratio at pulse-width control.

Inductance of the invertor reactor can be found from the following equation

$$L_{ir} = \frac{T \cdot \gamma \cdot U_{2T} \cos\beta \cdot (1 - \gamma) - \Delta I_d \cdot L_1}{\Delta I_d} - 2 \cdot L_T; \tag{18}$$

$$\Delta I_d = \frac{\gamma \cdot U_{2T} \cos\beta \cdot \left(1-\gamma\right)}{f_k \cdot \left(L_1 + L_2\right)}, \tag{19}$$

where ΔI_d is the ripple swing value of the rotor rectified current; f_k is the switching frequency of the power chopper.

The capacitance value of capacitor must be selected so as to ensure release of the energy trapped by the rotor winding to the capacitor

$$\frac{L_1 \cdot \left(I_{d\max} - I_{d\min}\right)^2}{2} \cdot f_k \le \frac{\left(U_{C\max} - U_{C\min}\right)^2}{2} \cdot C, \tag{20}$$

where

$$I_{d\min} = I_{dav} - \frac{\Delta I_d}{2}; \tag{21}$$

$$I_{d\max} = I_{dav} + \frac{\Delta I_d}{2}; \tag{22}$$

$$U_{C\min} = U_{2T(0)} \cos\beta - \frac{U_{2T} \cos\beta \cdot \Delta U_C^*}{2}; \tag{23}$$

$$U_{C\max} = U_{2T(0)} \cos\beta + \frac{U_{2T} \cos\beta \cdot \Delta U_C^*}{2}. \tag{24}$$

The pulsation value of the voltage across the capacitor in relative units can be found from the following expression

$$\Delta U_C^* = 1 - \frac{u_{2T} \cos\beta}{u_C}. \tag{25}$$

The capacitance value of the capacitor, according to (20), can be found from the following expression

$$C \ge \frac{L_1 \cdot \left(I_{d\max} - I_{d\min}\right)^2 \cdot f_k}{\left(U_{C\max} - U_{C\min}\right)^2}. \tag{26}$$

Thus, equivalent resistance of PCSUV can be found from the following expression

$$\begin{aligned} R_{eq} = {} & 2 \cdot (R'_S + R_m) \cdot s + 2 \cdot R_r + 2\pi \cdot f_k (L_1 + L_2) + R_{ir} + \\ & + R_T + \frac{3 \cdot x_M \cdot s}{\pi} + \frac{3 \cdot x_T \cdot s}{\pi}. \end{aligned} \tag{27}$$

All other variables in expressions (9, 15–27) are either output parameters of the converter or its ratings. Derived expressions allow determining the parameters of the converter for pulse frequency-circuit slip-power recovery scheme at the stage of its designing, to find required transformation ratio of the matching transformer as well as optimal value of PCSUV amplification factor, at which the converter has the most power efficiency.

Conclusions and recommendations for further research. Pulse frequency-current slip-power recovery drive system having improved performances in respect to power efficiency is proposed. Calculation procedure for amplification factor and parameters of pulse frequency-current slip-power recovery drive is developed. At desired voltage amplification factor, it allows determining transformation ratio of the matching transformer. The expression, which allows determining the minimum value of the time delay of the inverter of the converter providing a stable operation during start-up are obtained. Relation between voltage amplification factor and equivalent resistance of the converter for slip-power recovery scheme is established. Derived findings can be used in designing of the converter for slip-power recovery scheme both for high-voltage electric drives applied in stationary fan installations for main lines of mine ventilation and for low-voltage drives for carrying and lifting machines.

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Мета. Розробка аналітичних виразів, що дозволяють встановити зв'язок і визначити параметри й коефіцієнт посилення за напругою перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду.

Методика. На підставі аналізу перехідних процесів при комутації силових ключів перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду використовується метод розв’язання системи лінійних диференціальних рівнянь другого порядку.

Результати. Запропонована система електроприводу за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду, що поєднує в собі позитивні властивості класичної системи імпульсного регулювання та асинхронно-вентильного каскаду з поліпшеними показниками енергоефективності. Розроблена методика розрахунку коефіцієнта посилення й параметрів електроприводу за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду, що дозволяє при бажаному коефіцієнті посилення за напругою визначити коефіцієнт трансформації погоджувального трансформатора. Отримано вираз, що дозволяє визначити мінімальне значення часу затримки включення інвертора перетворювача, за якого забезпечується стабільний режим роботи під час його пуску. Визначено зв’язок коефіцієнта посилення за напругою з еквівалентним опором перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду.

Наукова новизна. Встановлено зв’язок коефіцієнта посилення за напругою з еквівалентним опором перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду, що дозволяє визначити його найкращий рівень енергоефективності.

Практична значимість. Розроблена методика попереднього визначення параметрів перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду, що дозволяє раціонально підібрати величину коефіцієнта посилення за напругою перетворювача й визначити коефіцієнт трансформації погоджувального трансформатора. Отримано вираз, що дозволяє визначити мінімальне значення часу затримки включення інвертора перетворювача, за якого забезпечується стабільний режим роботи під час його пуску. Результати роботи можуть бути використані при проектуванні перетворювача за схемою імпульсного частотно-струмового асинхронно-вентильного каскаду як для високовольтних електроприводів стаціонарних установок вентиляторів магістралі головного провітрювання шахт, так і для низьковольтних електроприводів підйомно-транспортних механізмів.

Ключові слова: *перетворювач, коефіцієнт посилення, двигун, енергоефективність, комутація, частота*

Цель. Разработка аналитических выражений, позволяющих установить связь и определить параметры и коэффициент усиления по напряжению преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада.

Методика. На основании анализа переходных процессов при коммутации силовых ключей преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада используется метод решения системы линейных дифференциальных уравнений второго порядка.

Результаты. Предложена система электропривода по схеме импульсного частотно-токового асинхронно-вентильного каскада, которая совмещает в себе положительные свойства классической системы импульсного регулирования и асинхронно-вентильного каскада с улучшенными показателями энергоэффективности. Разработана методика расчета коэффициента усиления и параметров электропривода по схеме импульсного частотно-токового асинхронно-вентильного каскада, позволяющая при желаемом коэффициенте усиления по напряжению определить коэффициент трансформации согласующего трансформатора. Получено выражение, позволяющее определить минимальное значение времени задержки включения инвертора преобразователя, при котором обеспечивается стабильный режим работы во время его пуска. Определена связь коэффициента усиления по напряжению с эквивалентным сопротивлением преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада.

Научная новизна. Установлена связь коэффициента усиления по напряжению с эквивалентным сопротивлением преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада, позволяющая определить его наилучший уровень энергоэффективности.

Практическая значимость. Разработана методика предварительного определения параметров преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада, позволяющая рационально подобрать величину коэффициента усиления по напряжению преобразователя и определить коэффициент трансформации согласующего трансформатора. Получено выражение, позволяющее определить минимальное значение времени задержки включения инвертора преобразователя, при котором обеспечивается стабильный режим работы во время его пуска. Результаты работы могут быть использованы при проектировании преобразователя по схеме импульсного частотно-токового асинхронно-вентильного каскада как для высоковольтных электроприводов стационарных установок вентиляторов магистрали главного проветривания шахт, так и для низковольтных электроприводов подъемно-транспортных механизмов.

Ключевые слова: *преобразователь, коэффициент усиления, двигатель, энергоэффективность, коммутация, частота*

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