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Determining the Switching Frequency of a Transistor Converter for a Traction Collector Motor

The purpose of this work is to determine the switching frequency of a transistor converter for a traction collector motor of a locomotive based on the criterion of permissible current ripple. The stated goal is achieved by solving the following problem: a methodology for determining the consideration of changes in motor parameters when calculating the switching frequency of the transistor converter is proposed. The peculiarity of the proposed approach is that it takes into account the degree of saturation of individual parts of the magnetic system of the electric motor. The most significant result is an increase in the accuracy of calculating the switching frequency by taking into account the change in the inductance of the commutator motor windings when the degree of saturation of the magnetic system changes. The switching frequency for a DC traction motor with a pulse converter is calculated. Two main operating modes of the electric motor are considered: with full magnetic flux and with weakened magnetic flux. As a result of calculations, it was established that the dependence of switching frequency on currents is nonlinear. For the operating mode of the electric motor with full magnetic flux, the switching frequency is determined taking into account the processes in the field winding circuits and in the armature circuit windings. The most important results are the determination of the switching frequency of the pulse converter for powering and regulating the traction motor in all operating modes. The proposed methodology allows the selection of transistor devices for the converter according to the switching frequency.

Keywords: *energy efficiency, rolling stock, traction electric motor, traction system, semiconductor converter, switching frequency.*

Introduction. Stable operation of the railways requires the introduction of energy-saving technologies in all types of its activities. The locomotive fleet of railways is the most energy-intensive, as it consumes fuel and energy resources for train traction [1]. Therefore, in the context of a constant increase in the cost of fuel and energy resources, reducing their consumption is a priority. Taking into consideration that a large part of the traction rolling stock is equipped with outdated equipment with insufficient energy efficiency by modern standards, improving the energy efficiency of traction rolling stock is an urgent task.

Shunting operations are an integral part of the freight and passenger rail transport business.

A key area of modernisation of shunting locomotives is to improve their fuel efficiency. For this purpose, multi-diesel and hybrid power plants can be used [2, 3]. The first method is common on shunting locomotives manufactured or modernised by American companies [4]. Both approaches, as expected, reduce fuel consumption.

In the case of a hybrid power plant, as well as in some cases with a multi-diesel power plant, the use of pulse regulators is necessary to power and regulate traction collector motors [5]. Therefore, research that will form the basis for their modernisation is relevant.

Traction systems with collector motors and pulse converters are most common in the rolling stock of urban electric transport [6, 7]. On the rolling stock of mainline railways, switching regulators are used to control the excitation current. The use of switching regulators in traction systems of motor-car electric rolling stock is also known [8]. When collector motors are powered by a pulse converter, pulsating currents flow through its windings. The presence of pulsations in the currents of a traction motor leads to a change in the quality of switching, an increase in losses in the motor, and the appearance of electromagnetic torque pulsations.

For direct current traction electric motors, operation with current pulsations that do not exceed 10% is allowed. Therefore, to fulfil this condition, it is necessary to determine the switching frequency of the pulse converter, which depends on both the parameters of the electric motor and the structure of the semiconductor converter. In [9], a scheme of the traction system of the modernised diesel locomotive with a hybrid power plant is proposed. It provides individual power supply and regulation of traction motors. This solution makes it possible to adapt the traction parameters of the locomotive to the conditions of a specific train task, which helps to reduce the consumption of fuel and energy resources [10]. Currently, pulse regulators have been developed and implemented in which the armature and excitation circuits are powered exclusively by switching IGBT transistors. Such converters are most widely used in the traction systems of urban electric vehicles [11, 12]. Studies on the use of switching regulators to power and regulate traction collector motors of railway rolling stock are presented in [13-15].

The analysis of the considered sources shows that the scheme shown in Fig. 1 can be used for a DC traction motor [11]. The converter provides pulse-width control of the motor current with a series connection of the armature and field windings in the full excitation mode and pulse-width control of the excitation current in the magnetic flux attenuation mode.

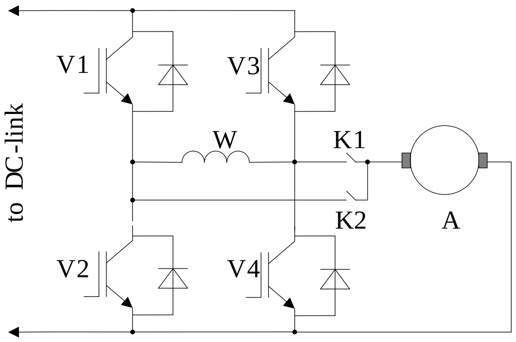

Fig. 1. **Power supply and control circuit for the traction motor: A – armature, W – excitation winding, V1…V4 – semiconductor keys, K1…K2 – contactors.**

General recommendations for determining the switching frequency are given in [16]. In [17], it is shown that when determining the switching frequency, it is necessary to take into account the additional losses that occur when a pulsating current flows through the motor windings, as well as losses in the traction converter. Refined models of the collector motor are presented in [18], considering the additional magnetic losses that occur when a pulsating current flows. The models can be used to calculate the switching frequency. At the same time, it can be noted that existing approaches use either simplified models or require detailed modelling. This work differs from the known ones in that it takes into account the change in the parameters of the electric motor when the modes of its operation are changed when determining the switching frequency of the pulse converter. This approach corresponds to the physical processes that occur in the traction electric motor and will allow to increase the accuracy of calculations, which ultimately determines the quality of electromechanical energy conversion and the reliability of the system.

The aim of the study is to determine the switching frequency of a pulse converter for a locomotive traction collector motor by the criterion of permissible current ripple. This approach makes it possible to provide the motor operating modes with an acceptable degree of switching.

Research material. The magnitude of the ripples is usually estimated by the current ripple coefficient, which is determined by the expression [6,19]

$$k_i = \frac{\Delta I}{I_0} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \qquad (1)$$

where $\Delta I = \frac{I_{\max} - I_{\min}}{2}$ – half the current ripple;

$I_0 = \frac{I_{\max} + I_{\min}}{2}$ – is the average current value;

$I_{\max}, I_{\min}$ – the highest and lowest current values, respectively (Fig. 2).

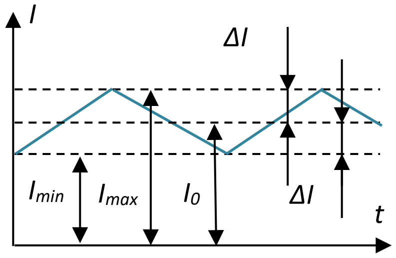

Fig. 2. **Determination the current ripple factor**

As noted above, when a DC traction motor is powered, pulsating current will flow through its windings. This can cause a commutation malfunction (sparking at the collector). Since it is not possible to make changes in the design of existing traction motors that would reduce the negative impact of the pulsating component on the commutation processes, it is necessary to limit the magnitude of this current pulsation. However, the standard for traction electric machines stipulates that for DC motors, the ripple factor cannot exceed 10 % (although the actual determination of the value of the ripple factor at which there is no commutation disturbance requires experimental determination and confirmation). In view of the standard, it is advisable to determine the switching frequency, provided that at 10 % current ripple the switching will be satisfactory.

Figure 3 shows the design scheme of the traction circuits, which corresponds to the scheme in Figure 2.

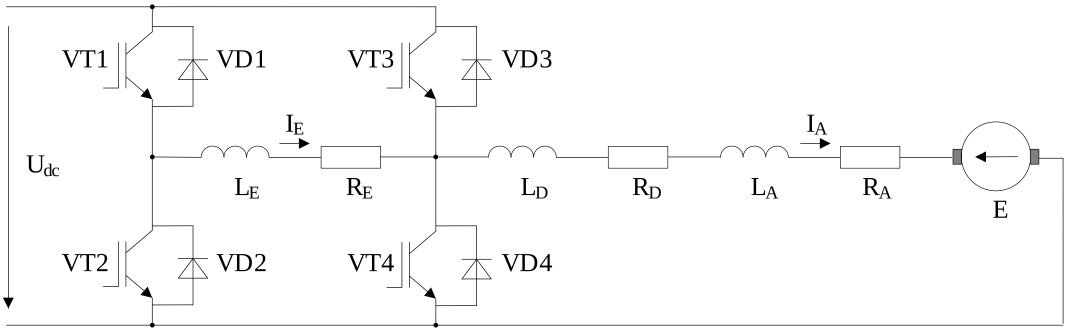

Fig. 3. **Electrical circuit diagram of the traction syst**em

In Fig. 3 the following designations are introduced: Udc - DC link voltage, E - electromotive force of electric motor, I_E - excitation current, I_A - armature current, VT1..VT4 - IGBT transistors, VD1.. VD4 - diodes, L_E - excitation winding inductance, R_E - excitation winding resistance, L_D - additional pole winding inductance, R_D - additional pole winding resistance, L_A - armature winding inductance, R_A - armature winding resistance.

As it is known, the traction electric drive of a vehicle operates in two zones: with a constant magnetic flux and with a weakened magnetic flux.

In the first zone, the traction motor is controlled by changing the voltage by pulse width modulation of the transistor VT1. The dependence of the current ripple value on the pulse filling factor is as follows [20]

$$k_i = \frac{\lambda(1-\lambda)U_{dc}}{2I_0 f L_\Sigma}, \tag{2}$$

where f – switching frequency;

λ – the occupancy rate;

U_{dc} – power supply voltage;

L_Σ – total inductance of the motor circuit, which includes the armature winding, the additional pole winding and the excitation winding.

The largest pulsation occurs at a filling factor of 0.5 [20]. From this condition, the switching frequency is defined as

$$f_{VT1} = \frac{U_{dc}}{8I_{0M} L_\Sigma k_{i\max}}, \tag{3}$$

where $k_{i\max}$ – the permissible value of current ripple, specified by 10%;

I_{0M} – average current of the electric motor.

When operating in the second zone, the field attenuation is provided by the pulse width modulation of transistor VT3. For this case, the current ripple in the field and armature windings is also determined by expression (2). However, for the excitation winding, it is necessary to take into account only its inductance, and for the armature circuit - the inductance of the armature and additional poles. Then the switching frequency for the field winding will be determined as follows

$$f_{swE} = \frac{U_{DC}}{8I_{0E} L_E k_{iE\max}} \tag{4}$$

where $k_{iE\max}$ – permissible current ripple coefficient of the excitation winding;

I_{0E} – is the average current of the excitation winding;

L_E – inductance of the excitation winding.

The switching frequency for the armature winding is determined by the expression

$$f_{swA} = \frac{U_{dc}}{8I_{0A}L_A k_{iA\max}} \tag{5}$$

where $k_{iA\max}$ – permissible current ripple coefficient of the armature winding;

I_{0A} – is the average current of the armature winding;

L_A – the total inductance of the armature winding and the windings of the additional poles.

Since switching of the field winding and the armature circuit is carried out simultaneously by transistor VT3, the switching frequency of transistor VT3 must be calculated taking into account the current ripple in both the armature circuit and the field winding circuit. Since the inductance of these circuits is different, the switching frequency can be determined as follows. For each of the circuits, the switching frequency at which the current ripple is 10% is determined. The largest of the two calculated values is selected.

$$f_{VT3} = \max\left(f_{swA}, f_{swE}\right). \tag{6}$$

A higher switching frequency corresponds to a circuit with a lower inductance. Therefore, for a circuit with a higher inductance, the current ripple will be less than 10%.

From the analysis of expressions (2) and (3), it follows that the switching frequency depends on the current and inductance of the windings. In turn, the winding inductances vary depending on the degree of saturation of the magnetic system, which is determined by the excitation current. In other words, there is a nonlinear dependence of the switching frequency on the currents. The switching frequency is directly proportional to the intermediate circuit voltage and inversely proportional to the current ripple factor.

Thus, to determine the switching frequency, it is necessary to know the inductances of the windings, which vary depending on the magnetic flux of the motor. In turn, the magnetic flux is determined by the field winding current. Therefore, it is convenient to determine the winding inductances depending on the current flowing through the field winding.

The winding inductances can be determined on the basis of analytical dependencies, by numerical analysis and experimentally. This paper uses an analytical approach that does not require lengthy calculations or expensive experiments, but provides acceptable accuracy of calculations.

The inductance of the excitation winding when all coils are connected in series is determined by expression [19]

$$L_e = \left(2p\sigma_e w_e \frac{d\Phi}{dI_e}\right)\left(1 + k_A\right), \tag{7}$$

where $2p$ – number of electric motor poles;

σ_e – is the scattering coefficient of the main pole;

k_A – the coefficient that takes into account the effect of eddy currents in magnetic circuits is in the range from 0.15 to 0.3;

w_e – number of turns of the excitation coil;

Φ – magnetic flux;

I_e – excitation current.

The motor magnetisation curve is used to calculate the derivative $d\Phi/dI_e$.

When calculating the winding inductance of auxiliary poles, the saturation of their magnetic circuit is usually neglected. Therefore, the inductance can be determined through the geometrical dimensions of the additional pole by the expression

$$L_d = 2p\sigma_d w_d^2 \Lambda_d \tag{8}$$

where w_d – number of turns of the additional pole;

σ_d – is the scattering coefficient of the additional pole;

Λ_d – magnetic conductivity of air gaps in the magnetic circuit of additional poles.

The magnetic conductivity is determined by the expression

$$\Lambda_d = \frac{1}{\dfrac{\delta_d k_{\delta_d}}{\mu_0 l_a \left(b_d + 3\delta_d\right)} + \dfrac{\delta_s}{\mu_0 l_d \left(b_d + 3\delta_s\right)}} \tag{9}$$

where δ_d – the air gap between the anchor and the additional pole;

k_{δ_d} – air gap coefficient under the additional pole;

l_a – length of the armature core;

b_d – width of the core of the additional pole;

δ_s – the air gap between the main body and the additional pole;

l_d – length of the core of the additional pole;

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

The armature winding inductance is mainly generated by the armature reaction flux. According to [19], the inductance value is affected by the saturation of the tooth layer. The armature inductance is determined by the expression

$$L_a = L'_a k_\mu \tag{10}$$

where L'_a – winding inductance excluding saturation,

k_μ – is a coefficient that takes into account saturation.

The inductance of the winding without considering saturation is determined by expression [19]

$$L'_a = \frac{\mu_0 \pi}{3} \frac{w'_a \alpha_\delta^3 l_a D_a}{\delta k_\delta} \tag{11}$$

where $w'_a = \dfrac{N}{8ap}$ – number of armatures turns per pole (N - number of armatures winding conductors;

$2a$ - number of parallel branches of the armature winding);

α_δ – pole overlap coefficient;

D_a – outer diameter of the armature;

δ – the air gap between the anchor and the main pole;

k_δ – air gap coefficient.

The coefficient that takes into account saturation is determined through the induction in the armature teeth, calculated for a section at a height of 1/3 from the base of the tooth (Table 1) [19].

Saturation coefficient takes into account the change in magnetic conductivity of the armature tooth layer depending on мagnetic flux density.

Table 1. **Dependence of saturation coefficient on induction in armature teeth [19]**

Parameter	Value					
Magnetic flux density, T	0.4	0.8	1.2	1.6	2.0	2.4
Saturation coefficient, f.u.	1.0	0.95	0.79	0.52	0.28	0.12

Thus, expressions (7)-(11) form a model for determining the inductances of the motor windings. Its use increases the accuracy of determining the switching frequency.

Research results. The calculations were carried out for the TE-006 traction motor when it is powered by a pulse converter according to the scheme in Fig. 1. The data from the technical documentation for the electric motor were used for the calculations.

Calculation of inductances. To determine the dependence of inductance on current, we used the magnetisation curve of the TE-006 electric motor, calculated according to [19]. Technical parameters of the electric motor are given in Table 2. The motor magnetisation curve is shown in Fig. 4.

Table 2. **Technical parameters of the traction electric motor TE006**

Parameter	Value
Power, kW	123/134
Voltage, V	197/283
Nominal current, A	750/522
Current at start-up conditions, A	1000
Rotation frequency, r.p.m.	295/2420
Excitation	series
Minimal field weakening,%	18
Weight, kg	2635

As can be seen from Fig. 5, due to the saturation of the magnetic system, the inductance of the excitation winding decreases significantly with increasing current.

The inductance of the additional pole winding, calculated by (8), is 0.0053 H.

Fig. 5 shows the inductance of the excitation winding without considering eddy currents (in formula (7), the coefficient is zero).

Fig. 6 shows the dependence of the armature inductance on the excitation current. The calculations were performed according to (10) and (11).

Fig. 7 shows the dependence of the total inductance of the motor windings on the current. In the calculations, it is assumed that the eddy current coefficient is 1.25.

From the analysis of the dependencies shown in Figures 5-7, the field winding inductance is significantly higher than the armature inductance. The inductance of the auxiliary poles is higher than the armature inductance. A comparison of the inductance of the field winding and the auxiliary pole winding shows that they are similar at excitation currents above 500 A. At excitation currents below 500 A, the inductance of the excitation winding increases and exceeds the inductance of the auxiliary pole winding.

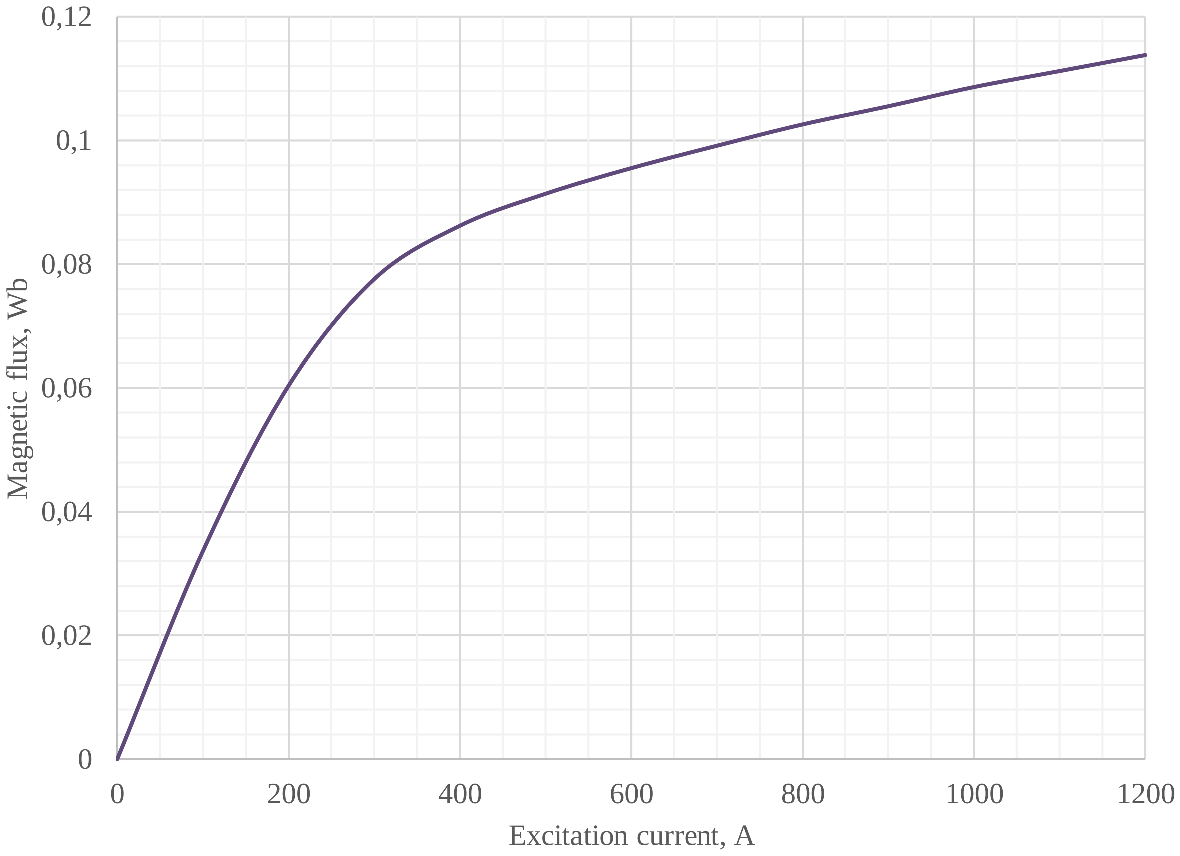

Fig. 4. **Magnetisation curve of the TE-006 electric motor (calculated by the authors)**

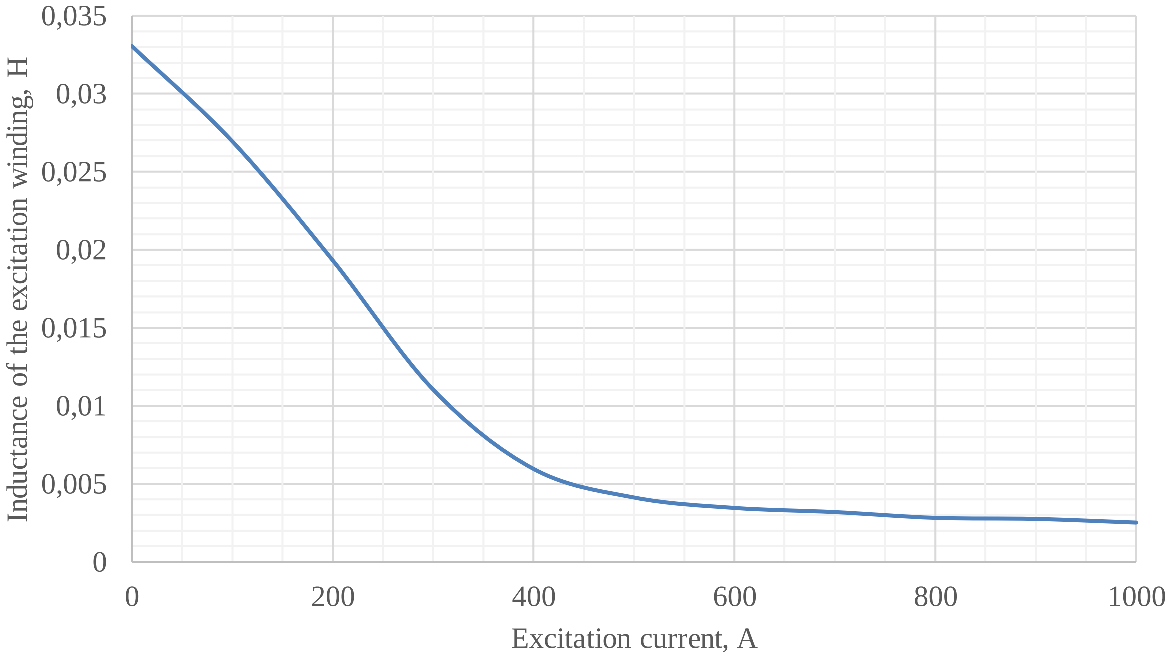

Fig. 5. **Dependence of field winding inductance on current**

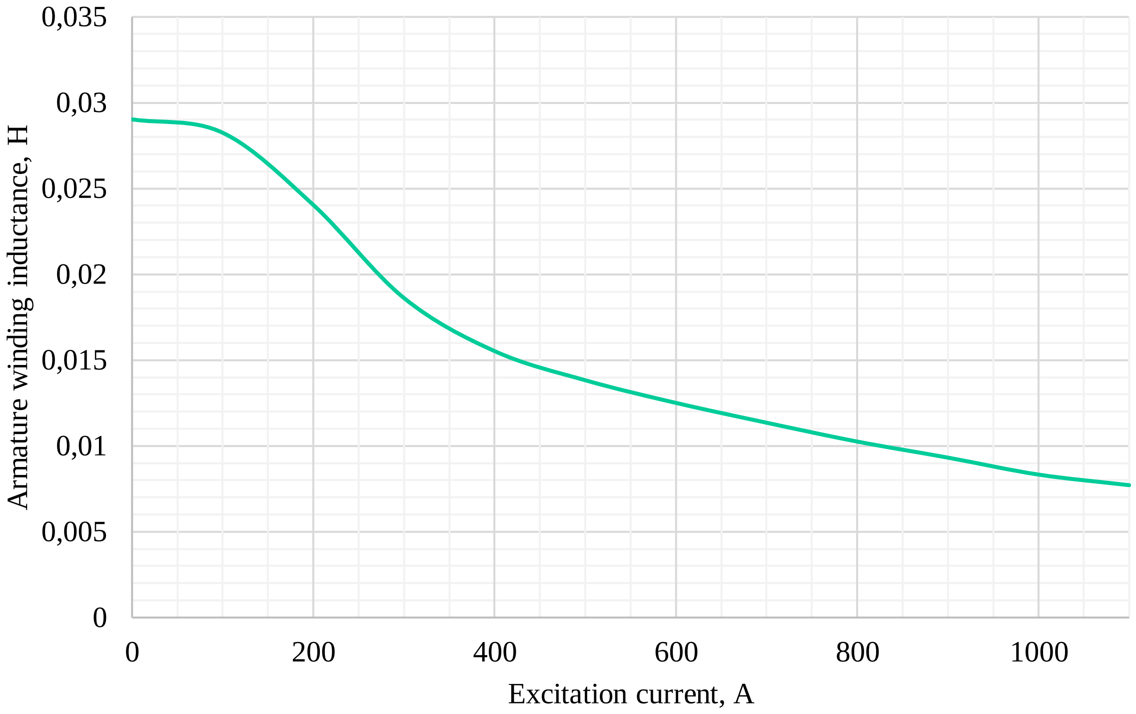

Fig. 6. **Dependence of armature inductance on excitation current**

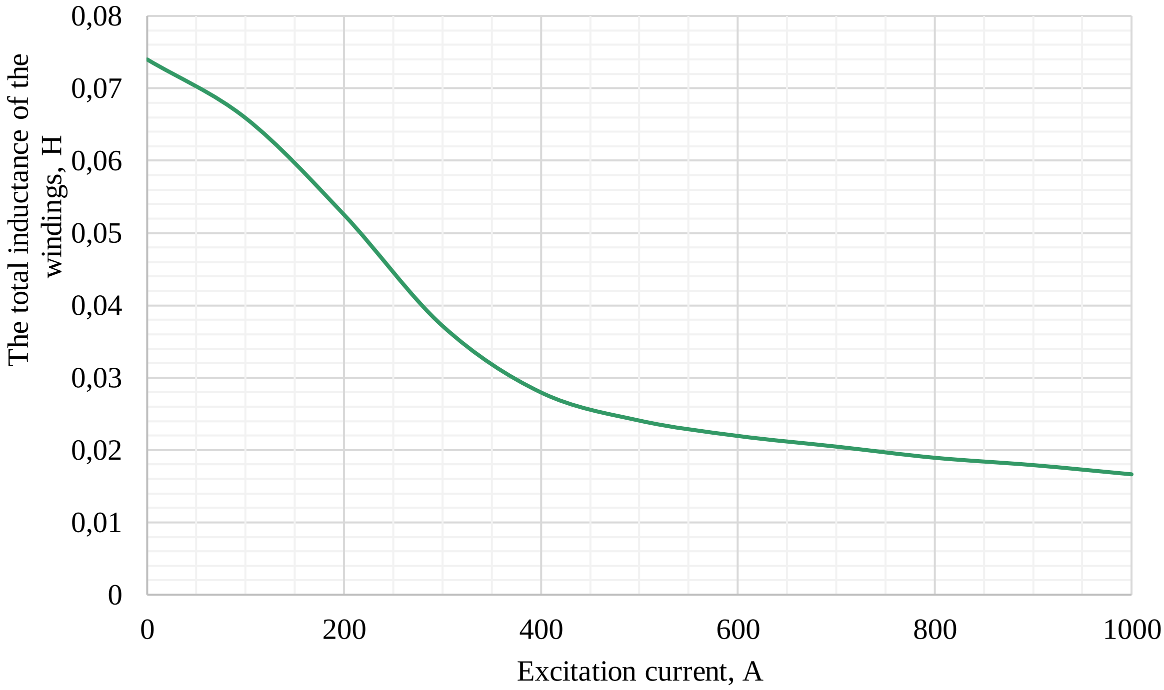

Fig. 7. **Dependence of the total inductance of the motor windings (armature winding, the additional pole winding and the excitation winding) on the excitation current**

Calculation of the switching frequency when operating with full magnetic flux. It follows from (2) that the switching frequency depends on the current. Since the traction motor operates with different currents, the frequency for each current must be determined.

Fig. 8 shows the dependence of the switching frequency on the current in the range from 100 A to 1000 A for the motor operation mode. In the calculations, it is assumed that the current ripple coefficient is 10% and the intermediate circuit voltage is 600 V.

The analysis of Fig. 6 shows that the switching frequency varies depending on the motor current. The switching frequency decreases as the motor current increases. At a motor current of 100 A, the frequency is 114 Hz. At a current of 1000 A, the frequency is 45 Hz.

Calculation of the switching frequency when operating with magnetic flux attenuation. The calculation of the switching frequency for the excitation winding is performed according to (5), and for the armature circuit - according to (6).

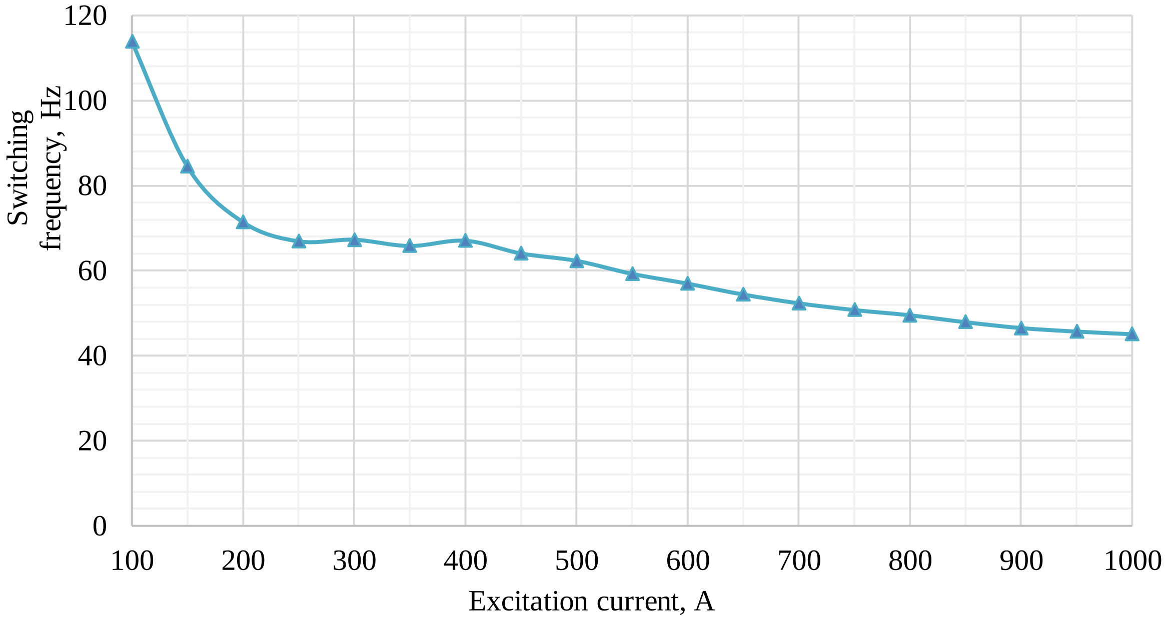

Fig. 8. **Dependence of the switching frequency of the transistor VT1 on the motor current in the full magnetic flux mode**

The analysis of Fig. 9 shows that the switching frequency varies depending on the motor current. The highest values of the switching frequency (about 290 Hz) are for currents from 500 A to 600 A. The lowest switching frequency (about 150 Hz) is for a current of 200 A.

Fig. 10 shows the dependence of the switching frequency of the transistor VT3 on the excitation current in the field weakening mode under the condition of 10% armature current ripple.

Analysis of dependencies in fig. 10 shows that a change in the degree of saturation of the magnetic system at a given armature current affects the switching frequency.

From fig. 10 shows that the switching frequency varies from approximately 22 Hz at 1000 A armature current to 225 Hz at 100 A armature current.

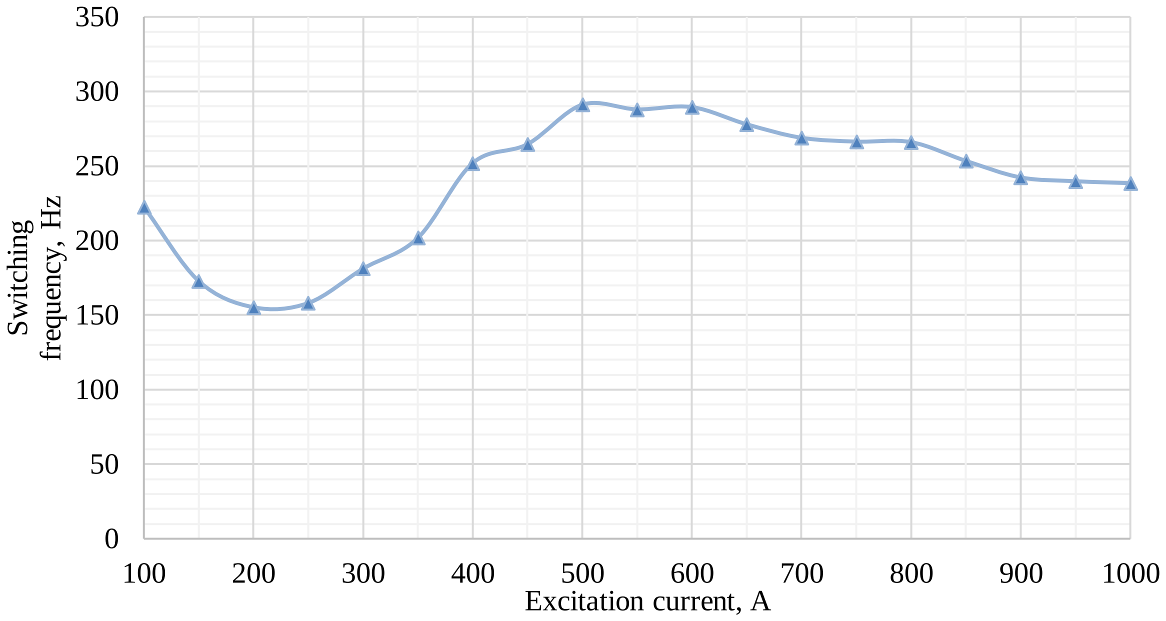

Fig. 9. **Dependence of the switching frequency of the transistor VT3 on the excitation current in the field weakening mode with a 10% excitation current ripple**

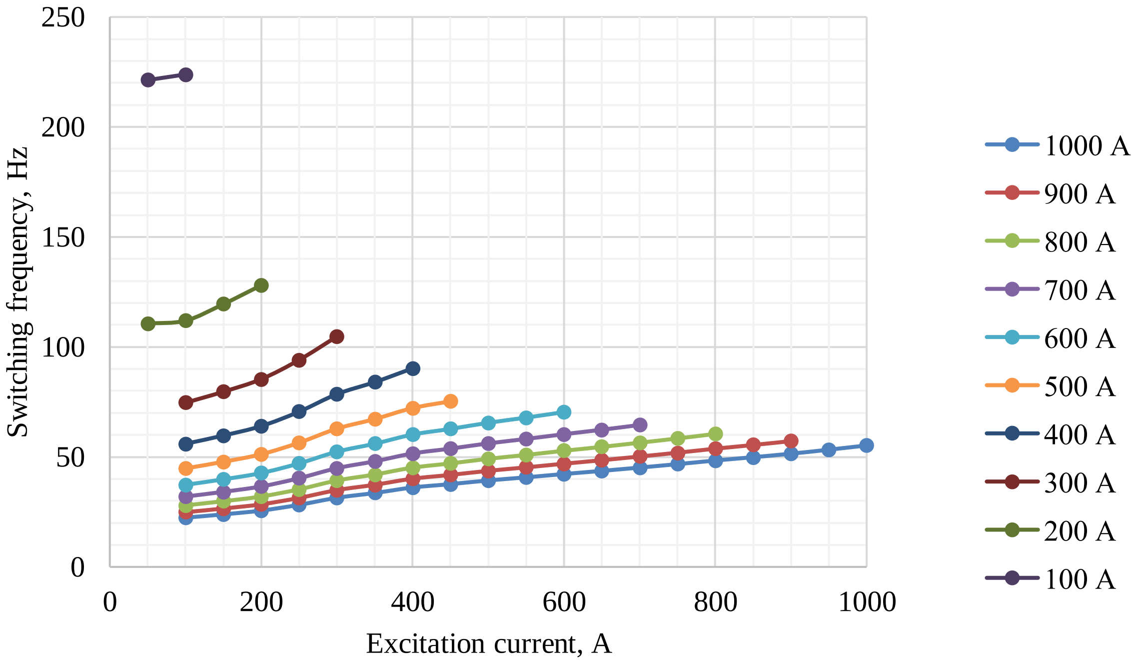

Fig. 10. **Dependence of the switching frequency of the VT3 transistor on the excitation current in the field weakening mode with the condition of 10% pulsation of the armature current (armature current is shown on the right)**

Then, considering expression (6), the switching frequency should be 290 Hz.

Thus, the study shows the need to take into account the degree of saturation of the magnetic system when determining the switching frequency of a pulse converter.

Discussion of the results. The paper deals with determination of the switching frequency of a pulse converter for power supply and regulation of a DC traction motor. The study was carried out for the traction motor TE-006. It is shown that when determining the switching frequency, it is necessary to take into account the effect of the degree of saturation on the winding inductance. The degree of saturation of the magnetic system has a significant influence on the change in the value of the inductance of the excitation winding. The effect of the saturation degree on the armature inductance is insignificant.

The switching frequency was determined on the condition of ensuring a current ripple coefficient of 10%. This corresponds to the condition of high-quality commutation on the collector. Other aspects arising from the flow of pulsating current were not considered.

In full-field operation, the switching frequency varies from 45 Hz at 1000 A to 114 Hz at 100 A. Therefore, either constant operation of the pulse converter with a frequency of at least 114 Hz is possible, or the switching frequency can vary depending on the current.

The research results show that the switching frequency when working with a weakened field depends on such parameters as: excitation current, armature current and saturation of the magnetic system. When the pulse converter operates at a constant frequency, the switching frequency must be at least 290 Hz for the entire armature current range. At the same time, excitation current pulsations will be close to 10%, and armature current pulsations will be much smaller than 10%.

Thus, the results obtained can be used to create traction systems for diesel locomotives with pulse controllers to power and control DC traction motors.

Conclusions. The paper considers the use of switching regulators for power supply and control of DC traction motors during the modernisation of shunting locomotives. An algorithm for calculating the switching frequency for the selected switching regulator scheme is presented and the necessity of considering the effect of magnetic system saturation on winding inductances is shown. The switching frequency is calculated on the condition of ensuring the current ripple coefficient. It was determined that in the full field mode, the switching frequency should not be lower than 114 Hz. In the weakened field mode, the switching frequency must be higher than 290 Hz.

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Визначення частоти комутації транзисторного перетворювача для тягового колекторного електродвигуна локомотива

Метою даної роботи є визначення частоти комутації транзисторного перетворювача для тягового колекторного двигуна локомотива за критерієм допустимої пульсації струму. Поставлена мета досягається завдяки розв'язанню такого завдання: запропоновано методику визначення врахування зміни параметрів електродвигуна під час розрахунку частоти комутації транзисторного перетворювача. Особливістю пропонованого підходу є врахування ступеня насичення магнітної системи, оскільки наявні методи розрахунку частоти перемикання або не враховують ступінь насичення магнітної системи, або оцінюють її вплив у спрощеній формі. Найсуттєвішим результатом є підвищення точності розрахунку частоти комутації за рахунок врахування зміни індуктивності обмоток колекторного електродвигуна при зміні ступеня насичення магнітної системи. Виконано розрахунок частоти комутації для тягового двигуна постійного струму з транзисторним перетворювачем. Розглянуто два основні режими роботи електродвигуна: з повним магнітним потоком і з ослабленим магнітним потоком. У результаті розрахунків встановлено, що залежність частоти перемикання від струмів має нелінійний характер. Визначено, що для режиму роботи електродвигуна з ослабленим магнітним потоком частоту перемикання слід визначати з урахуванням процесів як у колах обмотки збудження, *так і в обмотках якірного кола. Найважливішими результатами є визначення частоти перемикання імпульсного перетворювача для живлення і регулювання тягового двигуна в усіх режимах роботи. Запропонована методика дає змогу зробити вибір транзисторних ключів для перетворювача за частотою перемикань.*

Ключові слова*: енергоефективність, рухомий склад, тяговий електродвигун, тягова система, напівпровідниковий перетворювач, частота комутації.*