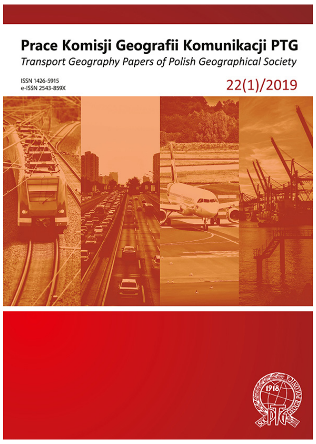

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INCREASING ENERGY PERFORMANCE OF URBAN ELECTRIC TRANSPORT

Wzrost wydajności energetycznej miejskiego transportu elektrycznego

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Abstract: In the 21st century new approaches to urban electric transport improvement are required. As a tram is one of the best means of passenger transportation it is essential to enhance its operation. So the aim of this article is to consider improving the energy performance of the electric traction drive of urban electric transport by improving its electrical equipment. The analysis of traction systems of electric trams which are in operation in the cities of Ukraine is carried out, their disadvantages are displayed. A new structure and control algorithms for the electric traction drive system with pulse converters of tram cars are proposed. The structure makes it possible to reduce the number of semiconductor devices in pulse converters and improve the energy performance of the electric traction drive.It allows to reverse tram trajectory without using contact equipment,to provide a smooth field weakening of traction motors, limit the voltage of the traction motors at the nominal level, provide redundancy of the equipment in pulse converters, as well as ensure electric braking. A modernized field attenuation circuit using a DC/DC converter for traction electric motors of sequential excitation is suggested. The results of research are given. The comparative characteristics of various traction drive systems in terms of energy indicators are provided.

Key words: converter, energy performance, electric traction drive, excitation

1. Introduction

City electric transport has an undeniable advantage in comparison with other types of transport as it is ecologically friendly and does not pollute the environment. Nowadays electric transport operates in more than 50 cities of Ukraine and carries over 60% of passengers. Due to the constant increase of the energy resources cost, the reduction of energy consumption is among the main technical requirements for the rolling stock of urban electric transport. A considerable part of the operated rolling stock does not meet the modern requirements. Therefore, the issues of improving the energy indicators of the electric traction of urban electric transport by development of the electrical equipment are topical.

2. Literature review

Issues of reforming urban electric transport are defined by the state program of its development (Kramarenko, 2008). There are two possible ways to solve them. The first one is the use of DC pulse converters on a modern element base with a microprocessor control system for traction motors, the second one is the use of autonomous voltage inverters with traction asynchronous motors and a microprocessor control system. In Ukraine in urban electric transport the use of pulse converters has become more widespread. This happens due to the fact that the tram cars T3M with pulse converters have already been operated.

Specific attention was paid to the improvement of traction electric drive systems for urban electric transport which was reflected in a number of works among which the following should be noted. In order to improve the energy performance of traction electric systems of tram cars, it was proposed to introduce pulse converters of domestic production instead of electromechanical controllers with starting rheostats (Zabarskij, 1976; Shipka, 2007; Daleka, 2009). The traction engine control system of the modernized tram Tatra-3E was considered in the scientific work of V. K. Krivovyaz et al. (2009) which allows to increase significantly its electromechanical characteristics and solve the problem of critical wear of the city electric transport fleet. The use of different concepts of traction drives in the Czech Republic and in the world is discussed and evaluated, the advantages and disadvantages of the new concept and the possibility of using systems with obsolete types are evaluated in the scientific work of L. Veg et al. (2017).

The possibilities for reducing electricity consumption in electric systems of urban public transport using the audit of their electrical system are identified in the work of I. Felea et al. (2013). To justify the importance of these problems, a mathematical model of the electrical energy balance of urban public transport system and its components is presented. The improvement of the energy performance of traction electric systems of tram cars in some cities of Ukraine is shown up to 35% due to the introduction of electrical equipment such as "TV Progress" based on a pulse converter of company ALSTOM (Cherny, Kachimov, 2009).

3. Research methodology

The most common electric traction drive of a tram car in operation is analyzed. The main criterion for evaluating the traction drive is its energy performance. When conducting a comparative analysis it is necessary to account for the following criteria:

- compliance with modern technical requirements;
- ramp up costs;
- operating costs;
- reliability;
- unification of electrical equipment.

4. Description

In the urban rolling stock of Ukraine three types of electric traction drives with DC motors differing in their power supply are mainly used. To the first group belong electric drives with a rheostat-controller power system, for example, trams of the T-3 series, whose production was stopped a long ago (Cherny, Kachimov, 2009). The disadvantages of such electric drives are substantial losses in starting rheostats, which reduces their energy performance to a great extent.

The control system of the electric drive does not meet modern technical requirements, as it contains a large number of contact equipment. This reduces its reliability and requires a lot of operating costs. In addition, such an electric drive has another drawback: the power supply of both groups of traction motors is implemented through the use of a single electromechanical controller, the failure of which makes it impossible for the tram car to move. The rolling stock with such electric drives is still in operation only because there is a shortage of trams in the depot. The urgent modernization of such electric drives is necessary.

In electric drives of the second type, the controller with start-up resistors is replaced with a DC pulse converter, in which the DC voltage of the network is converted into a pulse, which allows you to adjust the current smoothly and, accordingly, the torque of the traction motors. The use of a pulse converter considerably increased the efficiency of the drive.

Electric drives of the second type are used in tram cars T3Mof Czech production.

To their disadvantages it is necessary to refer the presence of contact equipment, which reduces the reliability of the circuit, the series connection of several power devices, which worsen the energy performance of the electric drive system, stepwise weakening of the traction motors field, outdated element base and the lack of redundancy in impulse converters.

In electric drives of the third type imported electrical equipment of the "TV Progress" type of the company ALSTOM (Cherny, Kachimov, 2009) is used. Some T3 trams are equipped with such electrical equipment. Structurally the power circuit of the electric drive consists of two groups of traction electric motors M1, M2 and M3, M4 which are connected to two individual containers SDS100 with pulse DC converters (Fig. 1). Each SDS100 container has a traction converter, a backup converter, a backup brake resistance, current and voltage sensors, inlet filter, and an induction motor/fan.

For a group of electric motors of one trolley, the only container SDS100 is intended. The main technical parameters of the traction power electrical equipment of the SDS100 container are given in table 1.

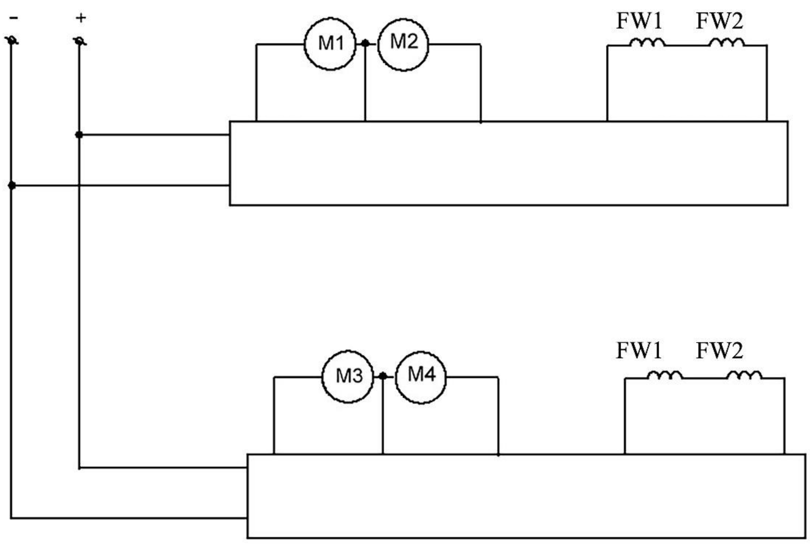

Fig. 1. The power circuit of the tram car T3 with electrical equipment "TV Progress".

Source: own elaboration.

Tab. 1. The main technical parameters of the container SDS100.

	Parameter	**Parameter value**
1.	Rated supply voltage, V	600 (750)
2.	Input voltage range, V	0 – 900
3.	Input voltage range in operating mode, V	400 – 900
4.	Maximum starting current, A	300
5.	Starting current range, A	60 – 300
6.	Hour current, A	200
7.	Braking maximum current, A	250
8.	Braking current range, A	50 – 250
9.	Operating frequency converter, Hz	500 – 2000
10.	The voltage that can be provided on the armatures of traction motors in the electric braking mode, V	1000
11.	Voltage that is limited at the armature of the traction motors in the mode of energy recovery in the network, V	750 – 820

Source: own elaboration.

Traction converter provides a given direction of movement of the tram car and a given amount of electric motors current, and also provides smooth control of the magnitude of the excitation current of electric motors up to the minimum possible field weakening. The standby converter provides limiting the supply voltage of the traction converter in the thrust mode and limiting the voltage on the input filter during energy recovery to the network, as well as limiting the short-circuit current when powered from the network.

Control of the modes of thrust and braking is provided by the electronic controller RDC100, which provides autonomous control of electric motors of one bogie. The regulator is equipped with a diagnostic system that provides a simplified indication and allows identification of electrical equipment failures in both low-current and power circuits. A simplified diagram of the traction and standbypulse converters is shown in figure below (Fig. 2).

This technical solution has several advantages in comparison with the previous ones, since most of their disadvantages have been eliminated and it allows unifying electrical equipment. At the same time, a large number of series-connected power semi conductor devices operating constantly in each group of electric motors in a traction mode, significantly reduces the energy performance and reliability of the traction drive system. In addition, significant financial expenses are required for the purchase of such equipment. Therefore, a new power curcuit of anelectric traction drive with an improved structure (Fig. 3) has been developed and it is proposed for the modernization of tram cars T3 (Koryagina, Koskin, 1982).

The innovation of such a curcuit is that a new structure of the control system for traction electric motors with sequential excitation and control algorithms are proposed. A pulse converter provides control of the current value of the traction motors at a given level, reverse of the tramway movement direction without the use of contact equipment, the smooth field weakening of the traction motors, voltage limitation of this vehicle, electric resistance braking of it as well as standby equipment to ensure electric drive operation in case of the main one failure. This uses a much smaller number of semiconductor elements than in the equipment of "TV Progress".

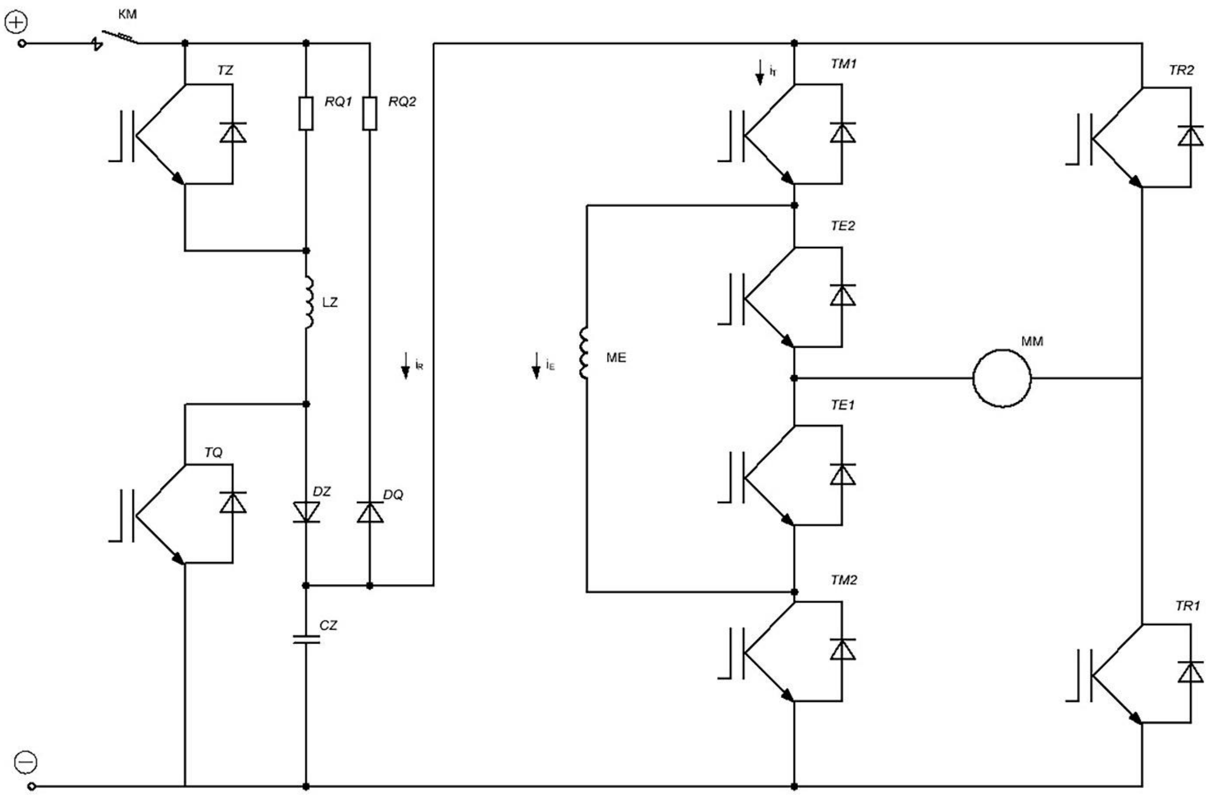

Fig. 2. Simplified diagram of the traction and standby pulse converters.

Source: own elaboration.

To ensure the reverse of the tram movement direction without the use of contact equipment, pulse converters are made according to the scheme of a single-phase transistor bridge with reverse diodes.

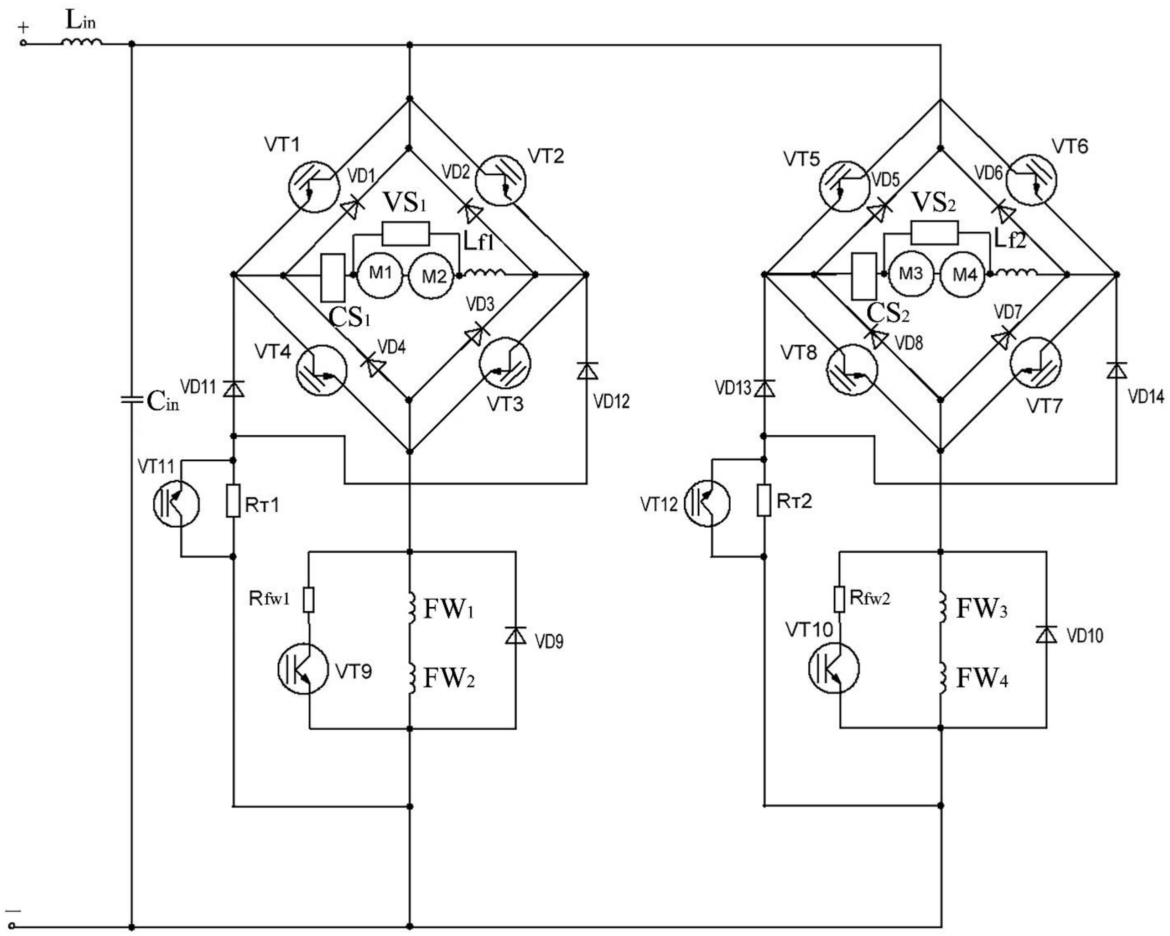

Fig. 3. The power circuit of the traction motor with an improved structure.

Source: own elaboration.

The diagonal of each bridge includes two anchors of electric motors connected in series with an individual current sensor and the armatures of electric motors are bridged by voltage sensors. In the thrust mode, two transistors operate in pairs, for example, the transistors VT2 and VT6 function as switches, and the transistors VT4 and VT8 operate in the pulse-width modulation mode ensuring the flow of a given current value through the windings of the electric motors to their natural characteristic. To weaken the field of the electric motors the pulse-width modulation mode transistors VT9 and VT10 are used. If the main voltage exceeds the nominal value then transistors VT4 and VT8 in the pulse-width modulation mode continue to operate and it limits the average voltage at the armature of the electric motors at the nominal level, and transistors VT9 and VT10 begin to function in the pulse-width modulation mode. The electric braking mode is provided by transistors VT11 and VT12, which operate in pulse-width modulation mode, as well as by transistors VT3 and VT7, which function as keys. In case of failure of the transistor VT4 or VT8, for example, the transistor VT2 or VT6 automatically switches to the pulse-width modulation mode to regulate the magnitude of the current of the traction motors with a corresponding failure signal.

The proposed traction drive system has better energy performance than the electrical equipment "TV Progress" of the company ALSTOM. Figure 4 shows the power loss in the pulse converter by calculation in the starting mode while using different traction drive systems.

Saving electricity when using the improved traction drive system of a tram car for a shift is the following:

$$A_l = (\Delta P_{l1} - \Delta P_{l2})t \tag{1}$$

where: ΔP_{l1} is the power losses in the pulse converters in the starting mode when using electrical equipment such as "TV Progress" of the company ALSTOM; ΔP_{l2} is the power loss in the pulse converters in the starting mode when using an improved traction drive system; *t* is the time of the pulse converter operation in the starting mode per shift. Energy savings when using an improved traction drive system

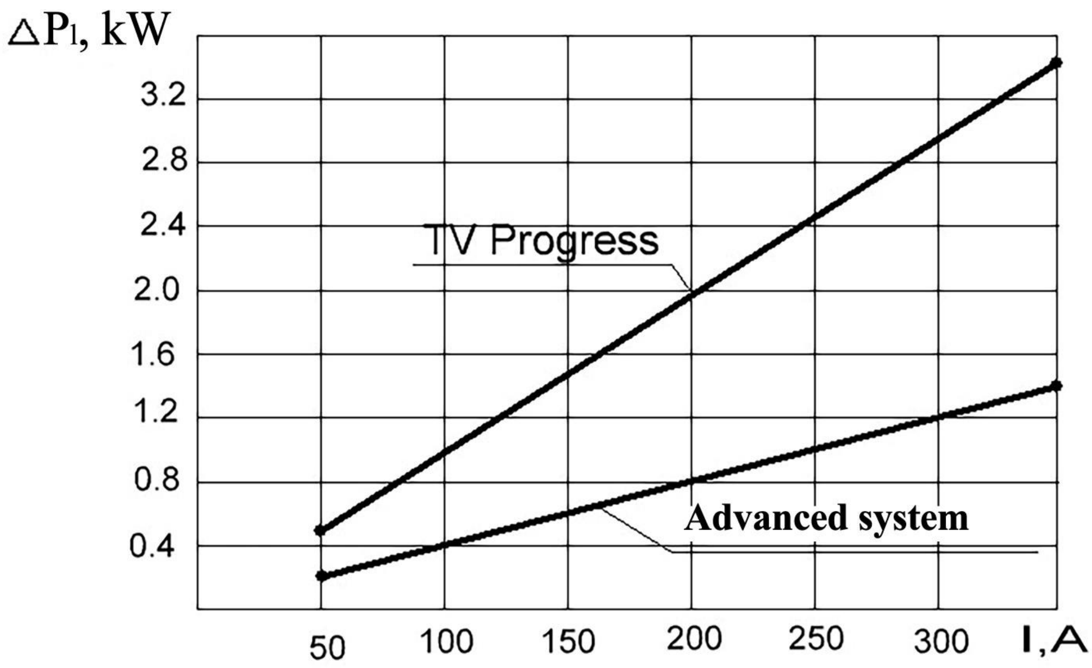

Fig. 4. Power losses in the pulse converter in the starting mode when using different systems of the traction electric drive.

Source: own elaboration.

for electric rolling stock of two cars per year is equal to:

$$A\Sigma = A_l nm \quad (2)$$

where: n is the number of pulse converters of the electric rolling stock; m is the number of working days per year. If we assume that t=10 hours, n=4, m=350 days, then the energy savings when using the improved system will be 16,800 kWh.

Further improvement of the energy performance of thetraction electric tram drive is possible by improving system of the field weakeningof traction motors. A new method of the field weakening of traction motors using high-frequency DC/DC converters (Besarab et al., 2015; Andrijczenko et.al., 2012) is proposed. This method using a DC/DC converter is illustrated by a simplified circuit shown in Figure 5.

The principle of the circuit is that with the help of an input circuit of a DC/DC converter a series excita-

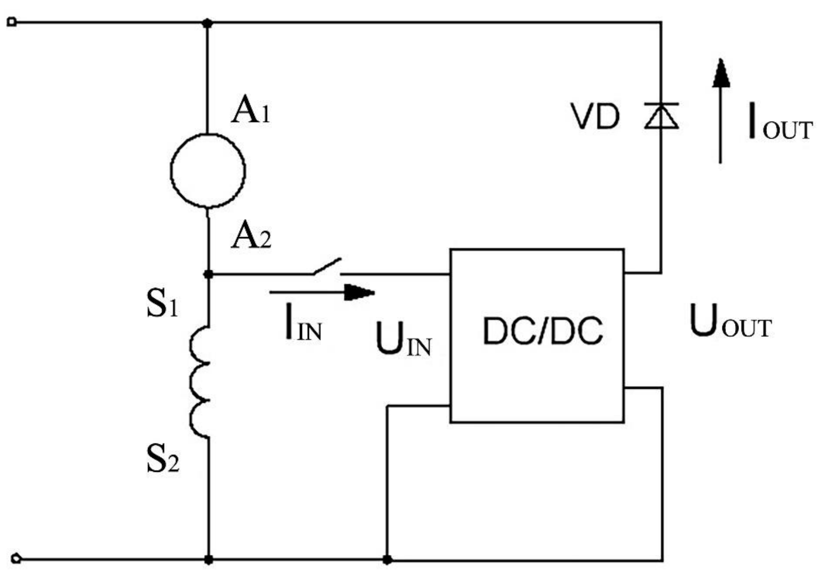

Fig. 5. Simplified electrical circuit of the field weakening of electric motors.

Source: own elaboration.

tion winding is performed. The output of the converter is connected in parallel with the main network through an isolating diode. Saving energy while using the proposed device is achieved because the DC/DC converter transforms the energy that was used in serial circuits to heat the resistors and sends it to power the electric motors. Smoothness and degree of field attenuation is achieved by changing the factor of the converter filling. Let's determine the ratio between the parameters of the proposed circuit and the traction motor excitation control factor. According to (Besarab et al., 2005) for the up converter the following is true:

$$U_{OUT} = \frac{U_{IN}}{(1-\gamma)} \quad (3)$$

where: U_{OUT} is the output voltage of DC/DC converter which is equal to the voltage of the contact network; U_{IN} is the input voltage of the converter, which corresponds to the voltage drop on the winding of the series excitation of the traction motor; γ is the factor of filling DC/DC converter.

In accordance with the law of energy conservation, you can write the following:

$$I_{IN}U_{IN} = I_{OUT}U_{OUT}K_{DC} \quad (4)$$

where: I_{IN}, I_{OUT} are the input and output current of the DC/DC converter; K_{DC} is the efficiency factor of the converter. According to (4) we have the following:

$$I_{IN}U_{IN} = I_{OUT}\frac{U_{IN}}{1-\gamma}K_{DC}. \quad (5)$$

In accordance with the circuit of the device shown in Figure 5, the output current of the DC/DC converter is:

$$I_{OUT} = \frac{(1-\gamma)}{K_{DC}}I_{IN}. \quad (6)$$

In expression (6), you can replace the input current I_{IN} of the DC/DC converter with the expression: $(I_A - I_S)$:

$$I_{OUT} = (I_A - I_S)\frac{(1-\gamma)}{K_{DC}} \quad (7)$$

where: I_A and I_S are the current of the armature winding and the excitation winding of the traction motor.

Dividing the expression (7) on the armature current of the traction motor, we can get:

$$\frac{I_S}{I_A}(1-\gamma) = (1-\gamma) - \frac{I_{OUT}K_{DC}}{I_A}. \quad (8)$$

As the ratio of the currents of the excitation winding and the anchor winding of the traction motor is equal to the traction motor excitation control factor:

$$\frac{I_S}{I_A} = \alpha \quad (9)$$

Therefore we can get:

$$\alpha = \frac{(1-\gamma) - \frac{I_{OUT}}{I_A}K_{DC}}{1-\gamma}. \quad (10)$$

Based on the fact that the ratio of the output current of the DC/DC converter to the current of the armature winding of the traction motor is equal to the load factor of the DC/DC converter. K we finally get the expressionfor the traction motor excitation control factor:

$$\alpha = \frac{(1-\gamma) - K \cdot K_{DC}}{1-\gamma}. \quad (11)$$

According to the expression (11), the dependences of changing α on γ at various values of K and K_{DC} = 0.9. These dependencies are demonstrated in Figure 6. According to the characteristics shown in Figure 6 we can see that they are non-linear. The decrease of the load factor of the DC/DC converter *K* causes the increase of non linearity. Taking into account the fact that in practice the traction motor excitation control factor α is not implemented below 0.3, the working area for the traction motor in field weakening mode can be determined. Using the proposed method the working area for the traction motor in the field weakening mode is limited by K = 0.1, α = 0.3 and $K = 0.5$.

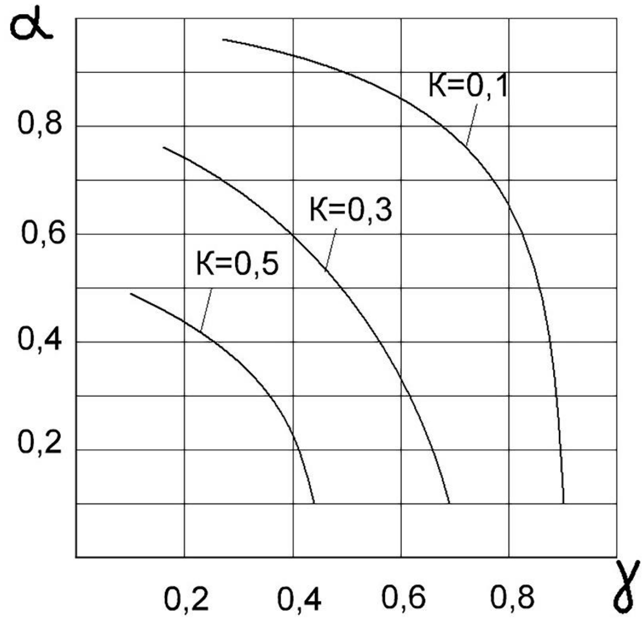

Fig. 6. Dependence ofthe traction motor excitation control factor α on the factor of filling DC/DC converter γ.

Source: own elaboration.

5. Conclusions

The analysis of electric traction drive of tram cars which are operated in the cities of Ukraine has been carried out. Their advantages and disadvantages have been shown. The following criteria such as energy performance, compliance with modern technical requirements, costs for modernization, operating costs, reliability, unification of electrical equipment were chosen. A new power circuit of a traction electric drive with an improved structure has been proposed.

The innovation of such a circuit is that a new structure of the control system for traction electric motors of sequential excitation and control algorithms have been proposed. A pulse converter provides control of the current value of the traction motors at a given level, reverse of the tramway movement direction without the use of contact equipment, the smooth field weakening of the traction motors, voltage limitation of this vehicle, as well as standby equipment to ensure the electric drive operation in case of failure of the main one. A much smaller number of semiconductor elements than in the same equipment of the foreign companies is used. A modernized field attenuation scheme using a DC/DC converter for traction electric motors of sequential excitation has been proposed. The dependences obtained analytically allow for the performance of field weakening when using a DC/DC converter. The proposed technical solutions will improve the energy efficiency of DC electric drives with traction electric motors of sequential excitation and can be used to modernize trams T3.

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