Перехід на новий тип тягового привода, з постійного на змінний струм, в громадському транспорті неможливо виконати миттєво. Це пояснюється наявністю значної кількості парку машин та потрібних на це коштів. В більшость країн Європи та Азії цей процес розтягується на роки.

Тому розвиток парку тролейбусів йде паралельно у двох напрямках. Перший – закупівля нових тролейбусів, тобто оновлення парку сучасними машинами, що мають тяговий двигун змінного струму. Другий – капітальний ремонт і модернізація "застарілих" машин, з метою поліпшення їх експлуатаційних характеристик. Більша частина "застарілих" тролейбусів обладнана тяговими двигунами постійного струму послідовного або змішаного збудження. Істотне енергозбереження та покращення характеристик тягового електропривода з цими двигунами досяжне при використанні системи імпульсного регулювання та шляхом оптимізації алгоритмів керування.

Метою дослідження є підвищення енергоефективності та покращення характеристик тягового електропривода тролейбуса, що має двигун постійного струму змішаного збудження. Це досягається за рахунок удосконалення системи керування цим приводом на основі системи імпульсного керування за допомогою DC-DC.

Працездатність тягового електроприводу було перевірено шляхом імітаційного та фізичного моделювання. Також було удосконалено математичну модель двигуна постійного струму із змішаним збудженням. Особливістю цієї моделі є врахування насичення елементів магнітопроводу тягового двигуна на базі проведених заздалегідь розрахунків магнітного поля методом скінчених елементів. Об'єднавши ці складові, отримано удосконалену математичну модель всього тягового електропривода тролейбуса.

Проведено імітаційне моделювання роботи тягового електропривода тролейбуса в режимі пуску. Результати його підтвердили підвищення енергоефективності тягового електропривода за рахунок зменшення втрат на збудження. Порівняння довело, що втрати енергії зменшилися з 0,587 МДж (0,163 кВт·год) до 0,531 (0,1475 кВт·год) МДж – на 9,54 %

Ключові слова: тяговий електропривод тролейбуса, двигун змішаного збудження, імпульсний перетворювач, імітаційне моделювання

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SIMULATING THE TRACTION ELECTRIC DRIVE OPERATION OF A TROLLEYBUS EQUIPPED WITH MIXED EXCITATION MOTORS AND A DC-DC CONVERTER

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1. Introduction

Urban electric transport such as subway, tram, trolleybus provides most of the intra-city passenger transportation. At present, in Ukraine, its share is (42–56) % of the total volume of passenger traffic [1]; this proportion will only increase in the future. This is explained by the fact that, given the increasing cost of fuel and the emission of carbon dioxide into the ambient air [2], the world is replacing conventional buses with electric buses (E-bus). The world's leading countries have developed and implemented the concept of urban (municipal) transport. One of the transport elements being given considerable attention is trolleybus [3]. However, in different countries, the trolleybus systems operate on different schemes [4]. It is, therefore, more useful for European scientists to study the experience of countries such as Poland or Latvia. The implementation of the principle of mobility, while implementing the concept of the development of trolleybuses in Gdynia, is described in work [5].

Currently, in the time of quarantine through the coronavirus, when many countries terminated, or considerably limited, the operation of subway, the main load is being transferred to trams and trolleybuses. This leads to the increased intensity of their operation and wear.

According to analytical data from [6], as of 2019, the trolleybus fleet of Ukraine consisted of about 2,900 cars. And only less than 80 % of trolleybuses were in proper condition.

Such a significant number of faulty machines is explained by the fact that the average service life of trolleybuses in Ukraine is 17.14 years [6]. Analytical data indicate that up to 24 % of the trolleybus fleet is made up of outdated machines of the ZiU-682 model (ZiU-9 made in the USSR). A similar situation was abroad 15–20 years ago, the average age of trolleybuses was 15–22 years.

A part of the existing trolleybus fleet in the cities of Ukraine, Russia, Argentina, Mongolia, and other countries, is equipped with a direct current traction motor (DCM) of consistent or mixed (combined) excitation [8, 9]. Modern trolleybuses are equipped with an alternating current traction electric drive. The induction motor with a cage rotor is mainly used as a traction engine. It is known that the replacement of direct current traction motors with induction traction motors improves the reliability of rolling stock, reduces energy and servicing costs [10, 11].

The situation is aggravated by the lack of funds in city budgets as the cost of a new "single" trolleybus made in Ukraine is about UAH 5–6 million (EUR 190–200 thousand) [12]. Therefore, cities buy foreign trolleybuses, which had already been in operation. Thus, in 2019, the city of Zaporizhzhia purchased two joint trolleybuses "Van Hool AG300T" at the price of just over UAH 2 million (EUR 70 thousand) [12]. The price of a similar new trolleybus produced by BOGDAN (Ukraine) makes about UAH 11 million (EUR 380 thousand). That is, the price of a foreign joint trolleybus that was already in use is 5.5 times less than that of the similar trolleybus made in Ukraine and is 2–3 times less than the price of a new "single" trolleybus.

Being aware of this issue, the Government of Ukraine developed a program to update urban electric transport – "The urban public transport", financed by credit funds from the European Investment Bank and the European Bank for Reconstruction and Development. The total amount of financing is EUR 400 million [13]. Below are the results of the analysis of this program for two years of its actual implementation.

In 2018, 167 trolleybuses were purchased in the cities of Ukraine [12], including 107 cars from Ukrainian producers. Of the total number of purchased vehicles, 13 trolleybuses had already been in operation. In 2019, 196 trolleybuses were purchased, including 144 cars from Ukrainian manufacturers and 23 foreign cars that had already been in operation [12].

However, the funds are not always allocated in the specified time while shipments are not carried out instantly; moreover, bidding tenders are often canceled because of the complexity of bureaucratic procedures [13]. That is why deliveries of new cars may be canceled or postponed for the following year.

A significant renewal of the trolleybus fleet began in 2018 only; before that time, the supply of new cars was limited. Most cars in the trolleybus fleet of Ukraine are already morally and physically obsolete. The issue of the outdated fleet of trolleybuses prevents the provision of regular and reliable transportation of city dwellers. The existing number of trolleybuses is too small, they often fail, and operate under overloads. The purchasing of foreign trolleybuses, which had already been in operation, by cities does not solve the problem. This situation is supplemented with the presence of trolleybuses with the drive of both direct and alternating current, which requires the increase of repair base and specialists.

There is no doubt that the renovation of the trolleybus fleet by purchasing new trolleybuses with an alternating current traction drive is the main and relevant task for ensuring the efficient operation of city electric transport [14, 15].

The lack of own funds at communal transport enterprises, a difficult economic situation, and the presence of a significant fleet of outdated trolleybus models in this country make it impossible to quickly solve this urgent task. Experts believe that while maintaining the pace of renewal of the trolleybus fleet at the level of 2019 (6.8 %), the renovation of the entire trolleybus fleet in Ukraine will take 14.7 years [12]. We consider that this is a rather optimistic forecast; the renewal may last for 20–25 years.

Management of municipal enterprises understands the current situation. Therefore, the development of the fleet of trolleybuses and the provision of efficient operation of electric transport proceed in parallel in two directions – the purchase of new trolleybuses and major repairs and modernization of the existing fleet of machines, in order to improve their operational characteristics [15, 16].

A second direction was chosen for this research as it would make it possible, at minimum cost, to improve the efficiency of operation of the existing fleet of trolleybuses and to reduce electricity consumption [17]. Now, the issue of energy savings in public transport has become a priority, both because of the higher prices for fuel and electricity [18] and environmental issues [19].

2. Literature review and problem statement

It is known that the efficiency of a traction motor is 92 % while the total efficiency of the entire traction complex is up to 60 % [20]. It is clear that reducing the losses of the entire complex despite the type of electric drive is a relevant task, which is addressed both by the domestic and foreign scientists. One of the main elements of the traction electric drive is electric motor, so selecting its type and power is paid much attention to.

Paper [21] compares the properties of three types of traction engines, such as induction motor, the synchronous engine with permanent magnets, and Switch Reluctance Motor (SRM). Work [22] compared the DCM, the induction motor, and three variants of synchronous motors. The most complete research is reported in paper [23], where the above motors are supplemented with engines with an axial magnetic flux. The issue of determining the optimum power of a traction motor for a trolleybus drive is investigated in works [24, 25]. Despite the reasoned belief that the traction induction motor dominates and outperforms the traction

DCM, researchers are still not sure of that. Thus, paper [26], published in 2015, reported the physical testing and comparison of the traction DCM with an induction motor. Based on the results, the authors note that the DCM demonstrated better characteristics and torque indicators but had a complicated structure and burdensome service.

Article [27] considers the structure of losses in a trolleybus, starting from power buses and finishing with loading.

The global trend of improvement is the use of hybrid systems and energy accumulators in electric transport. For trolleybuses, this tendency is related to the demand to ensure autonomous motion.

Paper [28] considers the possibility of saving the recuperative decelerating energy in the "Škoda 24Tr" trolleybus by installing an onboard energy storage system based on a supercapacitor. Work [29] reports the results from annual testing of the "Škoda 26Tr Solaris" trolleybus, which is equipped with a lithium-titanate rechargeable energy accumulator. The use of energy accumulators is typical not only for an alternating current drive. Thus, study [30] considers increasing the efficiency of direct current electric drive by applying supercapacitor energy drives. Different types of electric energy accumulators are compared in work [31].

Another direction of research is to improve the operational reliability of the traction motors of rolling stock of electric transport. This is the issue investigated in [32]. A given direction is relevant because the older a trolleybus the more often it breaks.

Substantial power saving and improvement of the characteristics of the traction electric drive with DCM is achievable when using pulse adjustment of power voltage and by optimizing their control algorithms [33, 34].

The issue of energy-saving control over the DC engine relates to the fact that trolleybuses earlier used a rheostat-contactor control system of the traction motor [35]. The defects of this system are known: a stepwise control of the rotation frequency, significant losses of energy in the rheostats, and the system's bulkiness. This system was eventually replaced with a thyristor-pulse system, and, with the advent of IGBT transistors, a transistor-pulse one. The pulse control system ensures the smooth adjustment of the rotation frequency and no current surges. The pulse adjustment of power voltage proved positive in electric transport when adjusting the speed from zero to rated (the so-called full field mode). But most of the time, during acceleration, electric rolling stock operates under the regime of a weakened magnetic field, that is, when adjusting the magnetic flux of the traction electric motor [36].

A traditional technical solution for field weakening is the stepwise current adjustment of a consistent winding of the excitation of a traction motor by active resistance leading to energy loss. It is possible to reduce energy losses by using, to implement the weakening mode, the high frequency converters [37].

Thus, it is a relevant task to improve the system of weakening a field of the direct current traction motor with mixed excitation using semiconductor converters.

The issue of reducing energy losses while controlling a DCM of sequential excitation, which were widely used as traction motors, was emphasized in the 1990s. Thus, to improve the economy of the use of the engine of sequential excitation, [38] proposed to execute the supply to an armature winding and the winding of excitation along two separate channels. In fact, that idea is a key element for further research towards increased energy efficiency of the DC engine control, both of sequential and mixed excitation. Research and improvement of these two types of DCM were performed in parallel. Advancements proceeded in several directions; first, the improvement of pulse circuits to control the frequency of rotation. The aim was to reduce the amount of contact equipment and energy losses under the modes such as start, braking, and running. Paper [33] suggested an improved scheme of the pulse speed control; the authors compared it with the classical one. The authors indicate the following advantages: the proposed scheme enables both braking techniques (dynamic and recuperative) without additional power sources. In work [39], the same authors investigated electromagnetic processes in the proposed scheme of pulse control under the mode of recuperative and rheostatic braking.

However, the presence of only the pulse control circuit without a control algorithm limits the effectiveness of its operation. The utilization of all possibilities of pulse control requires that a mathematical model should include a control system, a traction motor, and a load, which is determined by the trolleybus movement modes along the path sections. Work [34] suggested a mathematical model of the traction electric drive with pulse-width control to study a start-up mode. The generalized mathematical model is also used in a simulation model of the electric drive [33]. The use of such models leads to significant errors in electromagnetic calculations and when determining an electromagnetic moment [40]. In fact, most studies that employ simulations lay the basis of the mathematical model in the form of so-called generalized "weber-ampere" characteristic, that is, the dependence of the magnetic flux on the excitation current.

The authors of paper [41], in which a DCM of sequential excitation is modeled, agree with the shortcomings of the generalized "weber-ampere" characteristic propose its improvement, introducing the coefficient of a magnetic field weakening. However, in reality, it is also a simplification of a mathematical model. Other authors also deal with the improvement of a "weber-ampere" characteristic [42].

A breakthrough solution is proposed in [40], whose authors also demonstrate the drawbacks of using this characteristic and suggest determining it by using a finite element method in the software ELCUT. The dependences obtained are approximated by hyperbolic arcsine in the Mathcad package and are used in a classical mathematical model. A simulation model was created for the DCM of mixed excitation, the type of DK-201A-3, which is the traction engine of a trolleybus. This is a rather significant step in improving the drive control; however, only the model of a separate engine is considered in the cited work, without a drive.

The next step in the development of pulse control systems was the application of a DC-DC converter in the control circuit to enable a field weakening mode. That is, instead of shunt resistance, a DC-DC converter was connected. The magnetic field was weakened not by reducing the current due to the connection of additional resistance but via control. As a result, the energy was no longer scattered "for nothing" at the additional resistance and was used. Paper [43] gives a theoretical justification for this solution; the solution itself was patented as a method [44]. Subsequently, the authors improved the proposed technique for adjusting DCM excitation and analyzed various circuit solutions [45]. Article [46] suggested an algorithm to control a DC-DC converter; work [47] represented a mathematical model of the traction electric drive with a DC-DC converter. However, the mathematical model of the DCM has drawbacks. A load on DCM is taken into consideration using the characteristics of magnetization in the form of a functional dependence. Further, study [48] reported the simulation and physical modeling of the traction electric drive with a DCM of sequential excitation. The simulation results showed that the proposed control scheme was feasible and could be used for electric transport.

A similar path was chosen in [49], whose authors described in detail the use of a DC-DC converter in the rotation frequency control system. They modeled the traction DCM in the Simulink software but used the standard modules of DCM available in the software library. Paper [50] examined different types of DC-DC converters, their advantages and disadvantages. The further impetus for the development of DC-DC converters was provided by using them in the traction drive of alternating current to ensure the connection to an energy accumulator. Study [51] analyzed the application of a DC-DC converter in public transport; work [52] explores the factors that limit the use of energy drives in a trolleybus. In fact, the DC-DC converter is used to work with the energy drive for both induction motors and DCM [53].

In work [54], in addition to a DC-DC converter, it was suggested using a PI-controller, which eliminates a delay in the supply of voltage and enables rapid control. To control DCM, paper [55] proposed using a microcontroller. This is understandable as it is quite difficult and costly to construct a mathematical model for each engine. Scientists in [54, 55] chose the way of saturating a control scheme of electronic components, which eliminates delays in control signal delivery and simplifies the operation of a drive. That can be considered another area of the research field.

Given the shortcomings of the mathematical model of a DCM that employs the generalized characteristic of magnetization, the authors decided to improve the existing model. Similarly to work [40], it was decided to derive the characteristic of magnetization by numerical-field methods. That was accomplished in work [56], which reported a universal technique for determining the magnetic characteristics of the traction engine of mixed excitation and obtained the dependences of magnetic flux on current coefficients. In contrast to work [40], to build an uninterrupted mathematical model of the DCM traction characteristics, a regression analysis was performed using Chebyshev polynomials on a set of equidistant points. Paper [57] built on the study to derive the dependences of the electromagnetic moment of the engine on excitation currents. That is, the main disadvantages of the mathematical model of a traction DCM were eliminated. And now it has become possible to perform imitation modeling of the entire electric drive taking into consideration the improved mathematical model of the traction DCM.

To determine the energy characteristics of trolleybus traction drives based on the time diagrams of a start-up mode, it is necessary to improve the mathematical model of a traction electric drive and to simulate its operation.

3. The aim and objectives of the study

The aim of this study is to determine the energy characteristics of a trolleybus traction drive, equipped with a mixed-excitation DCM and a DC-DC transducer, by using the time diagrams of electromechanical processes through simulation.

To achieve the set aim, the following tasks have been solved:

– to build a generalized simulation model of the traction electric drive of a trolleybus, for determining the time diagrams of electromechanical processes;

– to determine, based on the results from simulating the start modes of the traction drive of a trolleybus, its energy indicators.

4. Generalized simulation model of the traction drive with a DC-DC converter

We used the software package MATLAB (SimPowerSystems) in simulation [58].

To construct the simulation model, we shall build a general circuit consisting of separate unit solutions. The generalized simulation model of the drive is shown in Fig. 1.

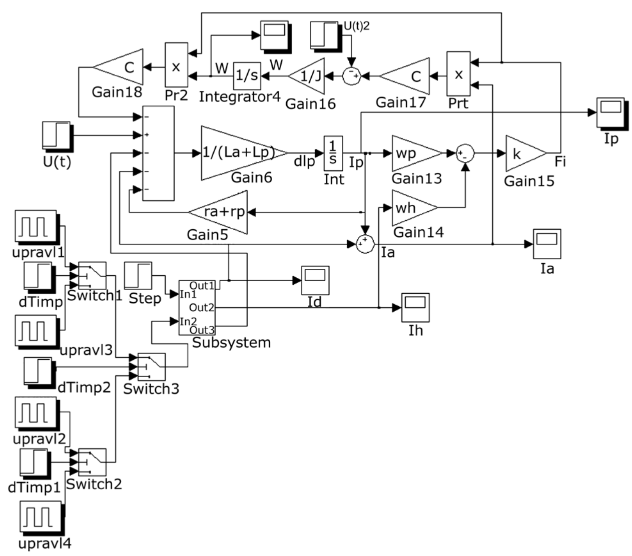

Fig. 1. General principal diagram of the simulation model of field weakening using a DC-DC converter

Units "I_p", "I_h", "I_a" in the diagram reflect changes in the corresponding currents over time. The "*W*" unit similarly reflects a change in the engine rotation speed. The "*upravl1-upravl4*" and "*dTimp1-dTimp4*" elements are designed to set the frequency of operation and the duty cycle of a clock generator, which controls a power key of the pulse converter. The "*U(t)*" unit sets the electric motor power voltage. The "*Subsystem*" unit is a subsystem shown in Fig. 2. The subsystem simulates the work of a pulse converter contour with a storage capacity.

The tractive engine parameters, defined in [37], are introduced, depending on the currents "I_p", "I_h", "I_a", to the "*Gain6*", "*Gain15*" and "*Gain17*" units. Such an approach makes it possible to improve the DCM simulation model taking into consideration the saturation of a magnetic system's elements depending on the drive's operating mode.

In Fig. 2: I_d – input current of the DC-DC converter; I_h – output current of the DC-DC converter; I_a – motor armature current; W – motor rotation frequency (in rad/s).

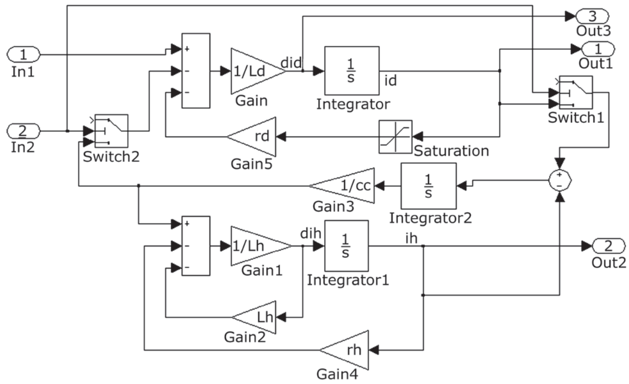

Fig. 2. A subsystem of the general simulation model with a DC-DC converter

The units to set the duty cycle of controlling pulses, shown in Fig. 3, determine the operating modes of the traction drive and its elements.

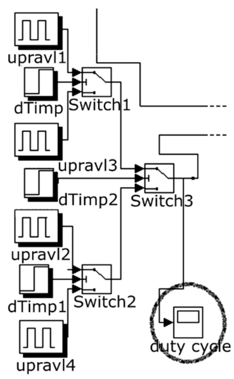

Fig. 3. Units that set the duty cycle of controlling pulses

An additional oscilloscope "duty cycly" is connected to identify the operational mode of a drive. A series of commands in the MATLAB Simulink programming environment is used to start the simulation of the system that weakens a field. The switch operation system is adjusted so that the motor start takes place on a weakened field, the initial duty cycle of the clock generator switch is 10 %.

A possibility to set time delays while enabling a particular duty cycle is provided by the *"dTimp-dTimp2"* units.

The inductance parameters for excitation windings ("L_p", ("L_d") and armature ("L_a") are determined by modeling using numerical-field methods. In the first stage, we modeled a magnetic field of the traction motor by a finite element method at different values of the currents of excitation windings and the armature. Fig. 4 shows the pattern of a magnetic field in the cross-section of the motor ED 193A (made by DP plant "Electrotyazhmash", Ukraine). The results of the magnetic field calculation correspond to the following regime: armature current is 280 A, a sequential excitation winding current is 280 A, an independent excitation winding current is 0 A.

Based on the results of the magnetic field calculations, at the second stage, we determined the discrete dependences of the DCM windings inductances and the electromagnetic moment in line with procedure given in [57].

In the third phase, we performed a regression analysis of the discrete dependences of inductances and a motor torque based on Chebyshev polynomials on a set of equidistant points [57]. The non-interrupt dependences of inductances and electromagnetic moment are determined. The inductance of the motor's armature takes the following form:

$$L_a = \sum_{i=0}^{I_{fa}} \sum_{j=0}^{J_{fa}} \sum_{k=0}^{K_{fa}} \begin{pmatrix} \phi_{aijk} \cdot (M_a \cdot I_a + Z_a)^i \times \\ \times (M_{v1} \cdot I_d + Z_{v1})^j \times \\ \times (M_{v2} \cdot I_h + Z_{v2})^k \end{pmatrix}, \qquad (1)$$

where φ_{aijk} is the regression coefficient of the polynomial, which approximates the inductance; M_a, M_{v1}, M_{v2} are the scale coefficients for the coefficients of the currents of an armature and excitations, respectively; Z_a, Z_{v1}, Z_{v2} are the offsets for the coefficients of the currents of an armature and excitations, respectively; I_{fa}, J_{fa}, K_{fa} are the powers of an approximating polynomial for the coefficients of the currents of an armature and excitations, respectively.

The inductances of the excitation windings and the dependences of the moment have a similar structure but they include the corresponding values of scale and shear coefficients.

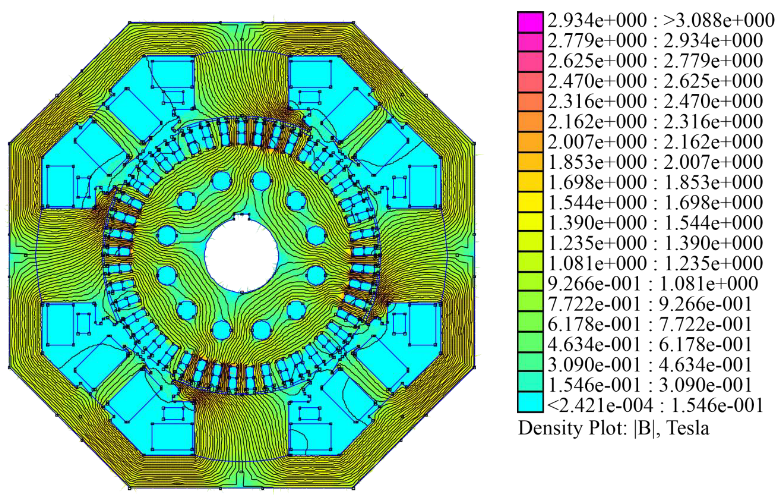

Fig. 4. A magnetic field of the traction motor ED 193A

Thus, Fig. 1–3 show the generalized simulation model of the traction drive whose field is weakened with the help of a DC-DC converter, which can take into consideration the peculiarities of the traction motor and its operating modes.

5. Determining the energy indicators of the traction drive of a trolleybus under a start mode

The diagram of controlling pulses of the DC-DC converter switch is shown in Fig. 5. The duty cycle of the controlling pulses is: 10 %; 50 %; 75 %; 50 %.

Thus, the motor is started in less than half a second. This is evidenced by the surge in the armature current at the beginning of the diagram and the speed curve reaching a more or less constant value (500 rpm) of the motor shaft rotation frequency. It should be noted that the motor was started with the already connected DC-DC converter, but with an insignificant duty cycle of the controlling pulses of the converter switch, 10 %. Next, in second 1, according to the unit schema settings, the pulse width increases to 50 % (Fig. 5). This increases the motor rotation frequency to 650 rpm. The armature current does not change significantly.

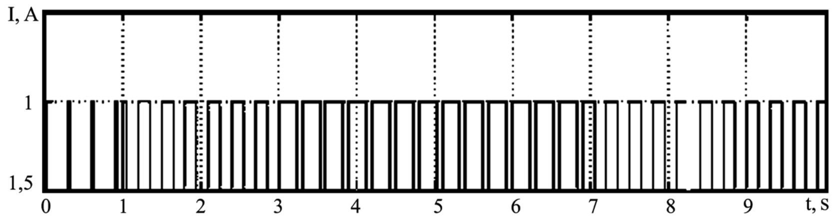

Fig. 5. The time diagram of controlling pulses

However, after setting the value of a duty cycle at the level of 75 %, in second 3 of the simulation, the armature current grows by 1.5 times, and the current of the input to the converter is jumped by more than 3 times. Instead, the current of the DC-DC converter output is significantly reduced. That gives a reason to assume that the converter operates under a sub-optimal mode; not as an energy converter but performs the role of an active consumer, scattering the energy consumed over the radiator of a power transistor and in the windings of the throttle in the form of heat. The motor rotation frequency still increases to almost 1,000 rpm via increasing the armature current and bridging the serial winding. In second 7 of the simulation of the motor operation, the system returns to its previous state.

One should note a positive point: the armature rotation frequency throughout the entire region grows smoothly, despite a stepped switch of the width of the key pulse. The motor armature current I_a can be characterized by a typical behavior for the current of a motor of sequential excitation. When switching the pulse width of the generator. there are some surges in current, which is associated with the likely transient processes in the system of field weakening.

The time diagrams of such a system of field weakening are shown in Fig. 6.

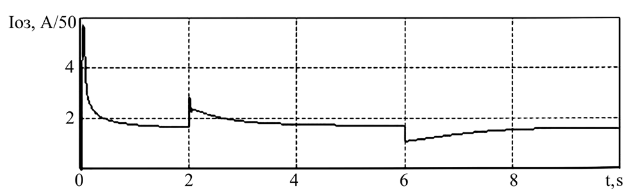

Fig. 6. Time diagrams of the currents of the armature winding in a model of field weakening with a DC-DC converter

The speed diagram of the improved model of field weakening is shown in Fig. 7. For a comparative analysis of the DCM currents and the power consumption by the trolleybus electric drive, we have derived, by using imitation modeling, a current time diagram in the basic system without weakening the armature field with a DC-DC converter, which corresponds to the speed diagram in Fig. 7, which is shown in Fig. 8.

It is determined that the maximum overrun of the excitation current with respect to a stable value is 2.8 times at trolleybus acceleration. When increasing the motion speed, the current overrun is 1.4 times. There is no overshooting of the motion speed.

Based on the results of modeling operation modes, we have determined the feasibility of the proposed scheme for weakening the field of traction motors.

To run a comparative analysis between the operation of a field weakening system and a standard rotation frequency control system, the simulation of the drive operation at launch with a similar load has been performed.

To determine the energy consumption, we integrated, during modeling, the instantaneous power consumed by the traction drive of a trolleybus by multiplying the input voltage ($U(t)$ unit, Fig. 1) by the armature current (Ia unit, Fig. 1). As a result of the traction drive operation, equipped with a system for weakening the field with a DC-DC converter, the power consumption decreased from 0.587 MJ (0.163 kWh) to 0.531 (0.1475 kWh) MJ, by 9.54 %, due to the reduction of losses for excitation.

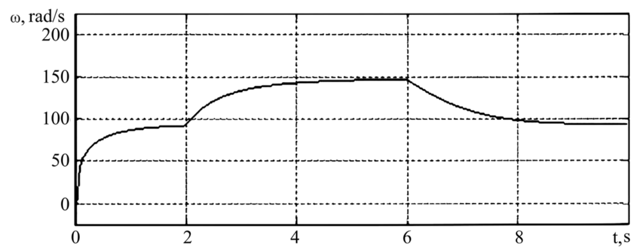

Fig. 7. The speed diagram of field weakening

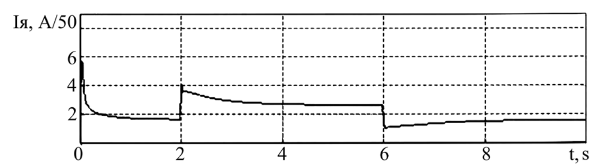

Fig. 8. The time diagrams of the currents of the armature winding in a model without field weakening with a DC-DC converter

6. Discussion of simulation results

The research reported in this article is a continuation of work started in 2010; its phased implementation was described in articles [44–47, 56, 57].

Based on the result of simulating the start mode of a traction drive with weakening the field using a DC-DC converter, we have proven the feasibility of the proposed scheme for weakening the field of traction motors and determined the following:

– the motor was started at the already connected DC-DC (Fig. 6) converter, but with an insignificant duty cycle of the controlling pulses of the converter switch, 10 % (Fig. 8);

– after setting the value of a duty cycle at the level of 75 % (Fig. 5), in second 2 of the simulation, the armature current grows by 1.5 times (Fig. 6), and the current of the converter input is increased by more than 3 times. Instead, the current of the DC-DC converter output is significantly reduced. That gives a reason to assume that the converter operates under a sub-optimal mode, not as an energy converter but performing the role of an active consumer, scattering the energy consumed over the radiator of a power transistor and in the windings of the throttle in the form of heat;

– the motor armature rotation frequency grows smoothly throughout the entire region (Fig. 7), despite the stepped switch of the width of the key pulse (Fig. 5), due to the inertia of the mechanical part of a trolleybus.

The proposed mathematical model could be used to control the traction drive of a trolleybus with a mixed excitation DCM. The developed model, in comparison with the existing one, makes it possible to save energy by converting losses that arose in the starting resistor of the contact-rheostatic control system into electrical energy, which is directed to the armature circle.

The model takes into consideration the saturation of the elements of a DCM magnetic circle under different modes of operation due to the use of the preliminary identified inductances of the windings and the moment on the basis of a magnetic field calculation by the method of finite elements. However, it requires additional calculations for each individual traction motor.

The prospect for the development of trolleybuses drives with DCM is the use of an energy accumulator. The reason for this is the fact that the charge and discharge modes of the accumulators can be adjusted at the expense of DC-DC converters. However, this is the next stage of our research.

7. Conclusions

1. We have improved a simulation model of the traction drive of a trolleybus, equipped with a traction DCM of mixed excitation, by weakening the field using a DC-DC converter. A special feature of the model is taking into consideration the saturation of the elements of a magnetic wire of the traction motor based on the preliminary calculations of a magnetic field by using a finite element method. When simulating the modes of operation of the traction drive, the parameters of the magnetic system of the traction motor (*"Gain6", "Gain15"* and *"Gain17"* units) change depending on the currents in its windings ("I_p", "I_h" and "I_a").

2. We have simulated the operation of a trolleybus traction electric drive under a start mode. The results have confirmed the increase in the energy efficiency of the traction electric drive by reducing the losses for excitation. The comparison has revealed that the losses of energy decreased from 0.587 MJ (0.163 kWh) to 0.531 (0.1475 kWh) MJ, by 9.54 %.

References

1. Hutyria, S., Yahlinskyi, V., Chanchin, A., Khomiak, Y., Popov, V. (2020). Evolution of trolley-bus: directions, indicators, trends. Diagnostyka, 21 (1), 11–26. doi: https://doi.org/10.29354/diag/116080
2. Grijalva, E. R., López Martínez, J. M. (2019). Analysis of the Reduction of CO_2 Emissions in Urban Environments by Replacing Conventional City Buses by Electric Bus Fleets: Spain Case Study. Energies, 12 (3), 525. doi: https://doi.org/10.3390/en12030525
3. Tica, S., Filipovic, S., Zivanovic, P., Bajcetic, S. (2011). Development of Trolleybus Passenger Transport Subsystems in Terms of Sustainable Development and Quality of Life in Cities. International Journal for Traffic and Transport Engineering, 1 (4), 196–205.
4. Stepanov, P. (2019). Characteristics of construction and operation of trolleybus systems in the world. Prace Komisji Geografii Komunikacji PTG, 22 (3), 64–72. doi: https://doi.org/10.4467/2543859xpkg.19.018.11284
5. Grzelec, K., Birr, K. (2016). Development of trolleybus public transport in gdynia as part of a sustainable mobility strategy. Scientific Journal of Silesian University of Technology. Series Transport, 92, 53–63. doi: https://doi.org/10.20858/sjsutst.2016.92.6
6. Lyagushkin, A., Yankivskiy, D., Vel'mozhko, A. (2019). Na kakih trolleybusah ezdyat ukraintsy. Passazhirskiy Transport. Available at: https://traffic.od.ua/blogs/antonlyagushkin/1217504
7. Zavada, J., Blašković Zavada, J., Miloš, K. (2012). Conditions for Implementing Trolleybuses in Public Urban Transport. PROMET - Traffic&Transportation, 22 (6), 467–474. doi: https://doi.org/10.7307/ptt.v22i6.212
8. Bogodistiy, P. (2016). Sovremenniy trolleybus: opisaniya ustroystva i printsipa raboty. Nauka i Tehnika. Available at: https://naukatehnika.com/sovremennyij-trollejbus.html
9. Karpliuk, L., Panchenko, B. (2012). Osoblyvosti zastosuvannia chastotnokerovanoho asynkhronnoho elektropryvodu dlia tiahovykh mekhanizmiv. Visnyk Natsionalnoho universytetu «Lvivska politekhnika»: Elektroenerhetychni ta elektromekhanichni systemy, 736, 49–53. Available at: http://ena.lp.edu.ua:8080/bitstream/ntb/15815/1/9-Karplyuk-49-53.pdf
10. Sharyakov, V. (2014). Dvadtsat' let vnedreniya asinhronnogo elektroprivoda na gorodskom elektrotransporte. Control Engineering Rossiya, 3 (51), 67–69. Available at: https://controleng.ru/wp-content/uploads/5167.pdf
11. Bartłomiejczyk, M., Połom, M., Jakimovska, K. (2013). Application of principal component and hierarchical cluster analysis in classifying defects of trolleybuses. Przeglad Elektrotechniczny, 89 (8), 48–51. Available at: http://www.pe.org.pl/articles/2013/8/10.pdf
12. Lyagushkin, A., YAnkivskiy, D. (2020). Kak v proshlom godu obnovlyalis' trolleybusnye parki Ukrainy. Odesskiy Kur'er. Available at: https://uc.od.ua/news/traffic/1222426
13. Lyagushkin, A., Vel'mozhko, A. (2019). Proekt EIB «Gorodskoy obshchestvenniy transport v Ukraine»: kakih uspehov dobilis' goroda. Passazhirskiy Transport. Available at: https://traffic.od.ua/blogs/antonlyagushkin/1220877
14. Mwambeleko, J. J., Kulworawanichpong, T., Greyson, K. A. (2015). Tram and trolleybus net traction energy consumption comparison. 2015 18th International Conference on Electrical Machines and Systems (ICEMS). doi: https://doi.org/10.1109/icems.2015.7385399
15. Cherny, M., Kachimov, V. (2009). Implementation of energy efficient equipment and technologies at the rolling stock city electric Ukraine. Municipal economy of cities, 88, 263–266. Available at: https://khg.kname.edu.ua/index.php/khg/article/view/1604/1596

16. Nicholson, T. J. (2008). DC & AC traction motors. IET Professional Development Course on Electric Traction Systems. doi: https://doi.org/10.1049/ic:20080505
17. Andreychenko, V. P., Donets, A. V., Gerasimenko, V. A. (2012). Povyshenie energoeffektivnosti na gorodskom elektricheskom transporte. Komunalne hospodarstvo mist, 107, 412–417.
18. Hamacek, Š., Bartłomiejczyk, M., Hrbáč, R., Mišák, S., Stýskala, V. (2014). Energy recovery effectiveness in trolleybus transport. Electric Power Systems Research, 112, 1–11. doi: https://doi.org/10.1016/j.epsr.2014.03.001
19. Sładkowski, A. (Ed.). (2020). Ecology in Transport: Problems and Solutions. Springer. doi: https://doi.org/10.1007/978-3-030-42323-0
20. Biryukov, V. V., Porsev, E. G. (2018). Tyagoviy elektricheskiy privod. Novosibirsk: Izd-vo NGTU, 312.
21. Gor, C. P., Shah, V. A., Gor, M. P. (2016). Electric vehicle drive selection related issues. 2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES). doi: https://doi.org/10.1109/scopes.2016.7955554
22. Kulagin, D., Chernetskiy, B. (2015). The choice of traction motors for building systems for mobile electrical systems. Technology audit and production reserves, 2 (1 (22)), 9–12. doi: http://dx.doi.org/10.15587/2312-8372.2015.39931
23. Thakar, D. U., Patel, R. A. (2019). Comparison of Advance and Conventional Motors for Electric Vehicle Application. 2019 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE). doi: https://doi.org/10.1109/rdcape47089.2019.8979092
24. Biryukov, V. V., Kalugin, M. V., P'yanyh, A. N. (2013). K opredeleniyu moshchnosti tyagovogo dvigatelya transportnogo sredstva. Transport: nauka, tehnika, upravlenie, 8, 43–46.
25. Bartłomiejczyk, M., Mirchevski, S., Jarzebowicz L., Karwowski, K. (2017). How to choose drive's rated power in electrified urban transport? 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe). doi: https://doi.org/10.23919/epe17ecceeurope.2017.8098948
26. Bitar, Z., Sandouk, A., Jabi, S. A. (2015). Testing the Performances of DC Series Motor Used in Electric Car. Energy Procedia, 74, 148–159. doi: https://doi.org/10.1016/j.egypro.2015.07.536
27. Apostolidou, N., Papanikolaou, N. (2018). Energy Saving Estimation of Athens Trolleybuses Considering Regenerative Braking and Improved Control Scheme. Resources, 7 (3), 43. doi: https://doi.org/10.3390/resources7030043
28. Brazis, V., Latkovskis, L., Grigans, L. (2010). Simulation of Trolleybus Traction Induction Drive with Supercapacitor Energy Storage System. Latvian Journal of Physics and Technical Sciences, 47 (5). doi: https://doi.org/10.2478/v10047-010-0023-0
29. Hurtova, I., Sejkorova, M., Verner, J., Šarkan, B. (2018). Comparison of electricity and fossil fuel consumption in trolleybuses and buses. Engineering for Rural Development, 2079–2084. doi: https://doi.org/10.22616/erdev2018.17.n342
30. Mukha, A. M., Kostin, M. O., Kurylenko, O. Y., Tsyplia, H. V. (2017). Enhancing the operational efficiency of direct current drive based on use of supercondenser power storage units. Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport, 5 (71), 48–60. doi: https://doi.org/10.15802/stp2017/114624
31. Jandura, P., Kubin, J., Hubka, L. (2017). Electric energy monitoring for applying an energy storage systems in trolleybus DC traction. 2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and Their Application to Mechatronics (ECMSM). doi: https://doi.org/10.1109/ecmsm.2017.7945904
32. Pavlenko, T., Shavkun, V., Petrenko, A. (2017). Ways to improve operation reliability of traction electric motors of the rolling stock of electric transport. Eastern-European Journal of Enterprise Technologies, 5 (8 (89)), 22–30. doi: https://doi.org/10.15587/1729-4061.2017.112109
33. Andrienko, P. D., Shilo, S. I., Kaplienko, A. O., Nemudriy, I. Yu. (2007). Issledovanie dinamiki seriesnogo elektrodvigatelya s razlichnymi impul'snymi shemami regulirovaniya. Elektrotekhnika i elektroenerhetyka, 1, 4–8.
34. Poluyanovich, N. K., Voloshenko, Yu. P., Shushanov, I. I. (2013). Mathematical model of the traction electric drive with pulse-width management for research of the mode of start-up. Izvestiya Yuzhnogo federal'nogo universiteta. Tehnicheskie nauki, 4 (141), 125–130.
35. Bogdan, N. B., Safonov, A. I., Mazanik, K. I. (2001). Sovremennye sistemy upravleniya tyagovymi elektrodvigatelyami gorodskogo elektricheskogo transporta. Energetika. Izvestiya vysshih uchebnyh zavedeniy i energeticheskih obedineniy SNG, 4, 22–30.
36. Chan, C. C., Cheng, M. (2013). Vehicle Traction Motors vehicle traction motors. Transportation Technologies for Sustainability, 1103–1132. doi: https://doi.org/10.1007/978-1-4614-5844-9_800
37. Veltman, A., Pulle, D. W. J., De Doncker, R. W. (2016). Fundamentals of Electrical Drives. Power Systems. doi: https://doi.org/10.1007/978-3-319-29409-4
38. Deev, S. G., Levykina, V. I. (2000). Energosberegayushchee upravlenie dvigatelem postoyannogo toka. Radioelektronika, informatyka, upravlinnia, 1, 139–142.
39. Andrienko, P. D., Shylo, S. I., Kaplienko, O. O., Shevchenko, N. M. (2011). Doslidzhennia reostatno-rekuperatyvnoho halmuvannia u systemi impulsnoho rehuliuvannia seriesnoho elektrodvyhuna. Elektrifikatsiya transporta, 2, 6–9.
40. Luchko, A. R., Strakolist, E. V. (2008). Utochnennaya imitatsionnaya model' tyagovogo elektrodvigatelya postoyannogo toka so smeshannym vozbuzhdeniem. Elektrotekhnika i elektroenerhetyka, 1, 31–36.
41. Shavelkin, A., Gerasimenko, V., Kostenko, I., Movchan, A. (2016). Modeling of traction electric drive with dc series motors. Eastern-European Journal of Enterprise Technologies, 1 (2 (79)), 42–48. doi: https://doi.org/10.15587/1729-4061.2016.60322
42. Drubetskyi, A. Yu. (2017). Approximation of universal magnetic characteristic for modelling electric traction machines. Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport, 1 (67), 106–116. doi: https://doi.org/10.15802/stp2017/94031

43. Andriychenko, V. P., Donets, O. V., Kostenko, I. O. (2012). Vdoskonalennia systemy keruvannia rukhomym skladom elektrychnoho transportu z vykorystanniam DC-DC peretvoriuvacha. Komunalne hospodarstvo mist, 103, 489–497.
44. Kharchenko, V. F., Daleka, V. K., Andriichenko, V. P., Kostenko, I. O. (2010). Pat. No. 60109 UA. Method for field reduction of traction electric motor of compound excitation type. No. u201013973; declareted: 23.11.2010; published: 10.06.2011, Bul. No. 11.
45. Andreychenko, V., Zakurday, S., Kostenko, I. (2014). Improvement of the method used for control of starting direkt-curren-trailway motor. Eastern-European Journal of Enterprise Technologies, 1 (8 (67)), 31–35. doi: https://doi.org/10.15587/1729-4061.2014.20123
46. Kostenko, I. A., Petrenko, A. N. (2015). The control algorithm DC-DC converter device for field weakening. Visnyk Natsionalnoho tekhnichnoho universytetu “KhPI”. Seriya: Problemy udoskonalennia elektrychnykh mashyn i aparativ. Teoriya i praktyka, 42 (1151), 31–33.
47. Shavelkin, A., Kostenko, I. (2015). Realization of the mode of weakening of a magnetic field in the traction DC electric drive. Visnyk Kharkivskoho natsionalnoho avtomobilno-dorozhnoho universytetu, 69, 53–60.
48. Soroka, K. A., Andreychenko, V. P., Kostenko, I. A. (2016). Analysis of Operation Mode Trolleybus Traction Motors with DC-DC Converter by Mathematical Modeling Package MATLAB. Transport: nauka, tehnika, upravlenie, 3, 47–51.
49. Abhishek, S. (2014). Speed Control of Dc Motor Using Chopper. International Journal of Engineering, Management & Sciences (IJEMS), 1 (10), 5–8. Available at: https://www.academia.edu/9451929/International_Journal_of_Engineering_Management_and_Sciences_Vol._1_Issue_10_October_2014
50. Forouzesh, M., Siwakoti, Y. P., Gorji, S. A., Blaabjerg, F., Lehman, B. (2017). Step-Up DC–DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications. IEEE Transactions on Power Electronics, 32 (12), 9143–9178. doi: https://doi.org/10.1109/tpel.2017.2652318
51. Vilberger, M. E., Vislogusov, D. P., Kotin, D. A., Kulekina, A. V. (2017). Bidirectional DC-DC conversion device use at system of urban electric transport. IOP Conference Series: Earth and Environmental Science, 87, 032053. doi: https://doi.org/10.1088/1755-1315/87/3/032053
52. Grygar, D., Koháni, M., Štefún, R., Drgoňa, P. (2019). Analysis of limiting factors of battery assisted trolleybuses. Transportation Research Procedia, 40, 229–235. doi: https://doi.org/10.1016/j.trpro.2019.07.035
53. Manjesh, Manjunatha, K. C., Bhoi, A. K., Sherpa, K. S. (2017). Design and Development of Buck-Boost Regulator for DC Motor Used in Electric Vehicle for the Application of Renewable Energy. Advances in Smart Grid and Renewable Energy, 33–37. doi: https://doi.org/10.1007/978-981-10-4286-7_4
54. Ramalingam, N., Sathishkumar, S., Balasubramani, K., Boobalan, C., Naveen, S., Sridhar, N. (2016). Chopper Fed Speed Control of DC Motor Using PI Controller. IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), 11 (3), 65–69. Available at: https://www.researchgate.net/publication/315684733_Chopper_Fed_Speed_Control_of_DC_Motor_Using_PI_Controller
55. Katke, S. P., Rangdal, S. M. (2015). Speed Control of DC Motor Using Microcontroller. International Journal of Scientific Research in Science and Technology, (1) 2, 62–67. Available at: http://ijsrst.com/IJSRST151227
56. Kostenko, I. O., Kharchenko, V. F., Khvorost, M. V. (2018). Calculation of the magnetic characteristics of the traction dc motor with combined excitation for trolley buses. Electrification of transport, 15, 117–123.
57. Kostenko, I. (2018). Improvement of the method of calculation of mechanical characteristics of a traction motor of direct current with combined excitation. Technology Audit and Production Reserves, 4 (1 (42)), 4–10. doi: https://doi.org/10.15587/2312-8372.2018.141384
58. Chernyh, I. V. (2008). Modelirovanie elektrotehnicheskih ustroystv v MATLAB, SimPowerSystems i Simulink. Moscow: DMK Press, Sankt-Peterburg: Piter, 288.