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 dif-
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 The issue of the outdated fleet of trolleybuses prevents the provision of regular and reliable transportation of city dwellers.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own funds at communal transport enterprises, a difficult economic situation, and the presence of a significant fleet of outdated trolleybus models in this country make it impossible to quickly solve this urgent task.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 “Skoda 24Tr” trolleybus by installing an onboard energy storage system based on a supercapacitor. Work [29] reports the results from annual testing of the “Skoda 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 the current due to the connection of additional resistance and was deleted “for nothing” at the additional resistance and was used. Paper [37] 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 disadvantage 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](image)

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 cycle” 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 “Electrotyzhmash”, 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:

\[
L_a = \sum \sum \sum \left( \varphi_{ijk} \cdot (M_{a1} \cdot I_a + Z_{a1}) \cdot (M_{a2} \cdot I_a + Z_{a2}) \right) \times \left( M_{v1} \cdot I_v + Z_{v1} \right) \times \left( M_{v2} \cdot I_v + Z_{v2} \right),
\]

where \(\varphi_{ijk}\) is the regression coefficient of the polynomial, which approximates the inductance; \(M_{a1}, M_{a2}\) are the scale coefficients for the coefficients of the currents of an armature and excitations, respectively; \(Z_{a1}, Z_{a2}\) are the offsets for the coefficients of the currents of an armature and excitations, respectively; \(I_{a0}, J_{a0}, K_{a0}\) 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.

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 con-
verter 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 con-
verter 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 opera-
tion, the system returns to its previous state.

One should note a positive point: the armature rotation
frequency throughout the entire region grows smoothly,
spite 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 weak-
ekening 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 weak-
ekening 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 exci-
tation 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 consump-
tion, we integrated, during modeling,
the instantaneous power consumed by
the traction drive of a trolleybus by
multiplying the input voltage \( U(t) \) unit,
and the armature current \( I_a \) unit,
Fig. 1. As a result of the traction drive
operation, equipped with a system for
weakening the field with a DC-DC con-
verter, 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.

6. Discussion of simulation results

The research reported in this article is a continuation
of work started in 2010; its phased implementation was des-
cribed 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 con-
verter, 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 op-
erates 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 (“Ia”, “Ib” and “Ic”).

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 %.

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