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Method to Improve the Efficiency of the Traction Rolling Stock with Onboard Energy Storage

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Abstract - This article presents the current problem of the introduction of onboard energy storages in electric transport. The energy diagrams of the electric transport operation have been analyzed, and the main stages of the rational selection of onboard energy storage capacity have been determined. A schematic of traction asynchronous electric drive system combined with onboard capacitive storage, with an improved energy storage module control system, has been provided. A simulation model of the underground rolling stock carriage in the Matlab/Simulink environment has been developed to confirm the proposed technical solution. The simulation modelling results demonstrate the more effective operation of the onboard storage control system at energy absorption, containment and recycling modes at rolling stock acceleration. The proposed algorithm of energy storage will reduce the cost of electricity for traction, reduce the power transfer and smooth the electricity consumption through an electric-traction network; it will improve traction and braking characteristics of the rolling stock.

Keywords Electric transport, onboard energy storage, simulation model, asynchronous electric drive, energy recovery.

1. Introduction

Today, the transport sector globally absorbs almost one third of final energy demand and nearly two-thirds of demand for oil. It accounts for one quarter of global carbon dioxide (CO_2) emissions from fuel combustion is the main source of air pollution, especially in urban areas. Urbanization and continuous growth in demand for mobility provoke a monotonic increase the share of energy consumption for passenger transport sector, especially for electric vehicles in urban and suburban. So from 2005 to 2015 passenger traffic (in passenger kilometers) increased by 8,9% [1, 2]. 75% of all passenger rail transportation is carried out by electric rolling stock. Sufficiently intensive use of electric transport as a means of passenger and freight transport allows a significant reduction in CO_2 emissions due to better energy efficiency compared to other types of transport, while requiring the generation of electricity of sufficiently high power, which is possible only at the expense of fossil minerals. For example, by 2015, the share of generated energy from fossil fuels amounted to 86.5% and nuclear power 4,1% of the rest due to renewable energy sources. [1, 2]. Although there is a positive trend towards a reduction in the use of fossil fuels as raw materials for generating electricity, for the development of renewable energy sources and for optimizing energy consumption, it nevertheless proceeds rather slowly, prompting the search for alternative sources of energy [2].

The maximum cost factor at using electric vehicles is the cost of electricity for rolling stock traction (70%) [3]. The traction cost can be reduced, first of all, by energy recovery through regenerative braking. Analysis of work on the regenerative braking energy usage shows that energy saving can range from 15% to 40% of the total traction electricity cost [4 - 6]. Regenerative braking advantages also include the cost reduction and electricity consumption smoothing. However, the issue of choosing the optimal way for energy recovery, recycling, containment, instantaneous transformation, the ways of energy-exchanged processes, etc. remains open. This determines the timeliness of finding new technical solutions for the most effective application of the indicated advantage of regenerative braking.

The purpose of the work is to develop a method for increasing energy efficiency and improving traction and energy properties of an electric traction rolling stock based on the integration of the on-board energy storage into a traction electric drive system.

To achieve this goal, the following tasks must be solved:

- analyze the energy diagrams of the electric traffic, identifying the approach to rational choice of the capacity of the on-board drive.

- determine the circuit decision and to develop the simulation model of the traction asynchronous electric drive system with on-board energy storage.

- create an algorithm for managing energy-exchange processes in the "traction electric-on-board" system for optimal utilization of the recuperated energy.

2. Search for an Optimal way to Increase the Energy Efficiency of Electric Transport

Kinetic energy recovery at electric transport is a problem of several decades and is a focus of attention of many scientists. Although some authors suggest that energy consumption can be reduced by implementing an appropriate method of driving [7], energy recovery seems to be more efficient, as this method will advantage the power supply network as well by reducing losses at electric substations, feeder and contact wire or the third rail. At the state-of-the-art level, the transformation of kinetic energy into electrical power is considered to be the most effective solution, due to the reciprocity principle of electric vehicles, where the motor mode can be switched to the generator mode. The development of power electronics of converters allowed for effective control of electric traction motors and precise torque adjustment. However, in the case of power regenerating motors, the available energy should be used properly. This energy is mainly dissipated on ballasting resistors by now, thus - without energy savings. This is caused by the fact that the power source is not bi-directional as of capacity in relation to the distribution network, and, therefore, energy recovery is possible only at braking of one of the trains and accelerating of the other one. In this case, kinetic energy recovery depends on the unpredictable traffic conditions and under preliminary estimates allows for recovery of a maximum of 10% of the energy used at acceleration [8]. Some authors suggest using inverting at substations to recover energy at the distribution networks [9] on the basis of controlled solid-state rectifiers, including an additional function of network harmonics suppression. The main drawback of this approach is associated with the high cost of new equipment and an impact on the current location of the existing substations. To avoid radical changes in the power supply system, the most effective solution is electric energy recovery using storages. In recent years, various storage technologies, such as using modern electrochemical batteries, flywheels, hydrogen cells and supercapacitors have been developed [10 - 13]. All these devices have different characteristics and lifecycle cost. Since the electric rolling stock of urban and commutation servicing of passengers are characterized with intermittent duty, start, running and braking and high set technical speed, power density and number of charge-discharge cycles are the most popular demands due to frequent start and stop of trains during the day. This way, flywheels and supercapacitors are the most acceptable in this field, as having a typical density of over 5 kW/kg and over 10^6 cycles. At the current level of technology development, the energy storages can be used [14 - 16] also onboard of the rolling stock [17 -19]. In the first case, neither a power source nor a rolling stock requires significant changes. But energy should be properly managed at the network level (which is technically difficult due to periodic changing of the time-schedules) and a lower efficiency can be expected due to the flow of energy through a contact network. The decision to install onboard storage can overcome this inconvenience, but the carriages shall need to be re-equipped to accommodate the storages. In this case, only supercapacitors can be successfully used due to practical limits of flywheels.

Although many authors are working on the problem of using electric accumulators for recovering energy in electric vehicles, the subject has not been fully resolved, especially concerning urban and commutation rail transport. In fact, some of the supercapacitors control methods are successfully used in the industry, but cannot be used at rolling stock traction drives, as the set voltage and currents of supercapacitors do not consider the effective torques and the speed of the drive motor. In addition, the recent experiments on an LV rail vehicle prototype by Bombardier Transportation Company show that the energy saved when using the supercapacitors is about 30% [20]. However, the most works do not consider the creation of effective energy exchange process of supercapacitors charging-discharging in details, thus, it is still unknown if the control methods, focused on maximizing energy recovery, will improve performance. Thus, under the necessity of energy resources saving, and the wide prospects for the introduction of electric transport with a modern traction asynchronous electric drive in Ukraine, this task gains ground and importance.

3. Development of an Electric Rolling Stock with Onboard Capacitive Energy Storage

The main parameters to define the maximum allowed accumulated energy is the capacity and operating voltage range of energy storage. The allowed energy accumulated during dynamic braking depends on the weight of the rolling stock, the original and terminal braking speed, motion resistance value and losses at electromechanical systems. It should be noted that the use of unified storage of high-energy capacity, able to absorb the entire braking energy at any run (regardless of the profile) is mostly unfeasible and brings a number of technical problems. To determine the potential of the rational capacity of onboard storage, the work contains an analysis of real oscillograms of carriages with traction asynchronous electric drive and recovery (Fig. 1). The figure shows that the average value of energy recovered during a period of a journey (Diagram below 0) is less than a half of a peak value of the recovery energy. Train energy consumption by various methods of braking energy use has been analyzed at the next stage of the research. Figure 2 contains the results of the analysis of joint energy consumption for a carriage operation in such modes as complete thermal scattering (A); accumulation in a volume according to the average value of recovery energy (B); unlimited accumulation (C). The obtained results can be used to say that the use of storage of unlimited capacity shall allow only 12% increase of energy savings compared to storage, the capacity of which corresponds to the average braking energy. At that, the capacity of two types of storages differs more than three times. Thus, we can make an important conclusion using unified energy absorbing devices in general, is unfeasible, and the storage capacity shall be selected based on the certain operating conditions. We propose the following three steps to be used to determine the capacity of onboard energy storage:

1. Design of time diagrams of electric energy consumption and recovery at route motion with the determination of weighted mean power of accumulation per one working cycle.

2. Setting the limits of changes in storage voltage taking into account the specifications of the traction electric drive.

3. Creation of a simulation model to specify the storage parameters considering the range of train weight and technical and average speed.

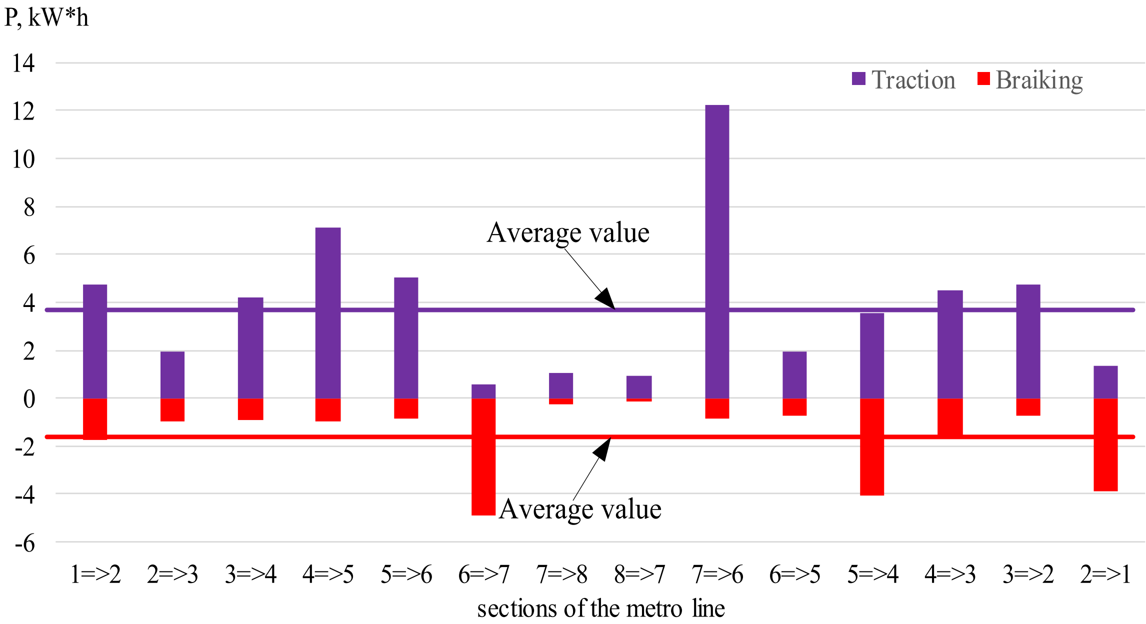

Fig.1. Energy diagram of a metro carriage operation

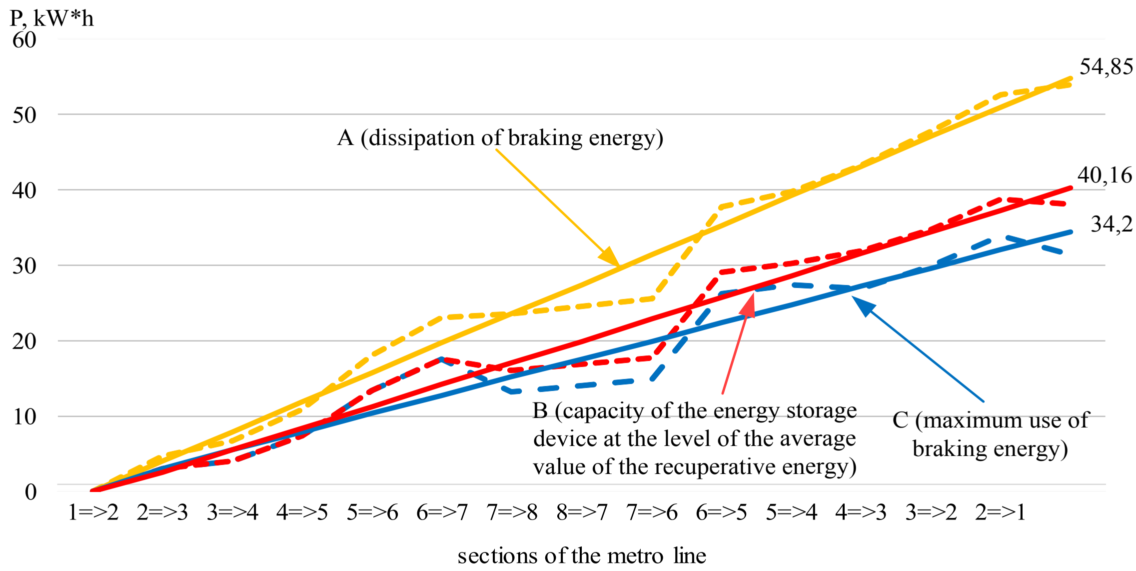

Fig.2. Total energy consumption of a metro carriage at various methods of electric braking energy use

The modern standard electric transport uses asynchronous motors as traction ones (Fig. 3). They are supplied from a three-phase voltage inverter connected to the power supply system through a direct current circuit, including a condenser filter, an input reactor, resistive braking module, protective devices and control and measuring instruments. Semiconductor switches of an autonomous voltage inverter and a brake module are controlled through a control unit (TCU).

Braking energy absorption and its recycling parallel to direct current circuit is provided with an energy storage module. In turn, the energy storage module has such functional units as traction four-quadrant converter of direct current (converter) with a control system, a smoothing reactor, a supercapacitor matrix, current and voltage control and measuring instruments. Charge control subsystem of the capacitive energy storage generates control signals for "charge/discharge supercapacitor" DC - DC converter that provides a controlled absorption of energy by the storage.

This drive braking is implemented through a transfer of the asynchronous traction motor to the generator operation mode with subsequent flow of recovery energy through the inverter by-pass diodes to the direct current circuit. The recovered energy shall be reset at brake resistive module or be transferred to supercapacitor storage.

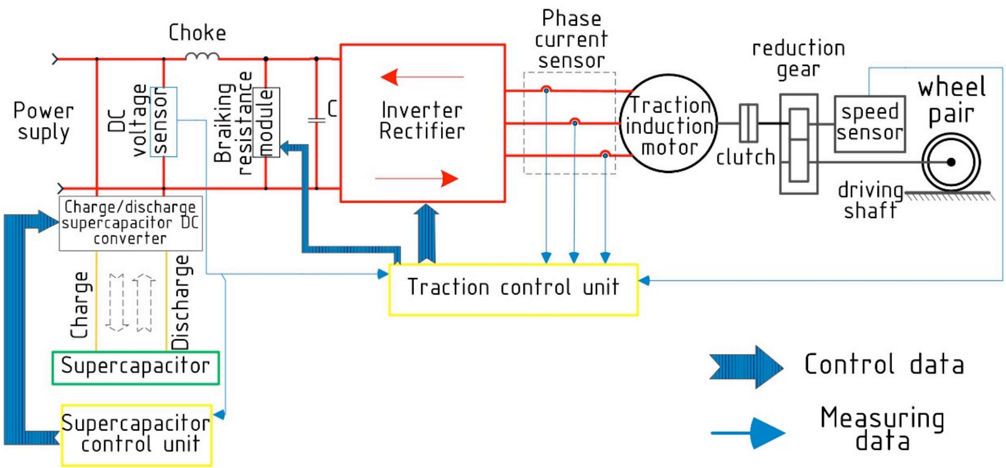

Fig. 3. Block diagram of a traction electric drive with onboard energy storage

The proposed control system for the energy storage module (Fig. 4) includes a set of interconnected subsystems, aimed at the most efficient braking energy storage and use.

Algorithm for separation of voltages in the direct current circuit has been implemented to select the energy direction in the control system. Its action is based on a division of the voltage range of the DC circuit from nominal to maximum value for regulation areas: braking module and storage module. Only one energy absorbing module can be operated in each area. Engagement of one of the modules is allowed by the subsystem, determining transfer to electric braking. This subsystem is based on measurements of the DC circuit voltage level $U_{\_dc}$, and uses units of relay nonlinearities with hysteresis; it forms an output logic control signal *S.C._mod* or *Brake_mod*. The signal allows activation of a control system of a certain energy storage module or a resistive braking module. The limits for activation of relay units are the maximum voltages in each of the specified areas. This way, for the storage module, the maximum voltage value $U_{dc.C}$, at the value of 110% of the nominal value $U_{\_dc}$, for the resistive braking module, the maximum voltage $U_{dc.R}$ - 120%. The nominal values of DC circuit are cut-off thresholds for relay units switching off, for the energy storage module $U_{dc.nom}$ and for resistive braking module $U_{dc.C}$ respectively.

The control of supercapacitor charging is based on the *VT2* semiconductor switch engagement control. With this purpose, the difference between the DC circuit voltage $U_{\_dc}$ and the setting voltage $U_{dc.C.set}$ shall be calculated first of all. The error value is corrected with a regulator, and then the pulse-width modulator uses the signal for creation of a corresponding pulse repetition method. In order to prevent the emergency currents of the storage charge during operation, the control system adjusts the setting of the charge current signal $I_{C.set}$. The moment when the regulator output signal needs to be adjusted is determined by tracking the excess of the actual current $I_{\_C}$ over the maximum permissible charge current of the capacitor. In this case, a logical signal appears and activates the controller setting fixation at the same level.

The control system transfers to the electric braking mode in case the DC circuit voltage is more than $U_{dc.R}$. In this case, the subsystem for defining the transition to the electric braking mode blocks the energy storage and activates resistive braking module to reset the excess energy. It allows preventing braking effort reduction or disappearance and, regardless of the storage, to keep the set parameters of the braking mode - the slowdown rate and the maximum DC circuit voltage.

The controller of the resistive braking module control system calculates the difference between the effective DC circuit voltage $U_{\_dc}$ and the setting voltage $U_{dc.R.set}$. The resulting difference signal is fed to the pulse-width modulator to create *Gate_VT1* control signal pulses for *VT1*controlled semiconductor switch.

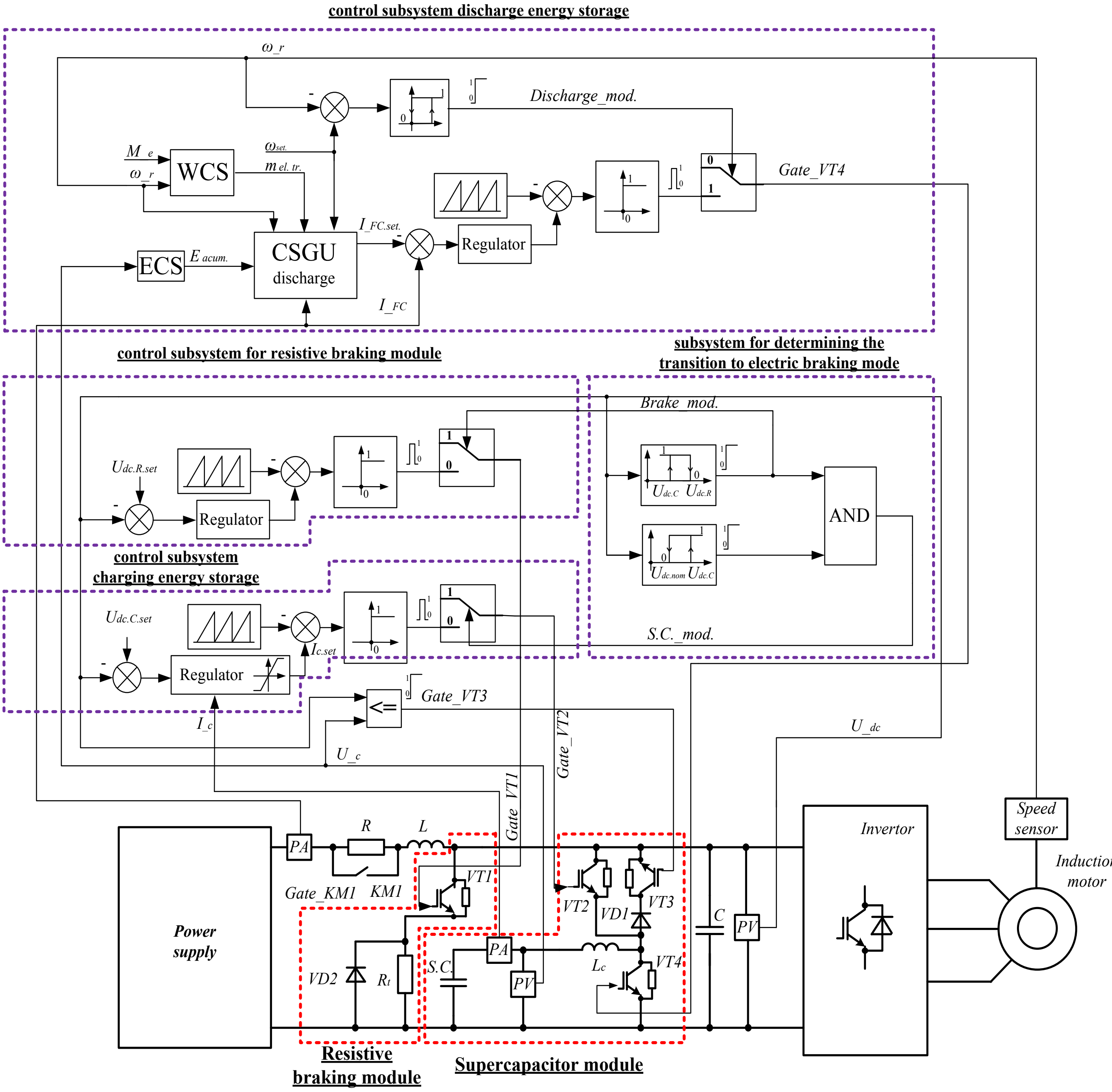

Fig.4. Energy absorbing modules control system

To improve the energy efficiency of electric vehicles, we propose using of stored energy as an additional source of traction electric drive supply. This will smooth the electricity consumption and bring no additional losses at transmission of power from the contact network to the electric rolling stock. These benefits can be achieved through creation of a stabilization loop of contact network absorbed current.

We propose to manage this process with a capacitor discharge control subsystem (Fig. 4). Contact network absorbed current I_{FC} is used as a controlled variable. Stabilization current setting $I_{FC.stab}$ at the input of frequency converter power module in the traction mode is formed based on calculation of v_{start} linear speed at the start of power transit optimization (Fig. 5).

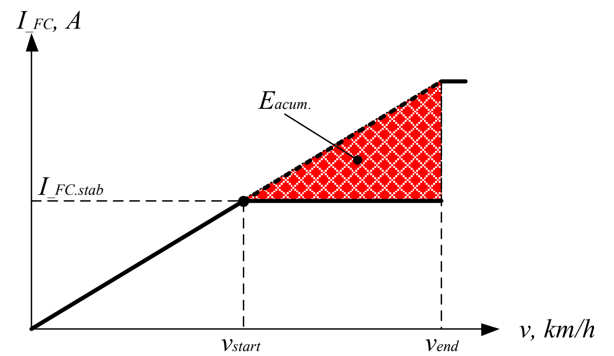

Fig. 5. Variation in start of power transit optimization with respect to linear speed

Taking into account all the factors that can affect energy consumption during acceleration (mass, main and additional resistance to movement), speed v_{start} for the tangential path can be determined by the formula below:

$$v_{start} = \sqrt{v_{end}^2 - \frac{2 \cdot \eta \cdot E_{acum.}}{m_{el.tr}}} \qquad (1)$$

Where v_{start} – is the linear velocity of rolling stock movement when the $I_{\_FC}$ input current is starting to stabilize; v_{end} - the final speed of rolling stock acceleration; η - electromechanical transmission efficiency; $E_{acum.}$ accumulated energy; $m_{el.\ tr}$ – the rolling stock weight.

Structural elements of the storage discharge control subsystem enable defining of individual components of equation (1). *CSGU discharge* unit is the main one in this structure; it receives information about the estimated total weight of the rolling stock $m_{el.tr}$, the speed setting ω_{set}, real speed $\omega_{\_r}$ and the traction motor shaft electromagnetic torque moment $M_{\_e}$. as input parameters. The linear speed of the rolling stock v_{start}, at which $I_{\_FC}$ current is starting to stabilize is calculated and the level of stabilization of $I_{\_FC.stab}$. current is determined inside *CSGU discharge* unit. Rolling stock weight (according to the basic equation of the train motion) and the of accumulated energy amount E_{acum} are calculated in *WCS* and *ECS* units.

The *CSGU discharge* unit allows evaluation of the continuing acceleration energy consumption, by comparing the calculation result with the energy already accumulated in the onboard storage. The input signal for the PWM generator is created on this basis; it makes the control signal for the semiconductor switch *VT4* of a step-up DC-DC converter (Fig. 4). This converter consists of an inductance L_c, a controlled semiconductor switch *VT4* and a *VD1* diode. Storage arbitrary depletion at DC circuit voltage overloading can be prevented with provided *VT3* semiconductor switch. This switch control system generates *Gate_VT3* logical opening signal, evaluating the voltage levels of the storage and the DC circuit voltage.

4. Simulation of an Electric Rolling Stock with Onboard Capacitive Energy Storage

To confirm the correctness of the circuit solutions made in a Matlab/Simulink software environment, a simulation model of a metro rolling stock with traction asynchronous electric drive with onboard energy storage has been designed (Fig. 6).

The simulation model is made in accordance with the real parameters and technical characteristics of the traction electric drive elements metro car 81-8070. This way, we used the parameters of 180 kW motor of type STDa 280-4B-UK (Table 1) as a traction asynchronous motor. The basic parameters of the drive elements, used for the simulation modeling are given in Table 2.

Table 1. Technical characteristics of a traction asynchronous motor type STDa 280-4B-UK

Parameter	Value
Rated power $P_н$, kW	180
Nominal supply voltage $U_л$, V	500
Nominal frequency f_{nom}, Hz	63
Rated current I_{rated}, A	257
Number of pole pairs Z_p	2
Rotation speed n, rpm	1854
Power factor $cos\varphi$	0.86
Efficiency η	0.94
Rotor inertia J, kg·m^2	1.75

Table 2. Basic parameters of the simulation model

Parameter	Value
Carriage weight at full load, t	55
Transfer factor of the traction gearbox	7.307
Tread circle nominal diameter of a wheel pair, mm	820
Acceleration value, m / s^2	1
Deceleration value, m / s^2	1
Nominal input voltage of the traction inverter, V	750
PWM frequency, Hz	2500
Capacity of the traction converter DC circuit filter, Φ.	0.009
Input reactor induction, Gn	0.003
Braking resistor resistance, ohm	4
Frequency of PWM regulator of the resistive braking module, Hz	2500
Frequency of PWM regulator of the capacitive storage charge, Hz	1000 -2500
Capacity of the energy storage device, F.	6
Nominal voltage of capacitive storage charge, V	500
Storage module reactor inductance, Gn	0.001

The traction electric drive control system is based on the principles of vector control with reaction of the rotor speed. The control is exercised by adjustment of a generalized vector of motor stator current in the d-q rotating coordinate system with a focus on the armature flux linkage vector. Currently, this type of system allows for high accuracy and wide range speed control; it is most widely used in modern microprocessor-controlled asynchronous traction electric drive [21, 22].

The necessary voltage vector and, accordingly, the stator current have been implemented with help of space vector PWM modulation. It allows for increase of voltage application in the DC circuit and for improvement of the shape and spectral composition of supply phase currents of an asynchronous motor.

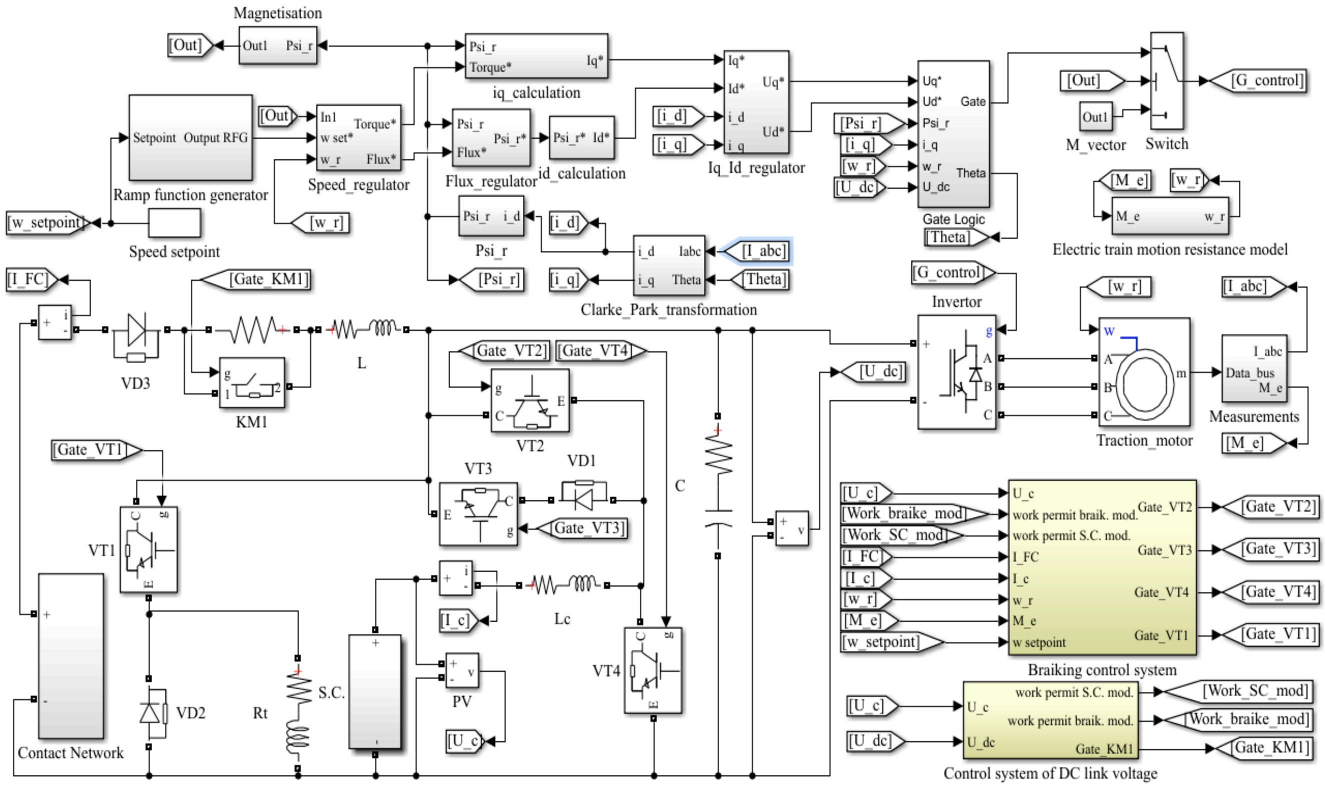

Fig. 6. Simulation model of an asynchronous traction electric drive with onboard supercapacitor storage

The oscillograms of a traction electric drive (Fig. 7, 8), obtained during the simulation time (26 s), show advantages of using onboard supercapacitor drive.

Fig. 7 shows, that the drive use allows reduction of amperage from the traction network, from a maximum value of 200 A to 80 A, i.e. more than twice within 7.5 seconds of the traction mode. This way, power transit through the power network is reduced as the increased traction current flow at the contact rail and the rolling rail results in significant additional losses both in the traction mode and in the braking mode.

Curves 5 and 7 (Fig. 7) show the process of smooth charge and discharge of a supercapacitor, which confirms the correctness of the made schematic decision and algorithm of energy control in TAED. At that, the voltage and current pulsing level is reduced, as well as abrupt voltage jumps and sags, which has a positive impact on traction equipment reliability and durability.

In contrast, the oscillograms of the TAED energy exchange processes are shown without using energy storage (Fig. 8). Thus, we can make a conclusion about a reasonable amount of wasted energy dissipated at braking resistors.

It is obvious that in a real system, the high velocity of the energy exchange processes between storage and the traction electric drive requires a microprocessor control system and fast control and measurement instruments of high resolution. Therefore, at study of TAED with onboard storage, the simulation modelling has been performed with a fixed integration step $2\times10e^{-6}$ sec.

The modeling used assumptions that do not affect the integrity and trueness of the results: the weight and resistance to movement of electrical train is evenly distributed between all axes of the rolling stock; the applied traction effort is not limited with a friction coefficient; the energy storage is pre-charged before the train movement is started; the external power supply is infinite.

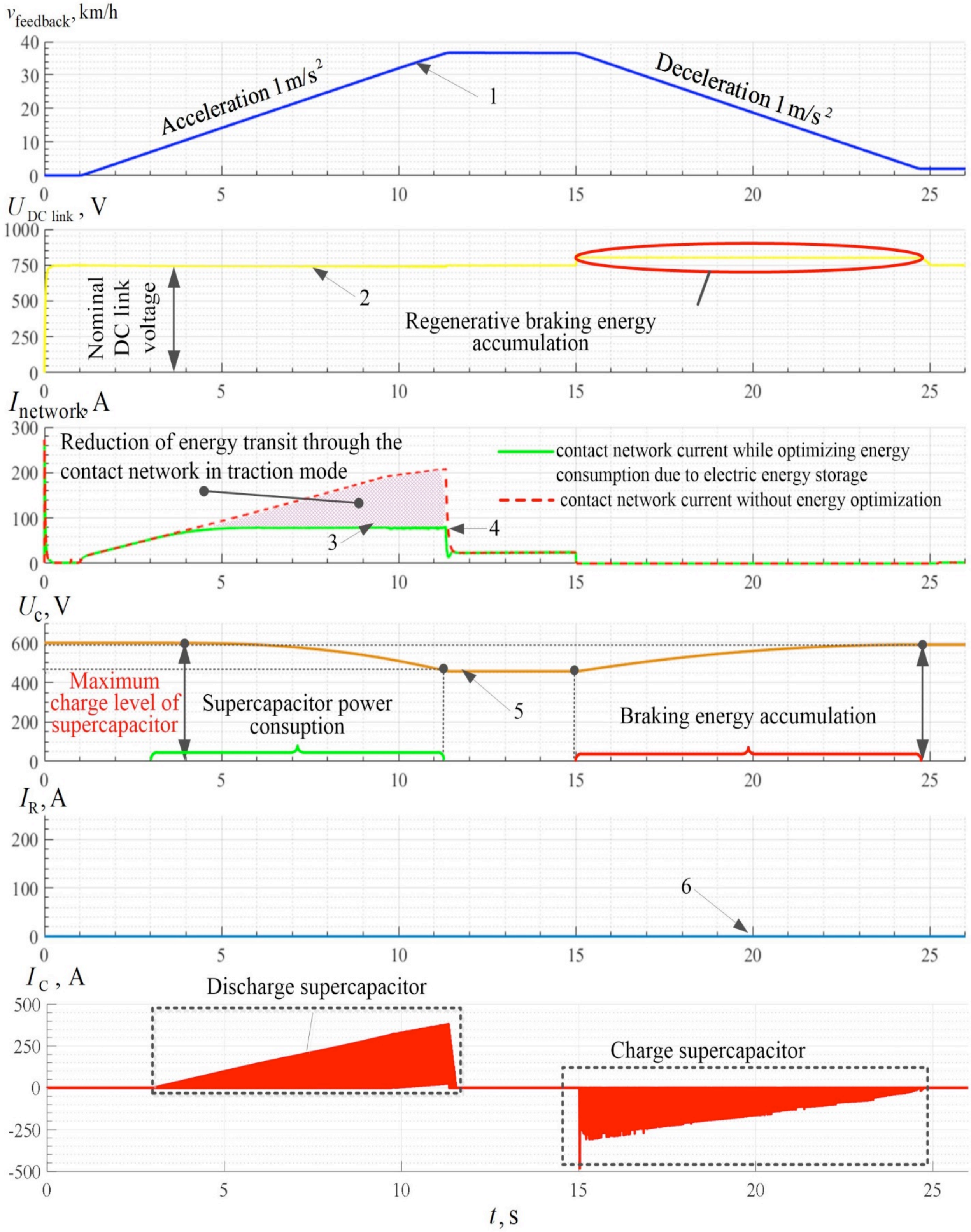

Fig. 7. Oscillograms of TAED with onboard energy storage:

1 - the actual speed of the rolling stock; 2 –DC circuit voltage of the traction frequency converter; 3 - traction frequency converter input current; 4 - traction frequency converter input current at traction network energy optimization due to the accumulated braking energy; 5 - voltage at the capacitive energy storage; 6 – resistor braking module current; 7 - energy storage current

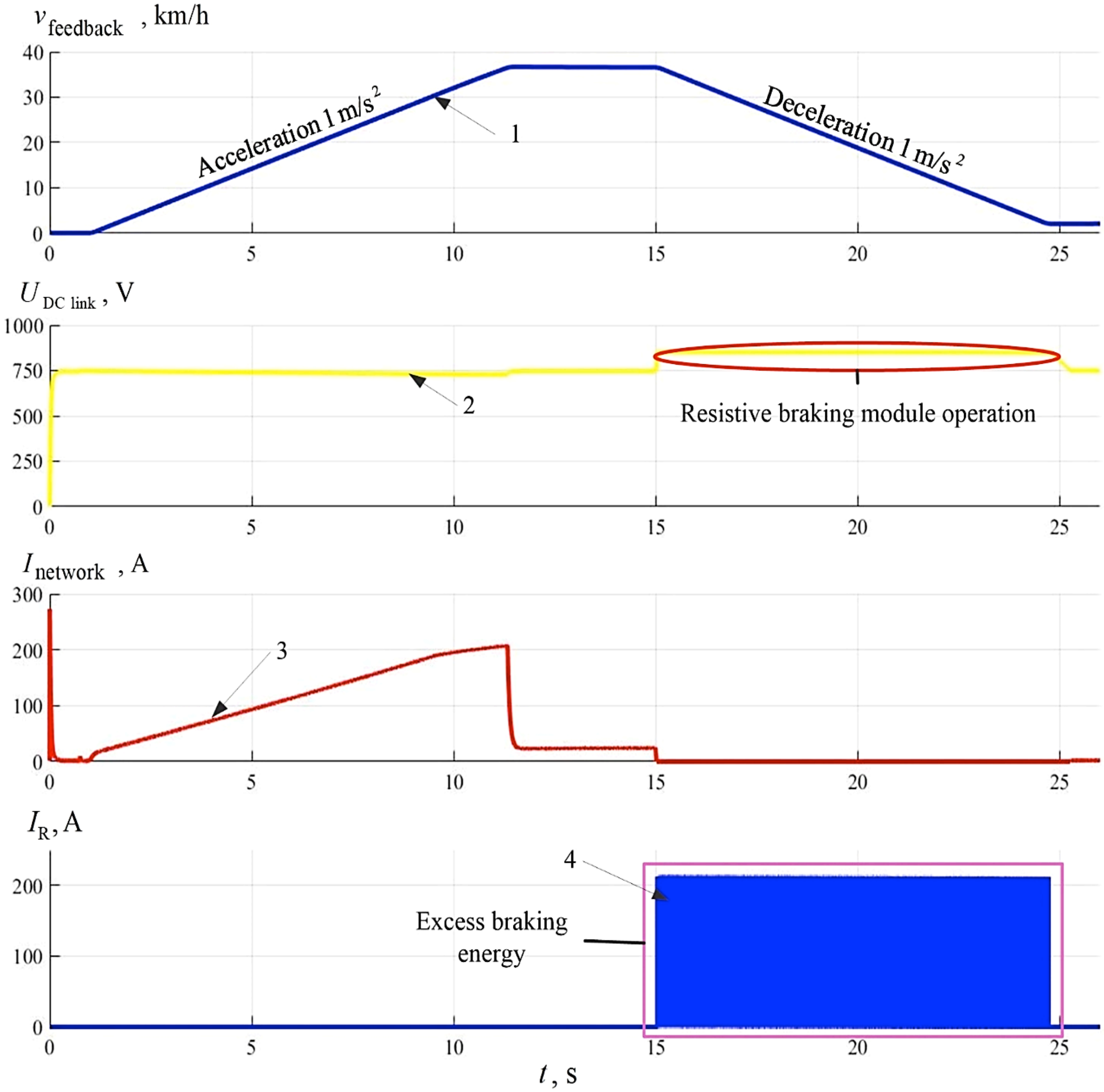

Fig. 8- Oscillograms of TAED at- electrodynamic braking:

1 - the actual speed of the rolling stock; 2 –DC circuit voltage of the frequency converter; 3 - traction frequency converter input current; 4– resistor braking module current

In fig. 8 gives the results of the simulation of the state-traction asynchronous electric drive of the metro car 81-8070. This simulation was carried out to clarify the correctness of the work of the developed model of the proposed scheme in order to prevent distortion of the results of its simulation in consequence of incorrect operation of the proposed model of the rod system of the traction asynchronous electric motor of the subway car on which it is based and for indirect evaluation of the basic technical parameters of the traction equipment and control systems. On curve 1 (fig. 8), an oscillogram of the vehicle's speed is shown, which shows the operation of the speed control system in the process of acceleration and braking with an intensity of 1 m / s^2 on the seventh speed range regardless of the resistance of the movement. In this case curves 2 - 4 (fig. 8) demonstrate the absence of abnormal electromagnetic processes both in traction and braking mode, with the possibility of realizing the required traction and braking effort, without exceeding the nominal power of the traction electric drive, which is confirmed by the input of the frequency converter (curve 2), the voltage of the DC link (curve 3) and the current of the resistive braking module (curve 4).

5. Conclusions

The analysis of the energy diagrams of the electric transport operation indicates the need to reconcile the capacity of the on-board drive with the operating conditions. A three-stage approach is proposed for rational determination of the choice of the capacity of the on-board storage device by the average value of the recuperated energy in the cycle of a particular route exploitation. For the research work on the definition of rational capacity of the onboard drive an imitation model of the traction asynchronous electric drive of a typical electric transport was developed.

An efficient algorithm of energy exchanging processes management in the developed system of "traction electric drive - onboard storage" has been created for optimal use of recovered energy. The system application for reduction of transit power through a traction network in a traction mode is over two times as much, smooth supercapacitor charge and discharge and efficiency of energy as an additional power source at rolling stock speedup.

The further development of the proposed system appears as a possibility of storage capacity adjustment under the specific route terms and improvement of energy consuming modules control subsystems through the use of expert and intellectual algorithms.

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