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NEW TECHNICAL SOLUTIONS OF USING ROLLING STOCK ELECTRODYNAMICAL BRAKING

Summary. The paper considers some theoretical and practical problems associated with the use of traction motor are operating in the generator mode (in braking). Mathematical and graphical relationships of electrodynamic braking, taking into account the requirements raised to braking systems in rail transport are presented. The latter include discontinuity of braking process, braking force regulation, depending on the locomotive speed, mass, type of railway and other parameters. Schematic diagrams of the locomotive braking and ways of controlling the braking force by varying electric circuit parameters are presented. The authors suggested contact-free regulation method of braking resistor for controlling braking force in rheostatic braking, and resistor parameters regulate with pulse regulation mode by semiconductor devices, such as new electrical components for rolling stock – IGBT transistors operating in the key mode. Presenting energy savings power systems, which are using regenerative braking-returning energy and diesel engine or any form of hybrid traction vehicles systems, circuit diagrams, electrical parameters curves.

НОВЫЕ ТЕХНИЧЕСКИЕ РЕШЕНИЯ ИСПОЛЬЗОВАНИЯ ЭЛЕКТРОДИНАМИЧЕСКОГО ТОРМОЖЕНИЯ ПОДВИЖНОГО СОСТАВА

Аннотация. В статье расмотренны теоретические и практические проблемы применения тяговых двигателей, работающих в генераторном режиме (при торможении). Представлены математические и графические изображения режимов электродинамического торможения. В статье включены режимы регулирования тормозного усилия в зависимости от скорости, массы локомотива, представлены диаграммы регулирования электрических параметров. Авторы предложили метод бесконтактного регулирования тормозного сопротивления, применяя новые электрические компоненты IGBT транзисторы, работающие в режиме электронного ключа. Представлены схемы, диаграммы, графики использования энергии рекуперативного торможения в экономных энергетических системах, в дизельных или любых форм гибридных тяговых подвижных единиц. В статье отброжены теоретические и практические вопросы данных предложений.

1. INTRODUCTION

Resources need to be deployed and utilized efficiently, in a manner that is easy on the environment-and today's rail transport systems are no exception. Environmental awareness plus

reduced operating cost are now major considerations in procuring advanced rail vehicles for considerations in procuring advanced rail vehicles. It is needed to reduce electric demand; it is used new energy savings and power supply optimization, hybrid traction vehicles systems, which are using regenerative braking energy.

Electric braking is effective on all speed. Air brake cannot be use. When a vehicle brakes, energy is released to date, most of this energy has been lost in air. The challenging alternative is to store the braking energy on the train when using it during acceleration of operation of the vehicle. Traditionally diesel locomotives powered electical transmision cannot use regenerative brake energy.

Economic indicators of electrodynamic braking have not been properly estimated. An essential difference between electrodynamic and traditional mechanical (pneumatic) braking is in the control of the braking force by adjusting the electrical parameters of traction motors. The paper addresses some basic theoretical and engineering problems of electrodynamic braking, presenting methods of braking force regulation and using of regenerative braking returning energy (energy savings systems) and diesel engine or any form of hybrid traction vehicles systems, circuit diagrams, electrical parameters curves.

2. THEORETICAL PROBLEMS OH ELECTRODYNAMIC BRAKING

When the speed of rolling stocks is increasing, traditional braking system becomes ineffective. Besides, it is not fully automated. Therefore, the interest in electrodynamic braking methods is continually growing. These methods are aimed at changing the operation of traction motors of the locomotive into the generator mode operation. Electric motors operating in the generator mode convert the kinetic energy of a locomotive into electric power, determining the type of electric braking, which may be either rheostatic or regenerative, depending on further use.

Electric braking may be divided into rheostatic, and regenerative. The main advantages of electric braking are precise regulation of braking force, while controlling the circuit parameters, as well as high speed and stability of system operation. Braking can be controlled either by engine-driver or automatically, when the latter is only an observer.

Regenerative braking is more energy-effective because power given to contact system is either used by another electric train or returned to power system. More than 25% of power used for traction can be returned to contact system.

Thus, the conditions for the motor at idle to exceed point n_0 of torque-speed characteristic $n = f(M)$, which is required in regenerative braking, cannot be satisfied (see Fig. 1).
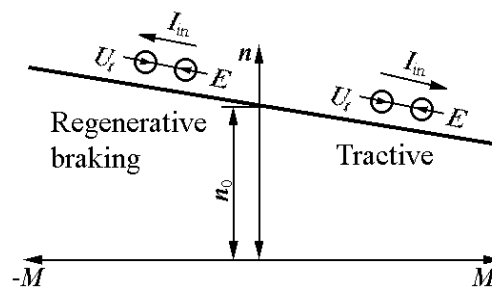

Fig. 1. Torque-speed characteristic of shunt-wound excitation motor's braking and traction modes: n_0 - motor's ideal no-load speed; U_t - contact system voltage; I_{in} - armature current of traction motor

Рис. 1. Механическая характеристика независимого возбуждения тягового двигателя в режимах тяги и рекуперативного торможения: n_0 - идеальная скорость холостого хода; U_t - напряжение контрольной сети; I_{in} - ток якоря DC тягового двигателя

When the load moment changes (e.g. when the locomotive is moving down the slope), the speed n of the motor armature exceeds n_0, e.m.f. of the motor E exceeds network voltage, the armature

current is reversed and electromagnetic braking moment is developed (see Fig. 1). The motor goes to the generator mode, while electromagnetic moment, which is a counter torque with respect to the armature, becomes a braking moment, and the power produced by generator is given to the contact system.

The power of modern electric trains, like TGV in France, ICE in Germany, and the motor car unit of electric locomotives reaches to 10 MW, therefore, brake horse power is very high. It can be found from the power balance equation as follows:

$$P_m = P_e + \Delta P ; \tag{1}$$

where: P_m is the mechanical power of the motor shaft, W; P_e is the electric power given to electricity supply network, W; ΔP denotes total power losses of the electric circuit of the motor, W.

Therefore, the power returned during the regenerative braking should be used by another traction locomotive. In particular, the regenerative brake power should be returned to substation transformer and power system by specially installed inverters or used by ballast resistors.

In rheostatic braking, traction motors operate in DCseries or separate generator excitation modes. Series excitation of generators is used in most of electric train traction motors.

Resistors used in starting are also used in rheostatic braking of electric locomotive drives.

Rheostatic braking of motors is feasible for both high and low armature speed, i.e. for low and high locomotive speed, because the voltage of traction motor operating in generator mode does not depend on the supply voltage and can be set according to the required braking force. Its value will depend on the locomotive speed, when it goes over to the braking mode.

To go over to rheostatic braking, the following conditions should be satisfied: series traction motor should be disconnected from the contact system in the electric drives of electric traction rolling stocks (from generator in diesel locomotives); armature or excitation windings should be connected so that the excitation current would not change its direction, traction motor should be connected to the dynamic braking resistor R_b.

The locomotive braking force can be adjusted by controlling braking current I_b of traction motor. Usually, the resistors, which are used for traction, are employed in rheostatic braking of electric traction rolling stock. Usually, electric train EMU for traction mode are used additional resistors $R_{p1} - R_{pi}$. Additional resistors parameters are regulated during traction with contactors. A circuit diagram of rheostat starting (traction mode) and of (braking mode) rheostatic braking, where is used new electrical components for rolling stock – IGBT transistors operating in the key mode is offered (see Fig. 2, 3). IGBT insulated gate bipolar transistors, realizing the highest capacity anywhere in the world. This created an inverter system with low noise levels, greater compactness and higher efficiency.
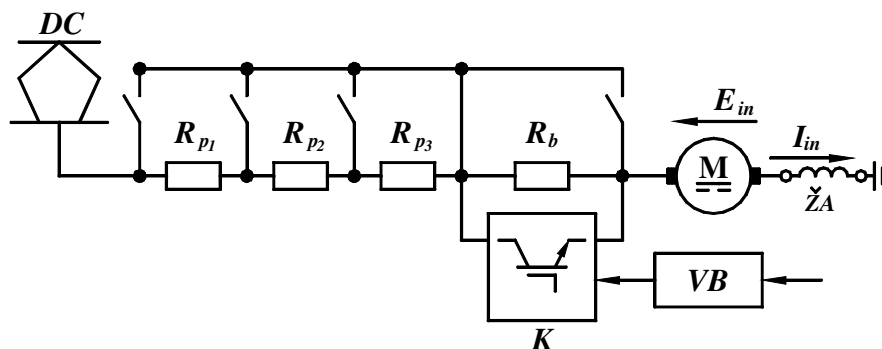

Fig. 2. A circuit diagram of rheostat starting (traction mode) of DC series excitation traction motor: DC - energy power supply; R_{p1}, R_{p2}, R_{p3} - additional resistors; ŽA - exicting traction motor winding

Рис. 2. Электрическая схема реостатного пуска DC тягового двигателя последовательного возбуждения (в режиме тяги): DC - энергетическая система постоянного тока; R_{p1}, R_{p2}, R_{p3} - дополнительные резисторы; ŽA - обмотка возбуждения тягового двигателя

Series-wound DC traction motors are disconnected from the power source (DC energy power supply) and traction motors of their armature windings are connected to braking resistors R_b (see Fig. 3).
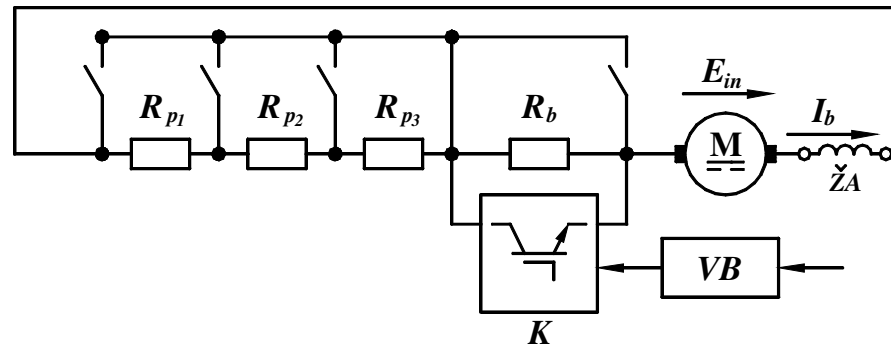
Fig. 3. A circuit diagram of (braking mode) of DC series excitation traction motor, where is used IGBT transistors module for pulse regulation of braking resistor R_b – parameters; K – IGBT transistors module; VB – IGBT transistors module operation bloc; I_b – braking current

Рис. 3. Электрическая схема реостатного пуска DC тягового двигателя последовательного возбуждения (режим торможения) с использованием IGBT транзисторного модуля для импульсного регулирования параметров тормозного резистора R_b: K – IGBT транзисторный модуль; VB – блок управления IGBT транзисторным модулем; I_b – ток торможения

Braking of trains in railway traffic should be controlled, implying that braking force, which could take into account all variables relating to braking and which could be adjusted, depending on the variation of the locomotive speed, rolling stock mass, road profile, etc. should be developed. Otherwise, the braking force could be insufficient for stopping the train in time, which might lead to failures and catastrophes. We suggest method of regulating resistor using a single braking resistor R_b, and resistor parameters regulate (see Fig. 4) with pulse regulation mode by semiconductor devices, such as new electrical components for rolling stock – IGBT transistors operating in the key mode.
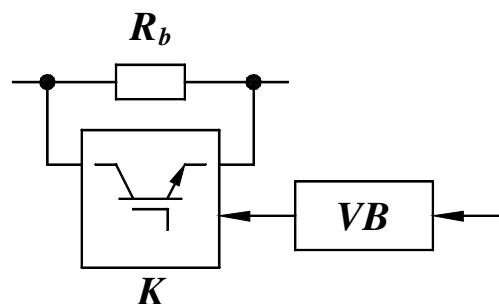
Fig. 4. A circuit diagram of IGBT transistors module can by used for pulse regulation of braking t resistor: R_b – braking resistor; K – IGBT transistors module; VB – IGBT transistors module operation block

Рис. 4. Электрическая схема IGBT транзисторного модуля при использовании импульсного регулирования тормозного резистора: R_b – тормозной резистор; K – IGBT модуль; VB – блок управления IGBT транзисторным модулем

IGBT transistor operating in the key mode forcibly commutated so that the commutation period remains unchanged, while the relationship between the duration of disabling t_{uzd} and enabling t_{atv} periods of transistor contact state varies (see Fig. 5). In other words, the width of the disabling pulse is being changed. This method of regulating braking resistor R_b as an electric circuit parameter is also referred to as width-pulse modulation. Another method called pulse-frequency modulation can also be used. In this case, $t_{uzd} = \text{const}$, while transistor commutation period T_k, i.e. its commutation frequency, is changed. By changing the disabling period of IGBT transistor, braking resistor resistance can be smoothly changed from the peak value to $R_b = 0$.
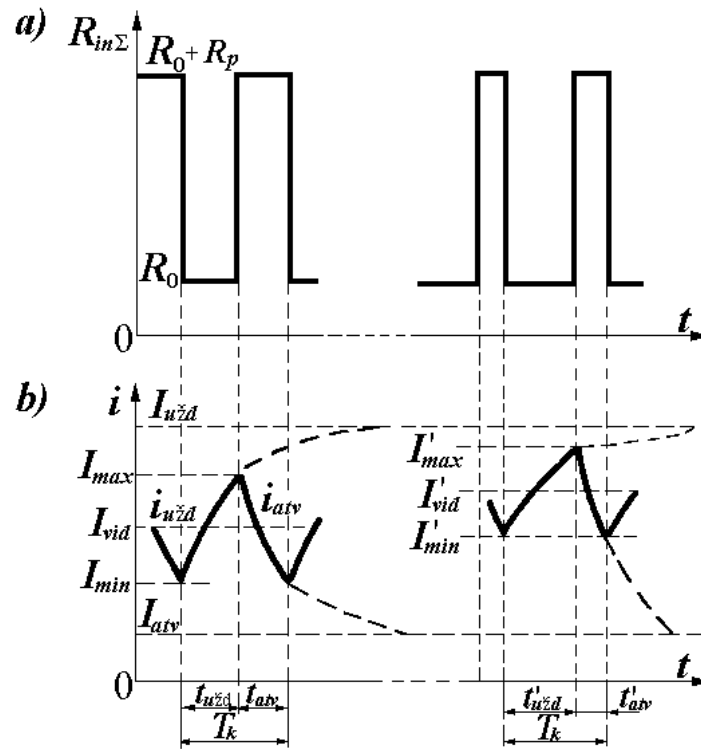
Fig. 5. Diagrams showing the changes in rheostatic braking circuit parameter (resistor) during pulse regulation (a) and braking current (b)

Рис. 5. Диаграмы илюстрирующие изменение параметров цепи реостатного торможения (a) резистора и тормозного тока (b)

The equivalent resistance can be obtained from the following expression:

$$R_{ekv} = \frac{E}{I_{vid}} \; ; \tag{2}$$

where: I_{vid} is the average value of the enabling current of armature circuit, A.

I_{vid} can be found as the average current value during the commutation period of IGBT transistor:

$$I_{vid} = \frac{1}{T_k} \int_0^{T_k} idt = \frac{1}{T_k \left(\int_0^{t_{uzd}} i_{uzd} dt + \int_0^{t_{atv}} i_{atv} dt \right)} . \tag{3}$$

Substituting the values of the currents i_{uzd} and i_{atv} we get:

$$I_{vid} = \frac{1}{T_k} \left[I_{uzd} t_{uzd} + I_{atv} t_{atv} - \frac{(I_{uzd} - I_{atv})(T_{uzd} - T_{atv})}{1 - e^{-\left(\frac{t_{uzd}}{T_{uzd}} + \frac{t_{atv}}{T_{atv}} \right)}} \times \left(1 - e^{-\frac{t_{uzd}}{T_{uzd}}} \right) \left(1 - e^{-\frac{t_{atv}}{T_{atv}}} \right) \right] ; \tag{4}$$

where: i is instantaneous value of armature circuit; i_{uzd}, i_{atv} stands for instantaneous values of armature circuit current for enabling and disabling states of IGBT transistor; $I_{uzd} = E/R_0 + R_p$ is the steady-state current value when the IGBT transistor conducts current; $I_{atv} = E/R_0 + R_p$ the steady-state current value when the IGBT transistor is disabled (the circuit is disconnected).

The expression obtained can be simplified because the circuit parameters are chosen in such a way that the commutation period T_k is much shorter than the time constant $T_{atv} (T_k << T_{atv})$ of the armature circuit, when R_p is connected. In addition, since $T_{uzd} > T_{atv}$, then, $T_k << T_{uzd}$. Under such

conditions, $t_{uzd} \ll T_{uzd}$, $t_{atv} \ll T_{atv}$, i.e. $t_{uzd}/T_{uzd} \ll 1$ and $t_{atv}/T_{atv} \ll 1$. Therefore, the deviation of instantaneous currents from the average value is insignificant, implying that the pulsing of current is low.

Substituting I_{uzd}, I_{atv}, T_{uzd} and T_{atv} in equation (4) and taking into account that $t_{atv} = T_k - t_{uzd}$, we get:

$$I_{vid} = \frac{T_k E}{T_k R_0 + (T_k - t_{uzd})R_p}.$$

(5)

Then, see (2):

$$R_{ekv} = R_0 + (1-\gamma)R_p.$$

(6)

The equivalent additional resistor, characterizing the control parameter, is as follows:

$$R_{pekv} = R_{ekv} - R_0 = (1-\gamma)R_p.$$

(7)

Thus, by changing the disabling time of IGBT transistor, additional braking resistor can be changed from R_b maximum, when ($\gamma = 0$, $t_{uzd} = 0$, $t_{atv} = T_k$) to zero when, ($\gamma = 1$ or $t_{uzd} = T_k$). The above statement is valid only for the finite braking resistor R_b value. The analysis performed allows us to conclude that by changing pulse ratio γ, which in turn changes R_{pekv}, the braking current (braking force) can be regulated with the required accuracy.

In using the above method, the main parameter of braking circuit-braking resistor will change according to the described regulation principle. The same applies to braking current I_{st} and braking force. High accuracy of braking force regulation can be achieved due to high speed of the system, using semiconductor elements IGBT transistors. IGBT transistors commutation frequency $f_k > 20000$ Hz (3300 V, 1200 A one element parameters).

DC/DC system diesel-electric locomotyves braking force is regulated by changing the electric traction motor's parameters in the following way: altering the excitation current of traction generator, when shaft revolutions of diesel generator are constant ($n_D = \text{const}$); varying the revolutions of diesel generator ($n_D = \text{var}$), when the excitation current of traction generator is constant ($I_z = \text{const}, \Phi = \text{const}$).

Let us consider a technique of determining braking characteristics of traction motors by analysing a circuit presented in Fig. 6.
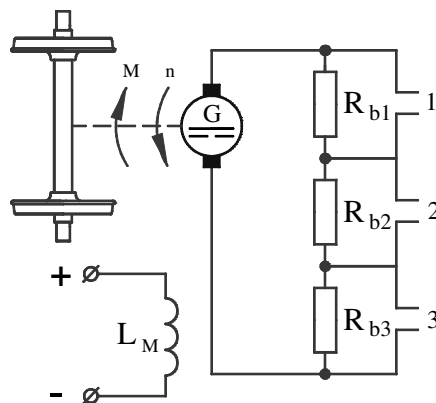

Fig. 6. Traction motor operating in generator rheostatic braking mode: R_{b1}–R_{b3} dynamic braking resistors; G – traction motor operating in generator mode; L_M – exciting traction motor winding; I_b – braking current; 1, 2, 3 – contactors

Рис. 6. Тяговой двигатель, действующий в режиме генератора при реостатном торможении: R_{b1}–R_{b3} – резисторы динамического торможения; G – работа тягового электродвигателя в генераторном-реостатном режиме; L_M – обмотка возбуждения тягового двигателя; I_b – тормозной ток; 1, 2, 3 – контакторы

The electromagnetic moment developed on the motor shaft can be expressed by the formula:

$$M_{em} = \frac{C_M}{\eta_{em}} I_b \Phi_{\check{z}};$$
(8)

where: $C_M = pn/2\pi a$ is constant of the motor; η_{em} is coefficient of mechanical and magnetic losses of the motor; p is the number of pole pairs; N is the number of armature winding conductors; a is the number of parallel branches; I_b is motor's armature (braking) current in rheostatic braking, A; $\Phi_{\check{z}}$ is main magnetic pole field Wb. $E_{in} = C_E \Phi_{\check{z}} n$ is obtained from the voltage balance equation:

$$C_E \Phi_{\check{z}} n = I_b \left(R_b + r_{in} + r_{pp} \right) = I_b R_b';$$
(9)

where: C_E motor constant; n is armature speed, r/min.; R_b is braking rheostat resistor, Ω; r_{in} is armature winding resistor, Ω; r_{pp} is resistor of additional poles, Ω; R_b' is total impedance of braking rheostat and armature circuit, Ω.

Thus, braking current can be expressed as follows:

$$I_b = \frac{C_M \Phi_{\check{z}} n}{R_b'}.$$
(10)

$$\Phi_{\check{z}} = \frac{I_b R_b'}{C_M \eta_{em}}.$$
(11)

Then, the braking moment directed oppositely to the rotation of the motor armature n can be expressed, based on (9), in the following way:

$$M_{em} = \frac{C_E C_M}{R_b' \eta_{em}} \Phi_{\check{z}}^2 n = Kn, \text{ when } \Phi_{\check{z}} = \text{const}$$
(12)

$$M_{em} = \frac{C_M R_b'}{C_E \eta_{em}} I_b^2 \frac{1}{n} = K \frac{1}{n}, \text{ when } I_b = \text{const}$$
(13)

As seen from the formulas (12) and (13), the linear braking moment relationship is obtained, when the excitation flux $\Phi_{\check{z}} = \text{const}$, while the hyperbolic relationship between the braking moment and the armature speed of the motor is established, when $I_b = \text{const}$.

To obtain diesel locomotive's braking characteristic, i.e. the relationship between the braking force on the wheelsets' rolling surface and the locomotive speed $B_{st} = f(v)$, the following formulas can be used [8]:

$$B_{st} = \frac{2M_{em}}{D} \frac{\mu m}{\eta_p};$$
(14)

where: μ is gear ratio of the gear drive; D is wheelset diameter, m; m is the number of traction motors; η_p is gear drive efficiency.

By using the above formulas (12, 13, 14), braking characteristics of a diesel locomotive $B_{st} = f(v)$ can be obtained. When the excitation flux $\Phi_{\check{z}} = \text{const}$, braking force is proportional to speed and can be depicted as a straight line, beginning at the origin of coordinates. When the braking current is constant – $I_b = \text{const}$, $B_{st} = f(v)$ is inversely proportional to speed, while the hyperbolic function changes.

The analysis of braking characteristics has shown that braking force can be regulated by varying the braking current I_b or excitation flux $\Phi_{\check{z}}$. Ideally, braking force can be maintained constant when the speed is varying.

3. REGENERATIVE ENERGY USE

Energy savings and power supply optimization possibilities. The most challenging operating for storage devises on board of traction vehicle are high number of load cycles during the vehicle lifetime, relatively short charge and discharge times as well as high charge and discharge power values. In contrast to high-maintenance, flywheel based, mechanical energy storage used in vehicles. Energy savings and power supply optimization system operates on purely electrical basis. The battery will charge when line voltage tends to go up so that it limits the line voltage increase. Regenerative braking energy is normally limited, when the line voltage goes up to a limit. Trains can unlimitedly generate regenerative braking energy when capacitors (see Fig. 7) conventional store batteries CCSB operated. The regenerative braking energy is consumed by the train itself and by other powering trains. Excessive power will be stored in the battery. The charging voltage at the bateries is higher than that of the substation. It is considered that all charged energy come from the regenerative braking**.**

Fig. 7. High-perfomance double layer technology capacitor (ultracapacitor)
Рис. 7. Конденсатор высокой емкости с технологией двойного слоя (суперконденсатор)

The inovative double layer ultra capacitors store the energy released each time a vehicle brakes and reduce it during acceleration or operation. Energy savings (optimazation) system where is used conventional storage battery which capacitor is offered (see Fig. 8). New technical solution is based on double layer capacitors with along service life and ten times higher performance than conventional batteries. High-performance storage cells are connected in series to create a storage unit. They store the electrical brake energy with relatively low losses.
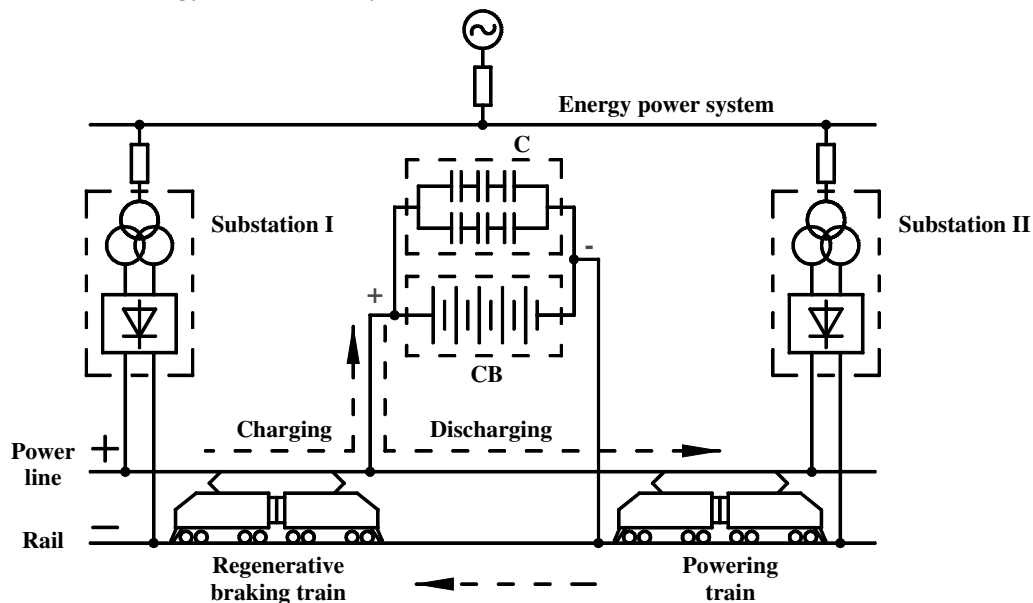

Fig. 8. A circuit diagram of using regenerative braking returning energy: C – capacitors; CB – conventional batteries
Рис. 8. Схема, илюстрирующая использование энергии рекуперативного торможения: C – конденсаторы; CB – традиционные батерии

Prevent losing effect of regenerative braking energy with limited line voltage drop. Regenerative braking energy will lose its effect when the line voltage goes up to 900 V (when nominal 750 V) and when substations operated with no batteries. The CCSB enables to limit the voltage increase when charging. In case of our proof test, line was 830 V when the CCSB operated so that it could prevent losing regenerative braking energy. When powered trains are congested at rush hours, since the line voltage tends to drop, the batteries discharge to make voltage balance between those of the CCSB and the substation. Receiving electricity can be reduced around 110 kW when battery/substation is connected by parallel operation, and 175 kW when the CCSB is operating (see Fig. 8–12) by itself. Prevent line voltage drop with discharging bateries. The lowest voltage of the power line was up to 680 V from when the CCSB operated. The new technical solution is used by conventional batteries with high-perfomance double layer capacitors (ultracapacitors). Energy-saving system can be use when provides vehicles with an energy source that allows frequent starting and braking. The system works by charging up these storage devices with electrical energy released when braking. This stored energy can be use in many ways. Energy-saving system can be use in conjunction with any traction converter. Energy savings and power supply optimization system can reduce the energy consumption of a light rail or metro system by up to 30 percent. Using power supply optimization system for diesel multiple units allows energy savings can be even up about 35 percent. Alternatively, the stored energy can be used as performance booster: enhances the performance of vehicle by adding extra power during acceleration.
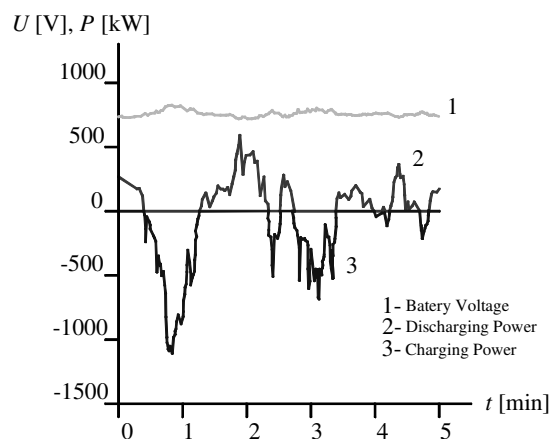

Fig. 9. A capacitors-conventional store batteries CCSB parameters curves: charging (regenerative braking) and discharging(acceleration) mode, battery voltage

Рис. 9. Кривые параметров (напряжения и мощности) конденсаторов и традиционной накопительной батерии CCSB при заряде (в режиме тяги)
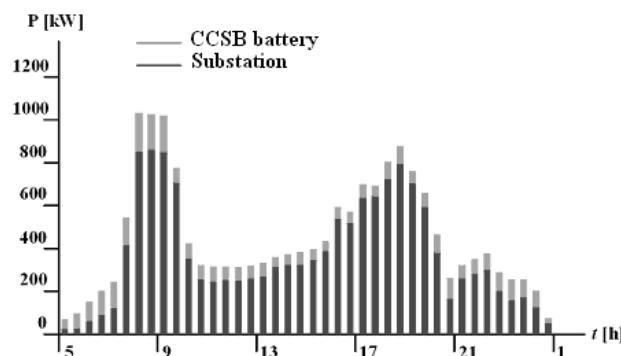

Fig. 10. Reduced electric power demand, when capacitors-conventional store batteries CCSB parallel connected with substation

Рис. 10. Уменьшение уровня потребляемой мощности подстанции при паралельном включении CCSB батерии

Perfomance boosting. The additional power from the energy savings and power supply optimization system can be used to boost the vehicle's speed when line current or engine power are limited. Assuming e.g. 30% power from the energy savings and power supply optimization system could result in 30% higher power while keeping the same line current demand. This extra power results in addional tractive effort and allows significantly higher train acceletation. Thus, the energy saver compensates the disadvantage of the usually limited power of diesel engines or increases the output capacity of light rail or metro system.
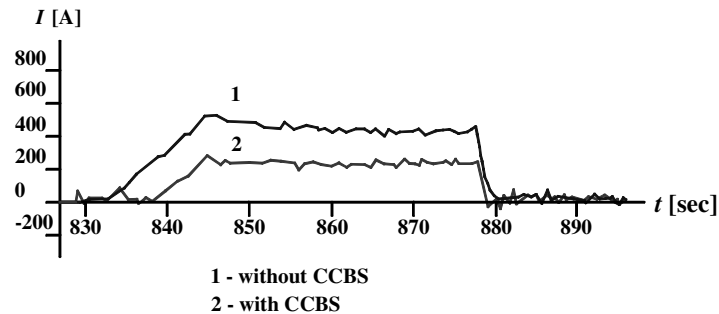

1 - without CCBS
2 - with CCBS

Fig. 11. A catenary current curves (train operation mode)
Рис. 11. Кривые тока контактной сети (режим тяги)

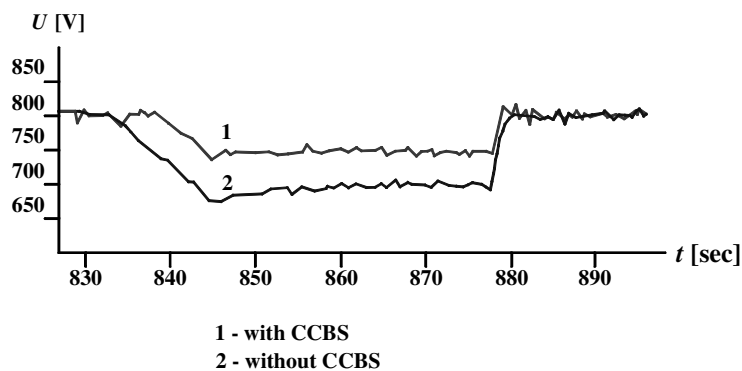1 - with CCBS
2 - without CCBS

Fig. 12. A catenary voltage curves (train operation mode)
Рис. 12. Кривые напряжения контактной сети (режим тяги)

Energy savings and power supply optimization system stores the energy released when braking and uses this energy during the next acceleration of the vehicle. Eact time the vehicle brakes, the energy storage devises are loaded again. During the next acceleration, the stored energy is released. This additional energy lowers current demands from the network, yet the traction effort stays the same. Acceleration up to 50 km/h shows a reduction of the peak power demand can be up to 50 percent.

4. HYBRID PROPULSION SYSTEM. HYBRID TRACTION TECHNOLOGY

Energy-saving propulsion system using storage-battery technology. As train, the train using its traction motors the authors suggest to use a hybrid propulsion system combining an engine generator with storage batteries. The traction batteries store the regenerated electrical power that would have otherwise been wasted in heat using friction/dynamic braking. Using regenerative braking, fuel consumption is minimized. Peak levels of energy effiency are regulated by the energy management system. Any recovered energy can be used for traction. This system provides regenerative braking not previously possible on conventional diesel-powered trains, and this makes it possible to increase energy savings via regenerated energy. The system can use a series-hybrid

configuration designed to allow immediate system conversion (by replacing the engine generator with a fuel-cell unit). As a step towards providing environmentally friendly propulsion systems. We are offering to use a hybrid traction technology. Traditionally diesel locomotives powered electical transmision cannot use regenerative braking energy.

As train, the train using its traction motors, the traction batteries store the regenerated electrical power that would have otherwise been wasted in heat using friction/dynamic braking. Using regenerative braking, fuel consumtion is minimized. Peak levels of energy effiency are regulated by the energy management system. Any recovered energy can be used for traction.

Regenerative braking mode (see Fig. 13). Under braking, the engine is stopped. The traction motors act as generators, and recovered energy is used to charge the batteries.
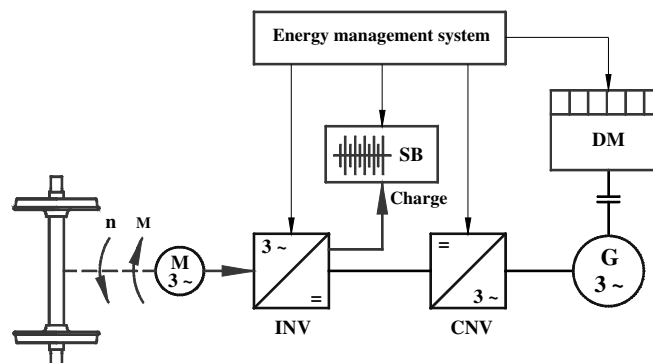

Fig. 13. A circuit diagram of Hybride Traction System (regenerative braking mode): DM – diesel engine; G – synchronous traction alternator (generator); INV – inverter; CNV – converter; SB – storage battery; M – asynchronous-traction motor

Рис. 13. Схема тяговой гибридной системы (в режиме рекуперационного торможения): DM – дизельный двигатель; G – синхронный тяговой генератор; INV – инвертер; CNV – конвертер (выпрямитель); SB – накопительная батерия; M – асинхронный тяговой двигатель

Departure mode (see Fig. 14). Whilst at a station, the engine can be stopped and necessary hotel power provided from the battery. Upon departure, the train accelerates using recovered energy only.
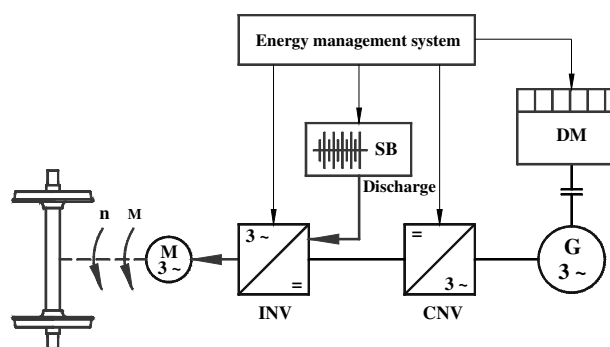

Fig. 14. A circuit diagram of of Hybride Traction System (departure mode)
Рис. 14. Схема тяговой гибридной системы (в режиме отправления)

Acceleration mode (see Fig. 15). For additional acceleration, the Energy Management system will start diesel engine, and begin to blend the power to keep the engine operating efficiently.
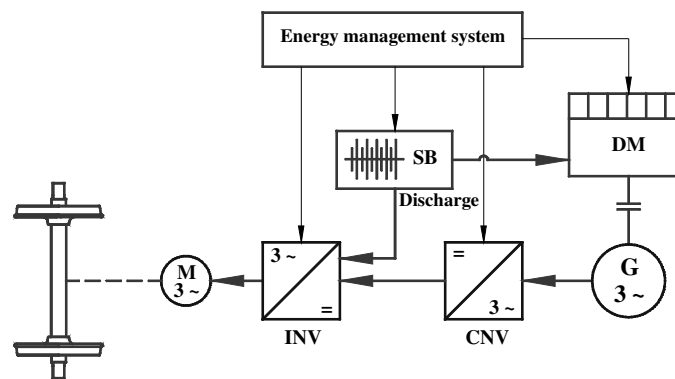
Fig. 15. A circuit diagram of of Hybride Traction System (accelaration mode)
Рис. 15. Схема тяговой гибридной системы (в режиме ускорения)

5. CONCLUSIONS

1. Electrodynamic braking is the main braking technique used for modern electrically-driven locomotives.

2. High accuracy of braking force regulation helps decrease longitudinal dynamic forces developed in stepwise pneumatic braking.

3. When lokomotives use regenerative braking of high-speed trains under the conditions of heavy railway traffic allows 25–40 % of electric power to be returned to the power system. The required braking forces can be obtained in a wide range, with regeneration braking used in a high-speed range and rheostatic braking – in a low-speed range.

4. Mechanical braking, commonly used now, should be kept in reserve as a technique duplicating the main braking method and used to completely stop a locomotive when its speed is 5–2 km/h.

5. An advanced method of braking force control in rheostatic braking by uniformly changing the main circuit parameter – rheostat resistor value in a non-contact way by means of semiconductor switches is suggested.

6. Energy savings and power supply optimization possibilities.

7. A scheme of using hybrid traction technology.

8. The regenerative braking power makes it possible to use in diesel electric locomotives for starting engine, accelaration, operation mode.

9. The power stored in the locomotive in traction is completely utilized. When ordinary mechanical braking is applied, no useful work is done by the power and it is not used in braking.

In upgrading the infrastructure and technical equipment of railways, the influence of electrodynamic braking of the elements of infrastructure should be taken into account.

10. Basic theoretical principles of electrodynamic braking and schemes of its practical realization is presented in the paper.

References

1. Liudvinavičius L., Lingaitis L. P.: *Electrodynamic braking in high-speed rail transport.* Transport, Vol. XXII, No 3, 2007, pp. 178–186.
2. Lingaitis L. P., Liudvinavičius L.: *Electric drives of traction rolling stocks with ac motors.* Transport, Vol. XXI, No 3, 2006, pp. 223–229.
3. Theeg G., Baumgartner S., Maschek U.: *Comparison of signalling systems for high-speed train movements.* Rail International, No 10, 2006, pp. 65–73.
4. *Mitsubishi Electric Transportation Systems.* Japan, 2003, pp. 2–21.

5. ECO4 *and the Climate is Right for Trains are trademarks of Bombardier inc. or its subsidiaries.* 2008, pp. 4–20.
6. Стрекопытов В. В., Грищенко А. Б., Крушек В. А.: *Локомотивные электрические передачи.* Москва: Маршрут, 2003.
7. Čilikinas M. G., Sokolovas M. M., Terechovas V. M., Šinianskis A. V.: *Elektrinių pavarų bandymo pagrindai*. Vilnius: Mokslas, 1978.
8. Smilgevičius A.: *Automatikos mikromašinos*. Vilnius: Technika, 2005.
9. Вилкевич Б. И.: *Автоматическое регулирование электрического привода*. Москва: Машиностроение, 1980.
10. Gasiński L., Kaszuba R.: *Jakość eksploatacji pojazdów – uwarunkowania i sterowanie jakością.* Materiały Konferencyjne KONMOT'96. Tom. 2. Politechnika Krakowska. Kraków, 1996, pp. 47–52.
11. Minotti P., Fereira A.: *Les micromachines*. Hermes – Collection automatique, 1998.
12. Mazaras S.: *Elektros mašinos*. I dalis. Vilnius: Mokslas, 1989.
13. Kageyama I.: *On a control of tyre force coefficient for vehicle handling with neural network system*. In. Proc. 13th IAVSD Symposium, China, 1993, pp. 31–34.