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Management of Locomotive Tractive Energy Resources

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1. Introduction

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 saving systems) and diesel engine or any form of hybrid traction vehicles systems, circuit diagrams, electrical parameters curves. Environmental awareness plus reduced operating costs are now major considerations in procuring advanced rail vehicles for considerations in procuring advanced rail vehicles. It is needed to reduce electric demand, to use new energy savings and power supply optimization, hybrid traction vehicles systems, which are using regenerative braking energy. Electric braking is effective on the all speed. Air brake cannot be used. When a vehicle brakes, energy is released to date, most of this energy is being wasted in air. The challenging alternative is to store the braking energy on the train and use it during acceleration of operation of the vehicle. Presenting energy savings power systems, which are using regenerative braking-returning energy and diesel engine or any form of hybrid traction vehicles systems, light vehicles catenary free operation, circuit diagrams, electrical parameters curves (Liudvinavičius L. *New locomotive energy management systems*, 2010; Sen P. C., *Principles of Electric Machines*, 1996).

2. New elements-supercapacitors of energy accumulation

Companies of electronics created capacitors of big capacity, which are called in different countries as ultra condenser, pseudo condenser, supercapacitors, ultracapacitors. In English literature besides is found the name *Electric Double Layer Capacitors*. The characteristics of



Fig. 1. High-performance double layer technology capacitor (ultra capacitor) picture

supercapacitors are very high. Single module capacities are 3000F, at the tension 2,7V and even more powerful. (P. Barrade, *Series connexion...*, 2001). All this has given an impuls to the various scientific researches. Structure of the supercapacitor is given in Fig.1

Comparative characteristics of the supercapacitors and accumulators are given in the table below:

| Performance | Accumulator | Supercapacitor |
|-----------------------|-------------|----------------|
| Energy (Wh/kg) | 10 – 100 | 1 – 10 |
| Number of cycles | 1000 | > 500 000 |
| Specific power (W/kg) | < 1000 | < 10 000 |

Table 1. Characteristics of accumulator and supercapacitor.

The charge – discharge time of conventional accumulative batteries is very long, because chemical reaction depends on time. The charge – discharge time of supercapacitors (J. D. Boyes..., *Technologies for energy...*, 2000). is only few seconds. In addition, their period of duty is incomparably longer. The authors performed first experiments on purpose to evaluate their technical characteristics in 1997. The diesel engines are used for creating of primary energy, which power is up to 6000kW. JSC *Lithuanian Railways* uses diesel engines, which power is up to 4000 hp. Using conventional systems of starting, from alkaline or acid accumulators, starting of such engines is very complicated because it requires powerful batteries of accumulators. During cold season the starting of such power diesel engines is particularly complicated. If in two or three attempts of starting the diesel engine fails, it is necessary to change the locomotive in line. If starting of diesel engine is not successful, main systems of diesel engine freeze, causing considerable material damage. Starting of high-power diesel engines also is a very complicated in ships. In this case, the consequences even worse than in the railway. The locomotives TEP-60 and TEP-70, which power of diesel engines is up to 4000 hp are used for pulling coaches. The locomotives TEP-60 and TEP-70 are with electrical drive. Conventional 110V X 550Ah accumulative batteries, weight of 3400 kg, are used for starting of diesel engines. The experts of Vilnius Gediminas Technical University and Vilnius locomotive depot have been researching how to extend the life of battery, reduce their weight, improve the conditions of diesel engine starting up. In Russia the supercapacitors were bought, for which evaluation of technical abilities the authors suggested to use them for starting up of the most powerful diesel engine of *Lithuanian Railways*, the locomotive TEP-60 with DC/DC current system. The supercapacitor assembled in a block (in Figure SCB), combining the separate elements sequentially, for the possibility to connect the capacitor to direct current (DC) of 110V voltage network, and parallelly, the total capacity must be enlarged (in Farads). For a fast discharge (charge) cycle of the capacitor, which is calculated by $T = RC$, the authors suggested to charge the supercapacitors from conventional charging equipment of accumulators, existing in locomotive. Fig.2 shows the first (preparatory) phase of diesel engine starting up: the charge of the supercapacitor (R. G. V. Hermann, *High performance...*,2001).

Charged supercapacitors to connect parallelly to accumulative battery (conventional battery of 110V X 550Ah) of much smaller capacity.

The structure of the locomotive TEP-60 electric drive Traction generator is used to start the diesel engine, i.e. is running as a conventional starter. In Fig. 3 the diagram is given, where the generator G, during the starting up is running in mode of direct current (DC) engine. The scheme of starting up of the diesel locomotive TEP-60 diesel engine is given in Fig.4.

Closing the chain of the contactor K, the starting up of the diesel engine is running, feeding from accumulative battery (of 110V X 550Ah) of much smaller capacity and parallelly connected supercapacitors.

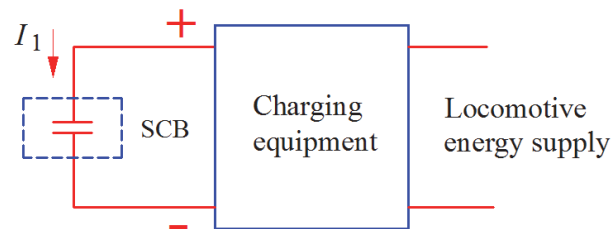


Fig. 2. The charge of the supercapacitors from the energy source of locomotive

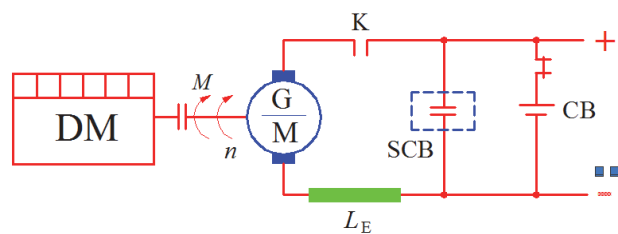


Fig. 3. The scheme of starting up of the diesel locomotive TEP-60 diesel engine:

DM- diesel engine; G/M- DC electric machine (generator or motor mode G/M) CB- conventional battery; SCB-block of supercapacitors; L_E - series existitation winding

3. The results of the research on new energy accumulation elements – using of the supercapacitors in starting up of diesel engines

In Fig.4 the diagram of locomotive TEP-60 diesel engines’ starter’s running of current accumulators in chain is given, where the diesel engine is starting up from conventional batteries (CB), whose parameters are 110V x 110V 550Ah, without SCB and the diagram 2 of current run, when the diesel engine is started using accumulative batteries of smaller capacity (110V x 160 Ah) and the block in parallel connected supercapacitors. Using the

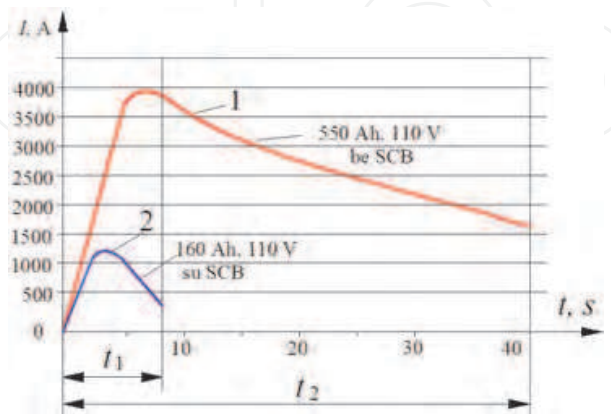


Fig. 4. The diagrams of starting up of the TEP-60 diesel engines starter in chain of current accumulators: 1- battery current without SCB, when traction generator operates in a starter mode; 2- battery current with SCB, when traction generator operates in a starter mode

conventional system of current starting up in chain of accumulators is up to 3700A. Using the conventional system of current starting up in chain of accumulators suggested by the authors is up to 1200A. The time of Diesel engine starting up, using the conventional system is 40-50 seconds, and using a complementary system is 7-10 seconds.

4. Locomotive energy saving systems

At this period of time locomotives new energy (3) saving technologies include: 1-optimized desing vehicle; 2-energy management control system; 3-energy storage system; 4- low energy climate system; 5-clean diesel motor power pack; 6- new technologies traction motor. Energy saving up to 8-15% using aeroefficient otimized train, up to 10-15% using energy management control system, up to 25-30% using energy storage system, up to 25-30% (Liudvinavičius..., *The aspect of vector...*, 2009) using energy storage system, up to 25-30% using low energy climate system. Clean diesel motor power pack reduced particle emission 70-80%. New technologies traction motor increased energy efficiency 2- 4% at reduced volume and weight. New technogies can create energy savings up to 50%. Fig. 5 shows the possibilities of new energy saving technologies.

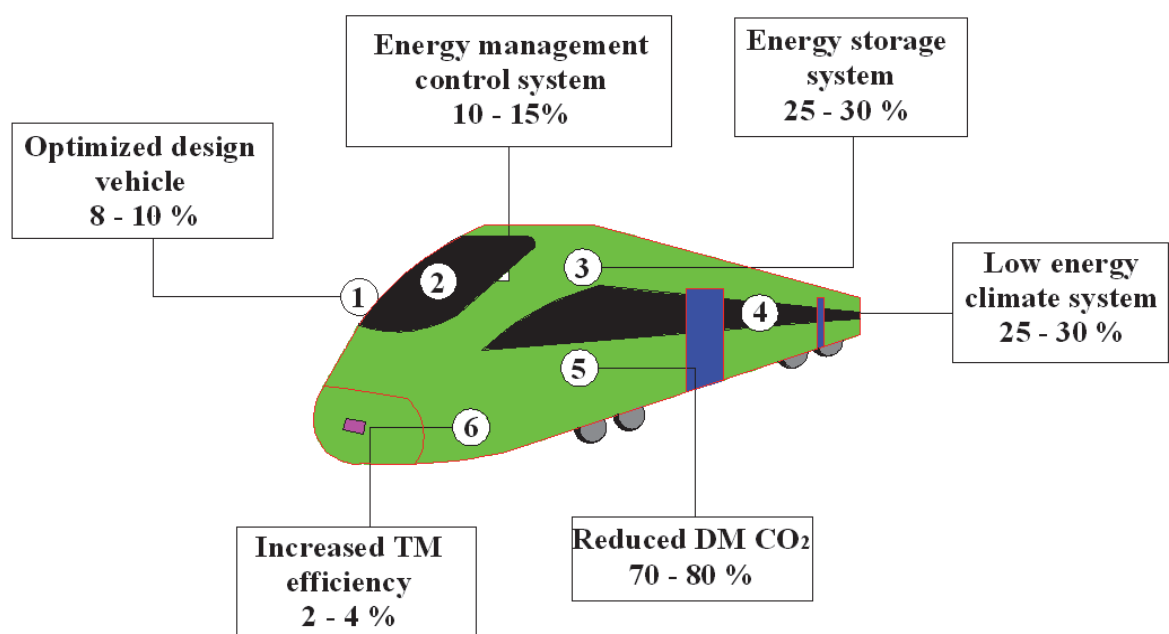


Fig. 5. Diagram of locomotive energy saving structure

5. Possibilities of new locomotives regenerative braking

Locomotive electric braking system may be divided into dynamic, and regenerative. Thus, the dynamic braking energy is converted into heat and dissipated from the system. In other words, electric energy generated is the typically wasted. In a typical prior art AC locomotive, however, the dynamic braking grids are connected to the DC traction bus because each traction motor is normally conected to the bus by the way of autonomous inverter. Fig. 6 shows that conventional structures electric locomotive AC traction energy transformed into heat through the braking resistor- R_b (Liudvinavičius..., *Electrodynamic braking...*, 2007).

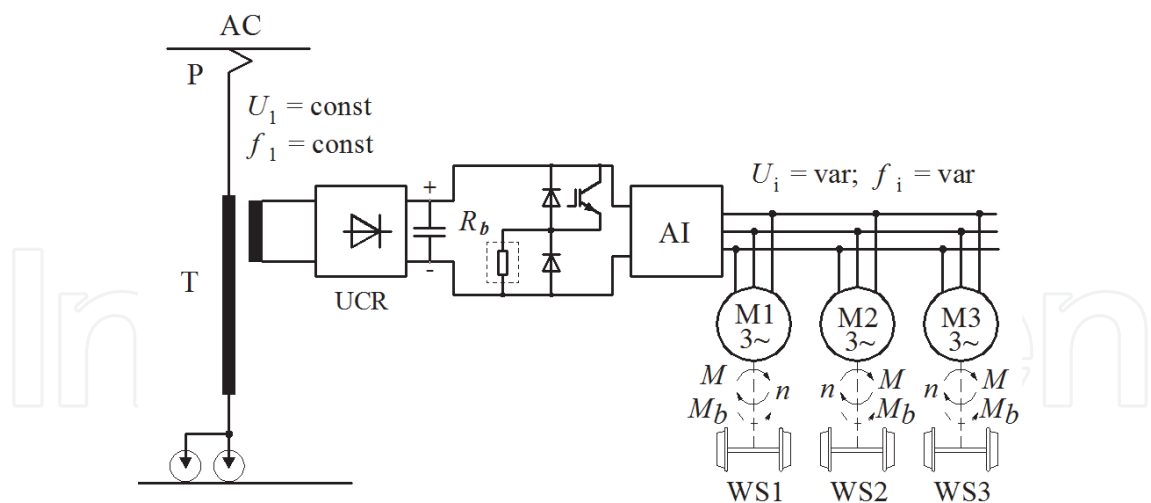


Fig. 6. A circuit diagram of AC/AC conventional electric locomotive dynamic braking: UCR-uncontrolled rectifier; AI- autonomous inverter; R_b -braking resistor; M1, M2, M3-one bogie asynchronous traction motors; WS,...,WS3-wheel-sets

Regenerative braking is more energy effective because power given to catenary power system is either used by another electric train or returned to power system. Thus, the conditions for the motor being idle to exceed point n_0 of torque-speed characteristic $n = f(M)$, which is required in regenerative braking, cannot be satisfied (see Fig 8). Locomotive traction motor regenerative braking energy is possibly returned in to energy supply system then AC traction motor's speed is above no -load speed n_0 . The traction motor goes to the generator mode, while electromagnetic moment, becomes a braking moment, and the power produced by generator is given to the catenary (energy power supply system).

6. Methods of new asynchronous traction motors speed control

The most modern kind of speed control of three-phase induction motors is the control by changing frequency f_1 . (Lingaitis L.P. ..., Electric drives..., 2006; Strekopytov V..., Electric drives..., 2003). It ensures a wide control of range of the speed and causes only little additional losses.

Relative slip expressed by the formula:

$$s = \frac{n_1 - n_2}{n_1}; \tag{1}$$

Where:

n_1 - the speed of the rotary field; n_2 -speed of the rotor (rotor speed on load)

f_1 - main frequency is: $f_1 = \frac{pn_1}{60}$, f_2 -frequency of the rotor voltage $f_2 = \frac{pn_2}{60}$ (there p -is number of pole pairs). Then:

$$s = \frac{f_1 - f_2}{f_1}. \tag{2}$$

Asynchronous motor's rotor speed:

$$n_2 = n_1(1-s) = \frac{60f_1}{p}(1-s); \quad (3)$$

may be adjusted in the following ways: by adjusting supply voltage U_1 ; by adjusting main frequency f_1 ; by varying the number of pole pairs- p , speed of the rotor's rotating field can be discretely changed; by adjusting slip s (not using slip energy), the nature of the speed-torque characteristic can be changed; by adjusting slip s (using a part of slip energy- cascade speed control circuits of asynchronous motors). Asynchronous motors with squirrel-cage rotors and their parameters expressed by the formula:

$$M = \frac{p_1 m_1 U_1^2 \frac{r_1}{s}}{2\pi f_1 \left(r_2' + \frac{r_1}{s} \right) + (x_1 + x_2')}; \quad (4)$$

Where p_1 and m_1 – are numbers of the stator's poles and phases; r_1 and x_1 – denote resistance and inductive impedance of stator; r_2' and x_2' – denote resistance and inductive impedance of rotor reduced in accordance with the stator's parameters; U_1 – is supply voltage of the stators windings. Optimal mode of operation of asynchronous motors with squirrel – cage rotors (Lingaitis L. P. ..., *Electric drives of traction rolling stocks with AC motors*, 2006):

$$\frac{U_1}{U_1'} = \frac{f_1}{f_1'} \sqrt{\frac{M_1}{M_1'}}. \quad (5)$$

Hence, an optimal mode of operation of asynchronous motors with squirrel – cage rotors is defined by the relationship between their three parameters - amplitude of voltage U_1 , frequency f_1 and the developed torque M_1 . A mode of operation of a locomotive can be described by the locomotive speed V and traction or braking force F_k of wheel - set. It was found that: $V = 0,188 \frac{D}{\mu} \frac{60f_1}{p} (1-s)$ or $V = 0,188 \frac{D}{\mu} \frac{60f_1}{p} = C_1 f_1$, and $F_k = \frac{2M}{D} \mu \eta_p = C_2 M$ (here: D – is diameter of the locomotive wheel-set; μ – is gear ratio; η_p – is gear efficiency). On the basis of the formula (8), we can determine mode control of locomotives with asynchronous motors:

$$\frac{U_1}{U_1'} = \frac{V_1}{V_1'} \sqrt{\frac{M_1}{M_1'}} \text{ or } \frac{U_1}{U_1'} = \frac{V_1}{V_1'} \sqrt{\frac{F_k}{F_k'}}. \quad (6)$$

In this case, speed V_1 and traction or braking force F_1 correspond frequency f_1 , and supply U_1 , or V_1' and F_k' – traction or braking force in presence of frequency f_1' and voltage U_1' . When the supply voltage increases, the characteristics move the area of higher speed (Fig 7, line 2). By changing simultaneously the supply of voltage U_1 and its frequency f_1 , depending on mode of regulation, any flat characteristics can be obtained.

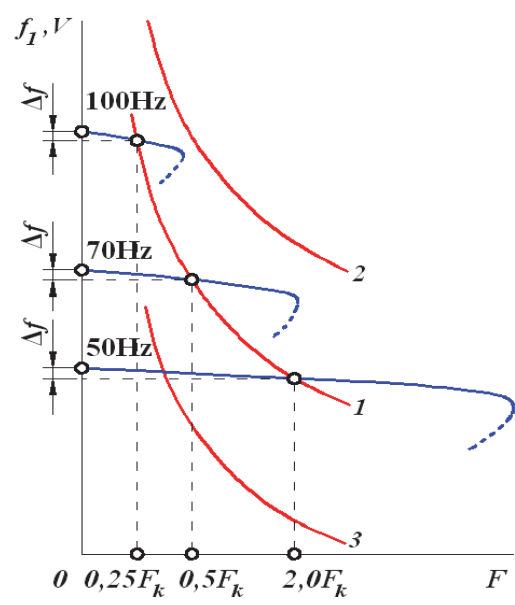


Fig. 7. Torque-speed characteristic of induction traction motor’s traction modes by changing main frequency f_1 - f_i - parameters

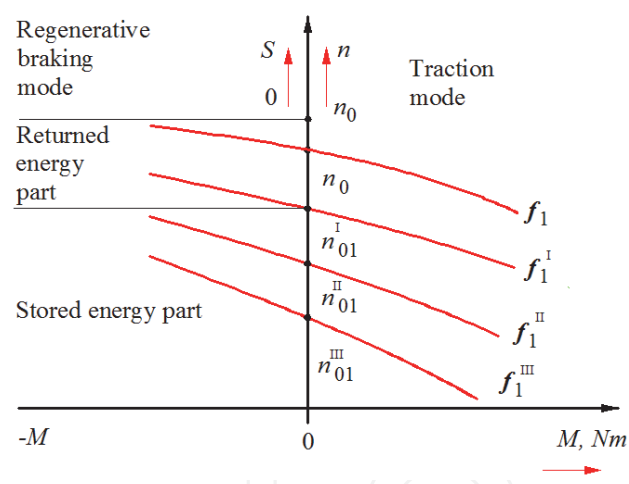


Fig. 8. Torque-speed characteristic of induction traction motor’s regenerative braking and traction modes by changing main frequency f_1 - f_i - parameters: $n_{o1} - n_{oi}$ is AC traction motor’s no-load speed

The frequency controlled squirrel-cage induction motor can be easily showed down by reducing the supply frequency.

Traction motor’s no-load speed n_o is possible by changing the frequency f_1 and to receive more regenerative braking characteristics and regenerative braking energy returned to network supply or charging storage battery. Fig. 9 shows AC traction motors new possibilities of traction and regenerative braking modes operating. The energy management structure suggested by the authors in Fig.9 will allow the full use of regenerative braking capabilities: in a high-speed range to return energy for the energy system, in a low-speed range - to accumulate the energy in a battery of energy accumulating for further use. The characteristics given in Fig.8 illustrate these findings.

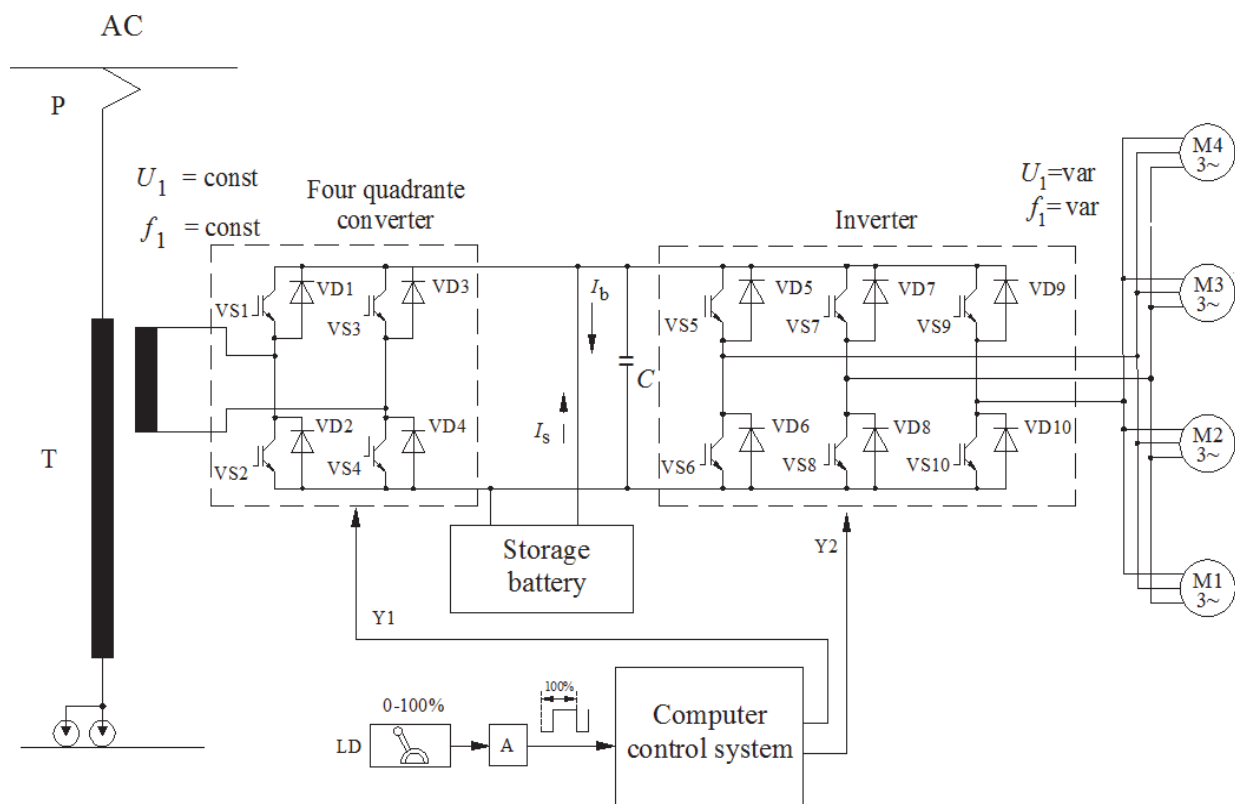


Fig. 9. A circuit diagram of AC/AC current system electric locomotive regenerative braking energy computer control system: M1-M4 – AC traction motors; LD- locomotive driver; A- analogic – digital converter; T- traction transformer; P- pantograph; VS1-VS10-IGBT transistors; VD1-VD10-diodes; Y1-four quadrant drive control signals; Y2- inverter drive control signals; I_b -braking current; I_s - stored current; WS1-WS4- wheel-sets

Authors suggested to install storage battery into AC/AC current system conventional electric locomotive. Fig.9. shows principle of the braking energy management system used in AC/AC electric locomotive, when a part of regenerative braking energy is returned into energy supply system and part of energy is stored in storage battery.

7. Hybrid traction propulsion systems

Hybrid traction technology. Energy-saving propulsion system using storage-battery technology. As the train uses its traction motors the authors suggest to apply a hybrid propulsion system combining an engine generator with storage batteries (A. Rufer ..., *A supercapacitor-based energy storage...*, 2002.). A hybrid energy locomotive system having an energy storage and regeneration system. The system uses a series-hybrid configuration, designed to allow immediate system conversion (by replacing conventional diesel-powered train the engine generator with a fuel-cell unit, in pursuance locomotive modernisation and ect.). We offer to use a hybrid traction technology. Conventional diesel locomotives powered with electrical transmission can not use regenerative braking energy. Any recovered energy can be used for traction.

This is expected to give fuel savings of approximately 20%-25% compared with conventional diesel-powered trains. An engine cutout control is also employed to reduce noise and fuel consumption while trains are stopping at stations.

Hybrid system configuration. This system uses a series-hybrid configuration (see Fig.10) that first converts the engine output into electrical power and then uses only motors for propulsion. Storage batteries are located on the intermediate DC section of the main converter. The charging and discharging of the storage batteries are controlled by using output adjustments of the converter and inverter. Charging and discharging processes of storage batteries are controlled by the converter and inverter output for management system.

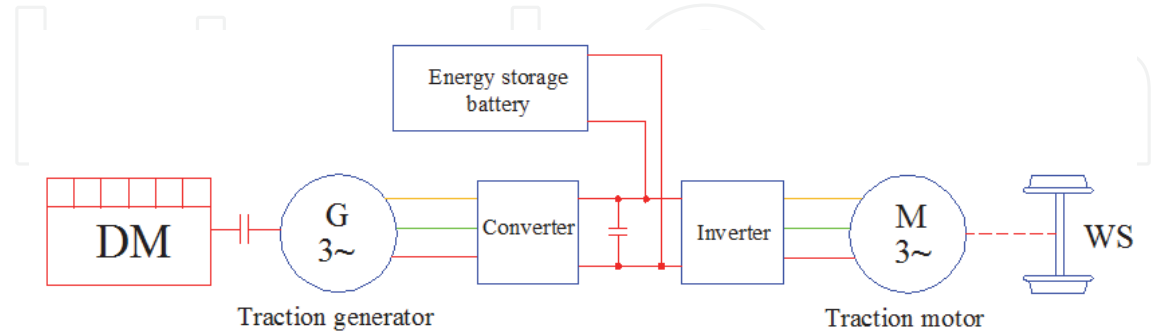


Fig. 10. A circuit diagram of Hybrid Traction System configuration with AC traction motors: DM-diesel engine; G-synchronous traction generator; M-induction traction motor.

A hybrid energy locomotive system can be used in AC or DC electric traction motors. When using DC traction motors, output of the alternator is typically rectified to provide appropriate DC power. When using AC traction motors, the alternator output is typically rectified to DC and traction inverter is shifted to three-phase AC before being supplied to traction motors.

Regenerative braking mode. The traction motors act as generators and recovered energy is used to charge the batteries. Storage battery operation of charging mode. Control of regenerative braking energy is carried out by using a bidirectional semiconductor converter of DC-AC energy which operates at a rectifier mode. In the braking mode, the control is directed from the energy source (AC - asynchronous traction motor) to energy storage batteries. (Takashi Kaneko.,et al.,. *Easy Maintenance...*, 2004).

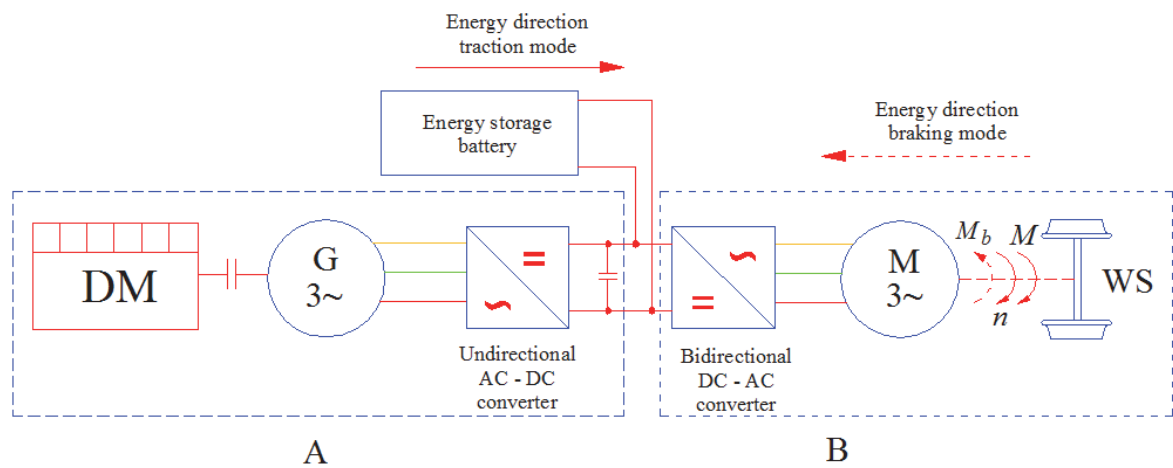


Fig. 11. AC/AC power structure diesel-electric locomotive complementary energy management system in regenerative braking and traction mode: DM-diesel engine; G-synchronous traction generator; M- AC traction motor. M_b - electromagnetic moment in the braking mode; n -speed of the rotor; A-energy generation part in the traction mode; B-energy generation part in the braking mode.

Departure and acceleration mode. The traction motors act as generators and while at a station, the engine can be stopped. For and necessary hotel power can be provided from the battery. Upon departure, the train accelerates using the recovered energy only. Storage battery operation of discharging mode.

8. Main requirements for hybrid traction system

The technical trends in train traction systems are shown in Fig.11, 12, 13. In line with those trends, it is possible to develop rolling stock electrical-system with the following features to meet the demand for reduced maintenance, energy savings, environmental friendliness, and compact and light weight structures (Strekopytov, V. ..., *Electric drives...*, 2003; Yamaguchi, J. , *Automotive Engineering*, 2006).

Propulsion equipment requirements.

Hybrid traction system is used for high power variable voltage variable digital frequency VVVF traction converter. The authors offer to implement the conventional converter-inverter systems and auxiliary power converters which were applied vector control [5] techniques and new semiconductor elements high-voltage IGBT (insulated gate bipolar transistors). Commutation frequency of IGBT transistors is $f_k > 20000$ Hz. (one element parameters: 3300V, 1500A)

Traction motor speed control requirements. The authors suggest using AC traction motor speed drive sensor less vector control methods. AC traction motor speed sensor less vector control eliminating the speed sensor of traction motors creates space for increasing their power and improving their maintenance.

All-speed range electric brake control. Hybrid traction system needs to use more accurate traction motors speed estimation technology which enables the combination of sensor less speed vector control (Liudvinavičius, Lionginas ..., *The aspect of vector...*, 2009) with all-speed range electric brake control.

Storage battery system. Storage battery system can be of different types, such as: C-with capacitors; CB- conventional battery; C-CB- capacitors; CB- conventional battery.

Storage battery energy management system. Storage battery management technology enables storing brake energy in diesel-powered trains, expanding regenerative brake energy into high-speed region in electric trains, and stably supplying DC (direct current) power to the auxiliary power converter. Using hybrid traction system electric train inverter control technology makes regenerative braking possible and regenerated energy, temporarily stored in the batteries, can be used as auxiliary power for acceleration. Fig.12. shows the Hybrid Traction System auxiliary power inverter schematic circuit diagram.

The authors suggest using stored energy for starting the diesel engine. Fig 13 shows block circuit diagram of the Hybrid Traction System equipment: the inverter control technology enables using regenerated energy as auxiliary power for acceleration, i.e. the Figure shows technical possibilities of using stored energy for starting the diesel engine.

Using this system, it is possible to start a 2000- 6000 kW diesel engine in a short time. Traction motors regenerative braking energy charges ultra-capacitors block and latter ultra-capacitors block energy is used for starting the diesel engine. The authors propose to use the main inverter of Hybrid Traction System which operates on pulse- width modulation (PWM) principle function.

Function principle of PWM inverter. The function of an inverter is to transpose the DC voltage of the intermediate circuit into symmetric tree- phase voltage of variable frequency

and amplitude. The necessary pulse diagram and the generated main voltage U_{UV} (at the terminals) are shown in Fig. 15. However, this voltage is non-sine-shaped. The effective value of the assumed sine-shaped supply voltage must be proportional to the frequency by changing the width of the single pulses in relation to the period duration. This kind of voltage control is called pulse-width modulation (PWM)

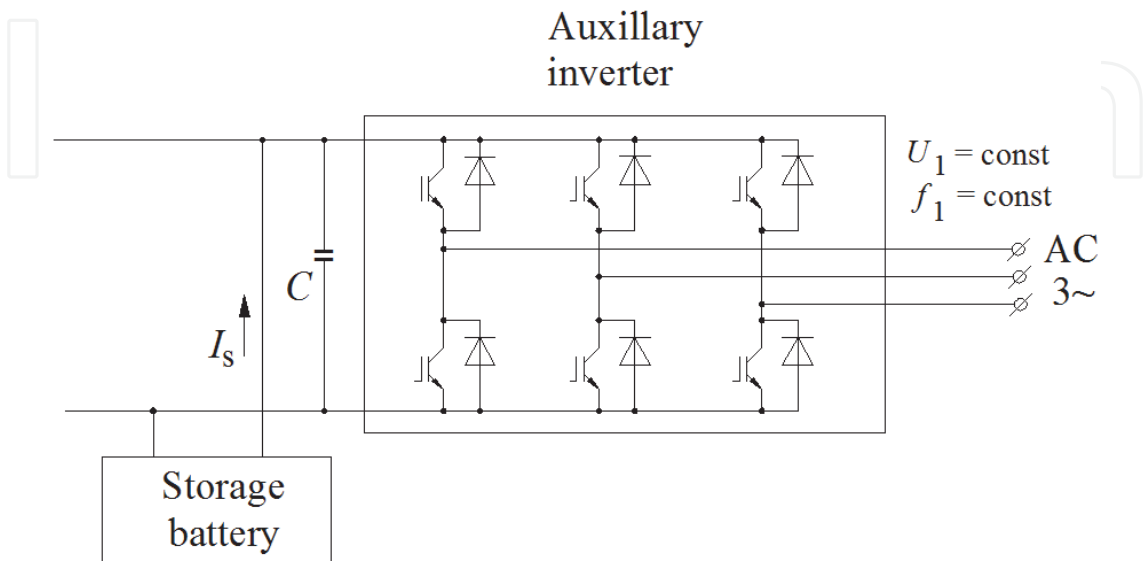


Fig. 12. Principal circuit diagram of Hybrid Traction System auxiliary power inverter

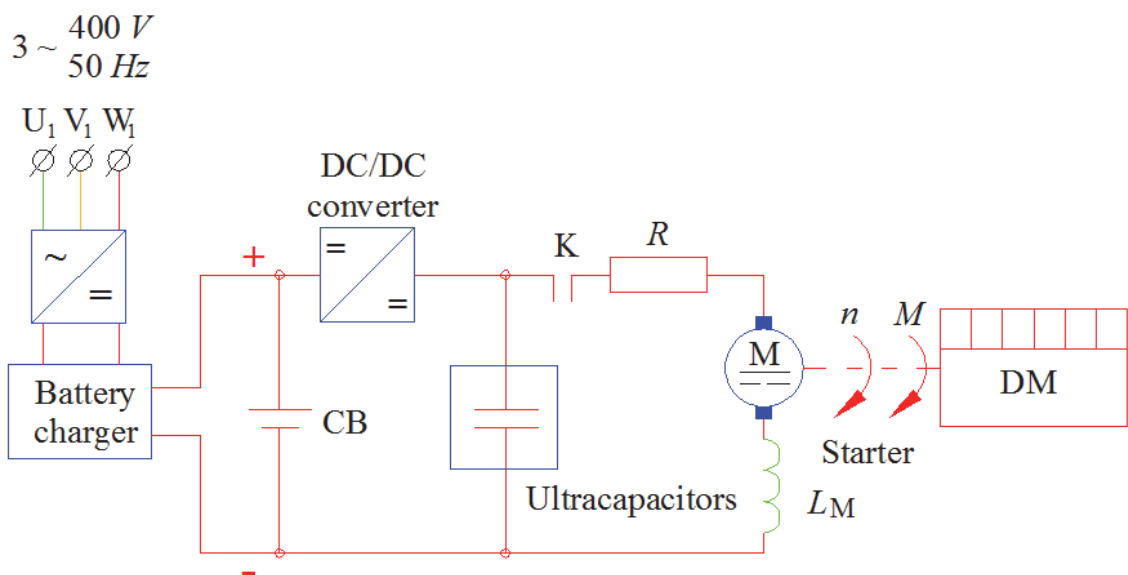


Fig. 13. Block circuit diagram of the Hybrid Traction System diesel engine start operation mode: DM- diesel engine; CB- conventional battery; K-contactor;

Fig 14 shows the example of a pulsed voltage block with five pulses per half-wave and the resulting main voltage U_{UV} . In this process, the voltage pulses of the main voltage become wider towards the middle of a half-wave as they first approach a sine-shaped course of the main voltage. For this reason, this kind of drive is called sine-weighted pulse-width modulation.

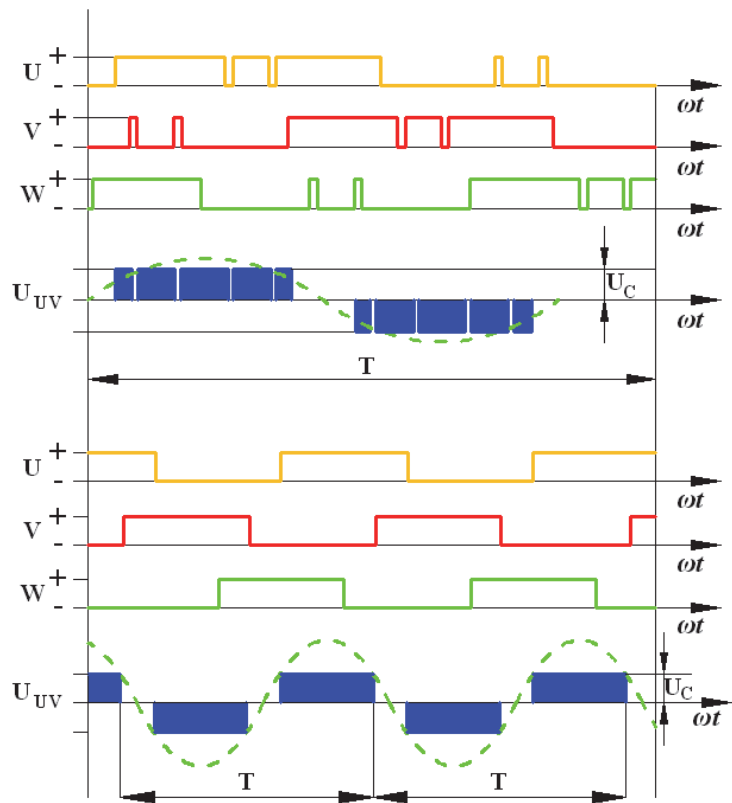


Fig. 14. Pulse diagram for 5 pulses and inverter per main wave

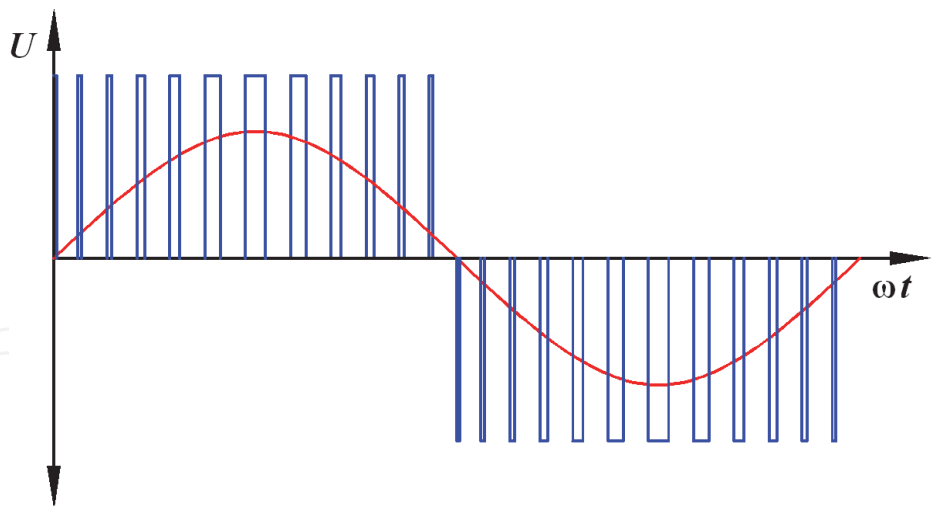


Fig. 15. The main voltage U_{UV} . pulse resulting diagram of the principle generation of a sine-weighted PWM

Fig. 15 shows the generation of pulse sequence for valve control and the resulting main voltage U_{UV} . Pulse frequency of the converter is determined by the frequency of delta voltage. The higher the switching frequency is, the better the sine weighting of the converter output voltage and the smaller the harmonic portion of the output currents are. A reduction of the harmonic portion leads to smaller oscillating torque and losses of the motor. Thus, the switching frequency should be as high as possible.

The authors suggest using an externally supplied energy system with energy tender.

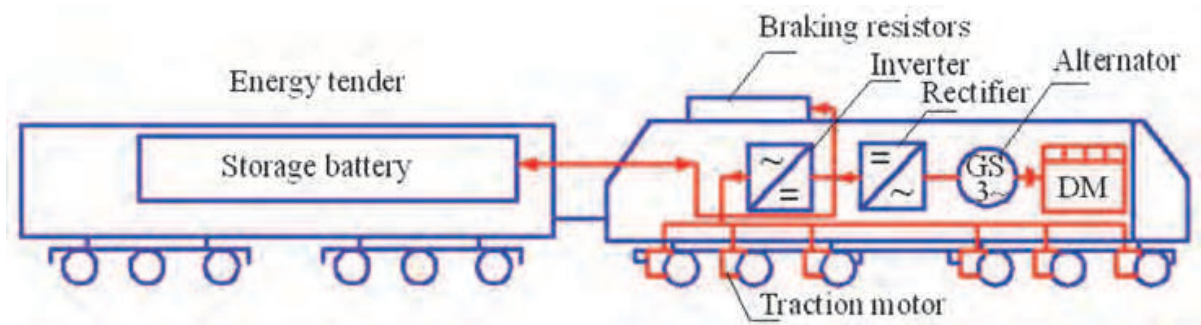


Fig. 16. Circuit diagram of hybrid energy traction system using energy tender vehicle

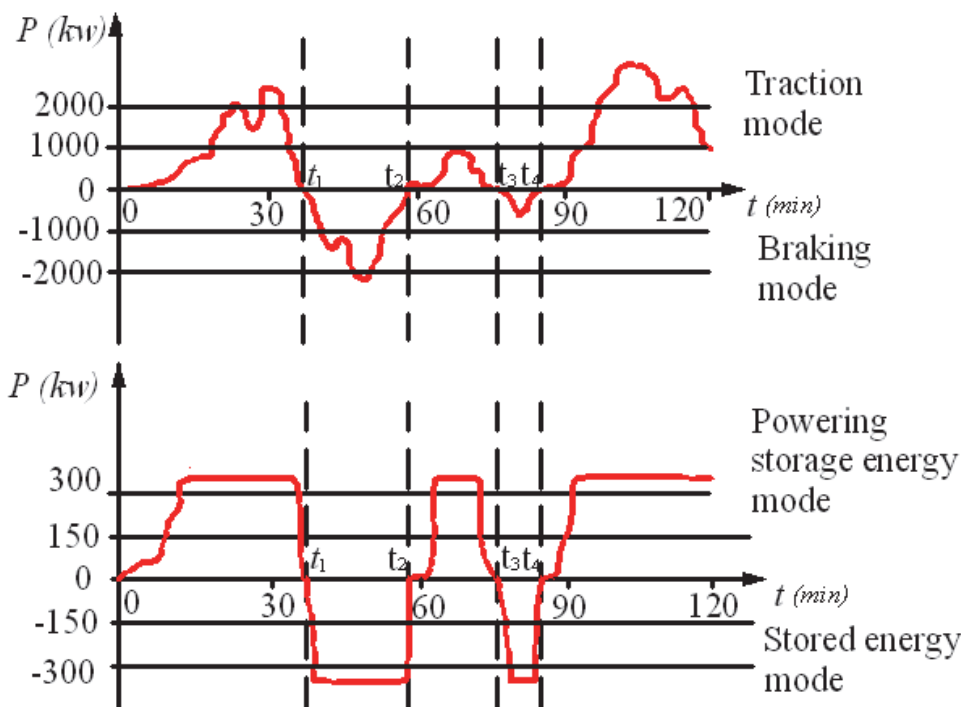


Fig. 17. Timing diagram of hybrid energy traction system using energy tender vehicle

Timing diagram is illustrating the locomotive energy management system, traction and regenerative braking mode. Timing diagram illustrating the hybrid traction system has the following energy storage possibilities: 0- t_1 , t_2 - t_3 -time cycles of using powered storage energy traction and auxiliary equipment mode; t_1 - t_2 time cycles of stored energy mode.

9. Energy saving and catenary voltage stabilization systems

Fig 18 presents the diagrams of voltage variation in direct current (DC) contact networks. Their analysis shows that when the load current I_C increases in the complementary (DC) contact network system, the voltage falls significantly (its value diminishes). In comparison to standard voltage of 3000V in the contact network, the values are lesser by 10%, i.e. 300V, whereas they are only -1% lesser in the complementary energy saving voltage stabilization

system proposed by the authors. This is achieved by using energy storage batteries parallelly connected to the direct catenary current (b). The batteries are charged from electric trains during the regenerative braking of electric locomotives. Locomotives operating in the traction mode use less electrical energy from traction substation I and substation II because a part of energy is supplied by the energy storage batteries. These batteries do not require a separate voltage source for charging as they are charged by using the kinetic energy of the trains which emerges during the regenerative braking mode of electric trains and electric locomotives. Conventional accumulators, a supercapacitors block or in parallel connected accumulators and a block of supercapacitors may function as energy storage batteries. The complementary system ensures the stabilization of catenary voltage (maintaining it in the set boundaries) when the load current increases (from point A to point B) in the contact network (Precision inductosyn position..., 1996).

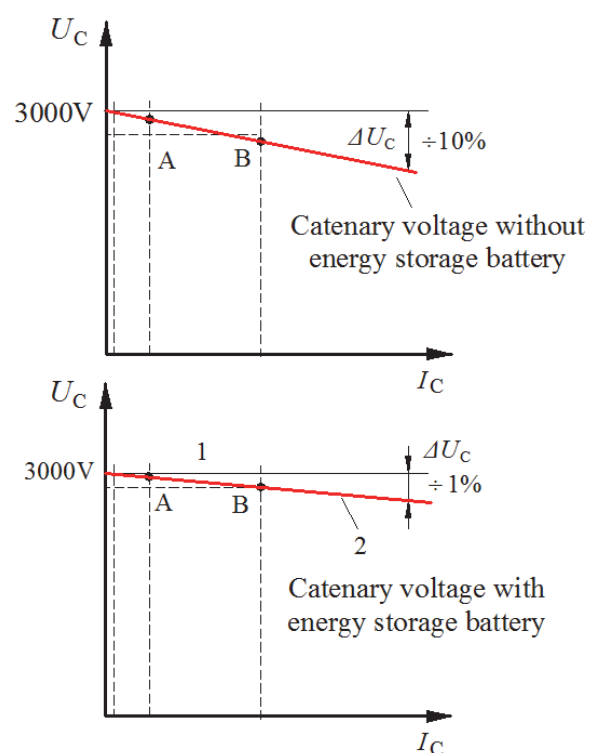


Fig. 18. Parameters of energy saving and variation of catenary voltage in a conventional a) and complementary energy management systems: U_C –catenary voltage; I_C –catenary current

10. Structure and energy management in complementary energy saving and current stabilization systems

Generally, first-generation electrified lines for railways, underground, trams and trolleybuses were exclusively of direct current with voltages of 600, 750, 1500 and 3000V. Although the catenary voltages 600, 750, 1500, 3000V are relatively low and do not meet the present-day requirements since they limit the speed and weight of the trains due to the voltage in the drop line. In order to increase the reliability and stability of DC contact network (present energy system) and save some energy consumed for traction, the authors suggest in parallel connecting energy storage batteries between the contact network and rail. The principled scheme of energy saving and catenary current stabilization structure is given

in Fig 19. Energy storage battery in parallel connected to the DC contact network is composed of conventional batteries (CB) and supercapacitors block (SCB).

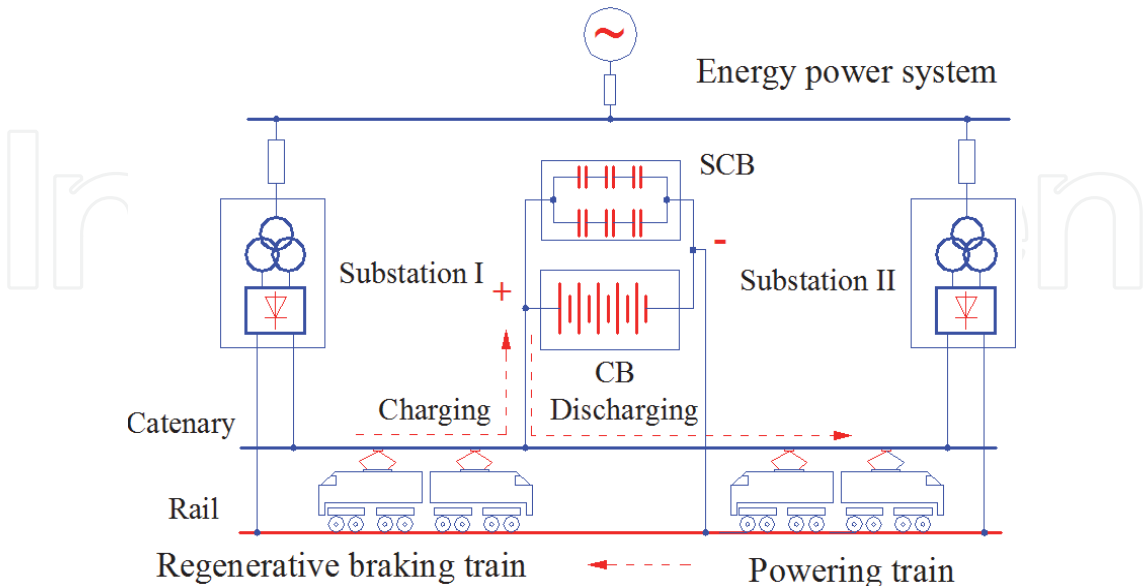


Fig. 19. Complementary principled scheme of energy saving and catenary current stabilization structure: CB- conventional batteries; SCB-supercapacitors block

Energy management system is presented in Fig 20. The authors propose using a semiconductor key K, composed of IGBT transistors and diodes, for energy direction control. In the traction-regenerative breaking modes, the energy direction and level of battery charge may be controlled by sending control signals to the electronic key K.

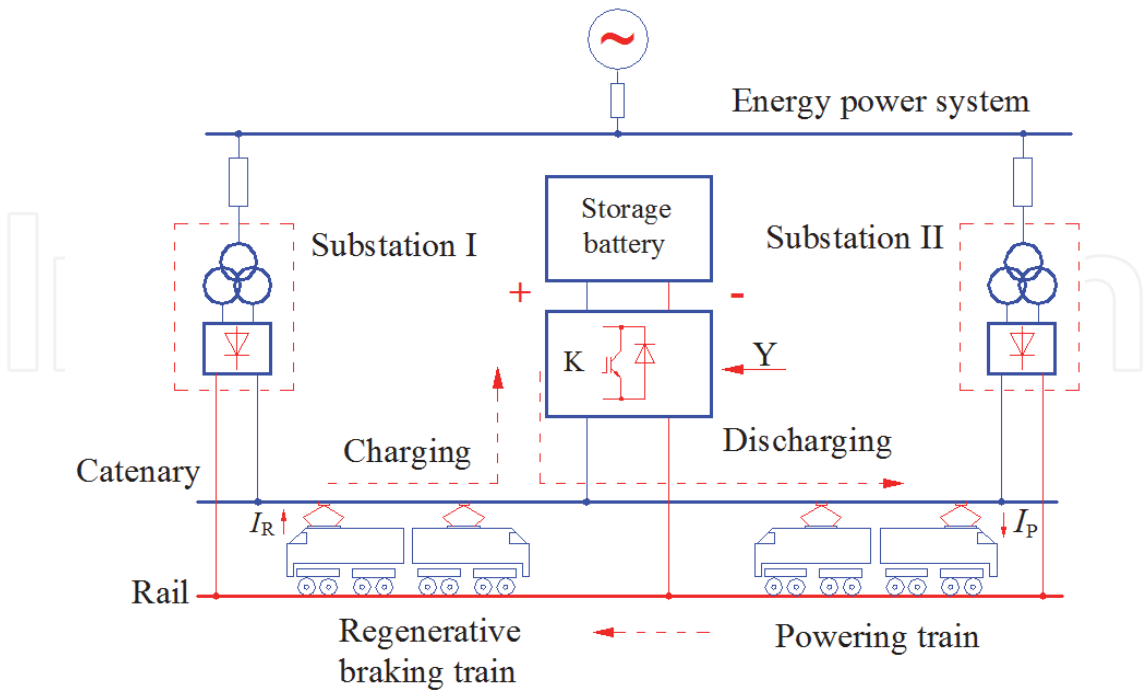


Fig. 20. Scheme of energy management system structure: I_R – regenerative current; I_P – traction mode current; K- semiconductor key for energy direction control

The most challenging operating for storage devices 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. The battery is charged when line voltage goes up so that it limits the line voltage increase. Trains can unlimitedly generate regenerative braking energy when capacitors SCB block and conventional storage batteries CB operate. The regenerative braking energy is consumed by the train itself and by other powering trains. Excessive power is stored in the battery. The charging voltage in the batteries is higher than that of the substation. All charged energy is considered to come from the regenerative braking. The SCB block and conventional store batteries CB enable limiting the voltage increase during the charge. When powered trains are congested at rush hours due to the line voltage tendency to drop, the batteries discharge to reach a voltage balance between the voltages of the SCB-CB block and the substation. The new technical solution is used in conventional batteries with high-performance double layer capacitors (ultra-capacitors). Energy saving system can be used when the vehicles are provided with energy source that allows frequent starting and braking. The system works by charging up these storage devices with electrical energy released when braking. 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 enables to save more than 35 percent of energy. Alternatively, the stored energy can be used as a performance booster, i.e. to enhance the performance of a vehicle by adding extra power during acceleration.

11. Vehicle catenary – free operation possibilities

In addition to these well-known factors, the municipal authorities are increasingly facing visual pollution caused by power poles and overhead lines obstructing the visibility of landmark buildings and squares. With catenary-free operation, trams can run even through heritage-protected areas, such as parks and gardens, historic market and cathedral squares, where conventional catenary systems are not permitted, thus preserving natural and historic environments. Authors suggest using catenary-free system for trams, light rail vehicles and trolleybuses. In many city centers, the overhead lines and their surrounding infrastructure contribute to visual pollution of historic streets, parks or architectural landmarks. The new system allows catenary-free operation of trams over distances of varying lengths and in all surroundings as well as on underground lines – just like any conventional system with overhead lines. Catenary-free system traction inverter is connected to the storage battery which is charged during vehicle traction motor operation in regenerative braking mode and discharged during traction motor operation in traction mode, where conventional energy lines are discontinued. Energy saver, which stores electrical energy is gained during operation and braking on board of the vehicle by using high-performance double layer capacitor technology. When running on conventional system, trams and light rail vehicles take energy from an overhead electrical line. The authors suggest installing the vehicle (inside or outside) with a storage battery (ultra-capacitors block) which stores the energy gained during regenerative braking operation and is constantly charged up, either when the vehicle is in motion or waiting at a stop, picking up the power from the storage battery. Fig.21 22, 23, show vehicle configuration and catenary-free operation possibilities. The power necessary for catenary-free operation is provided from the battery.

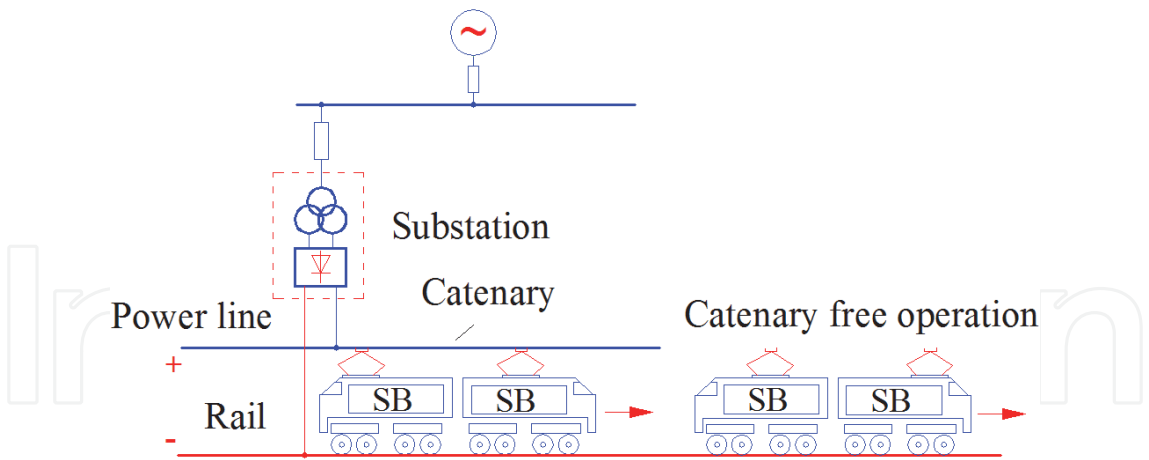


Fig. 21. Circuit diagram of vehicle catenary free operation: SB- storage battery

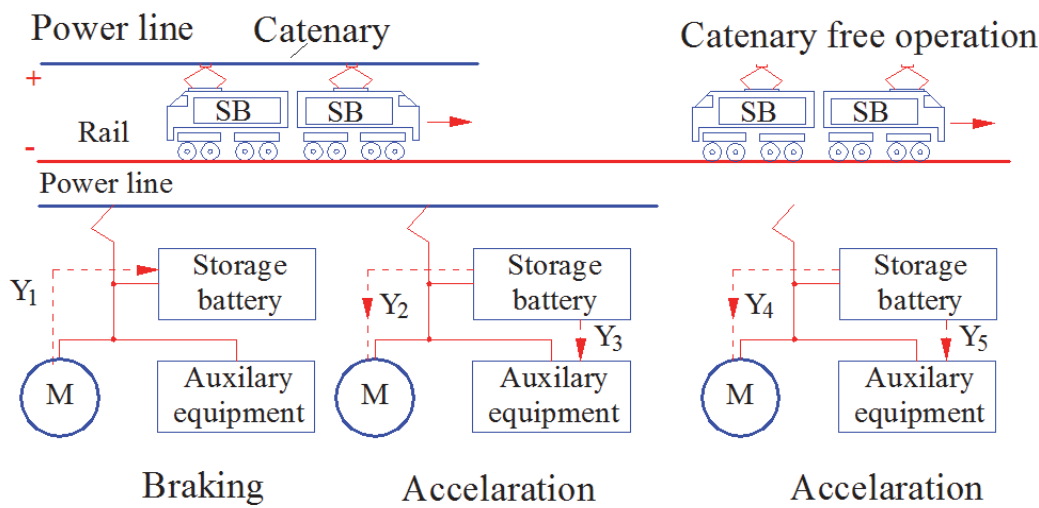


Fig. 22. Catenary-free operation of the vehicle: Y1-Y4-energy management drive signals; M- traction motor

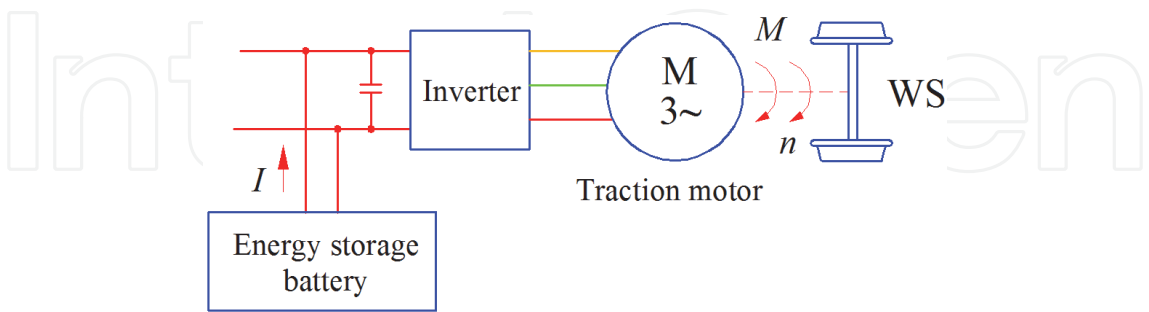


Fig. 23. Circuit diagram of catenary-free operation of the vehicle (traction mode)

The innovative double layer ultra-capacitors store the energy released each time a vehicle brakes and reduce it during acceleration or operation. 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 (Fuest, K.; Döring, P. *Elektrische Maschine und Antriebe*, 2000; Stölting, H.-D., *Elektronisch betriebene Kleinmaschine*, 2002).

12. Hybrid locomotive energy balance

Within the bounds of the present research, the question of qualitative evaluation of regenerative power during hybrid vehicle braking is of fundamental importance.

Vehicle power during braking on horizontal road P_{br} can be expressed by the following equation:

$$P_{br} = k_m \cdot m \cdot a \cdot V, \quad (7)$$

Where: k_m - coefficient of rotational masses; m - vehicle mass; a - vehicle acceleration (deceleration); V - vehicle velocity. The power that can be received during regenerative braking is:

$$P_{regen} = k_m \cdot m \cdot a \cdot V \cdot \eta_{regen}, \quad (8)$$

Where: k_m - coefficient of rotational masses; m - vehicle mass; a - vehicle acceleration (deceleration); V - vehicle velocity; η_{regen} - efficiency of regenerative braking (can be defined as rate of energy, received during braking up to decrease the kinetic energy of the vehicle). At the same time, regenerative braking power can be considered as electric power which is finally received by the storage element (in this case storage battery):

$$P_{regen} = P_{el} = I_{bat} \cdot U_{bat}, \quad (9)$$

Where: P_{el} - electric power received by the battery; I_{bat} - battery current; U_{bat} - battery voltage. The effectiveness of regenerative braking can be estimated using these equations:

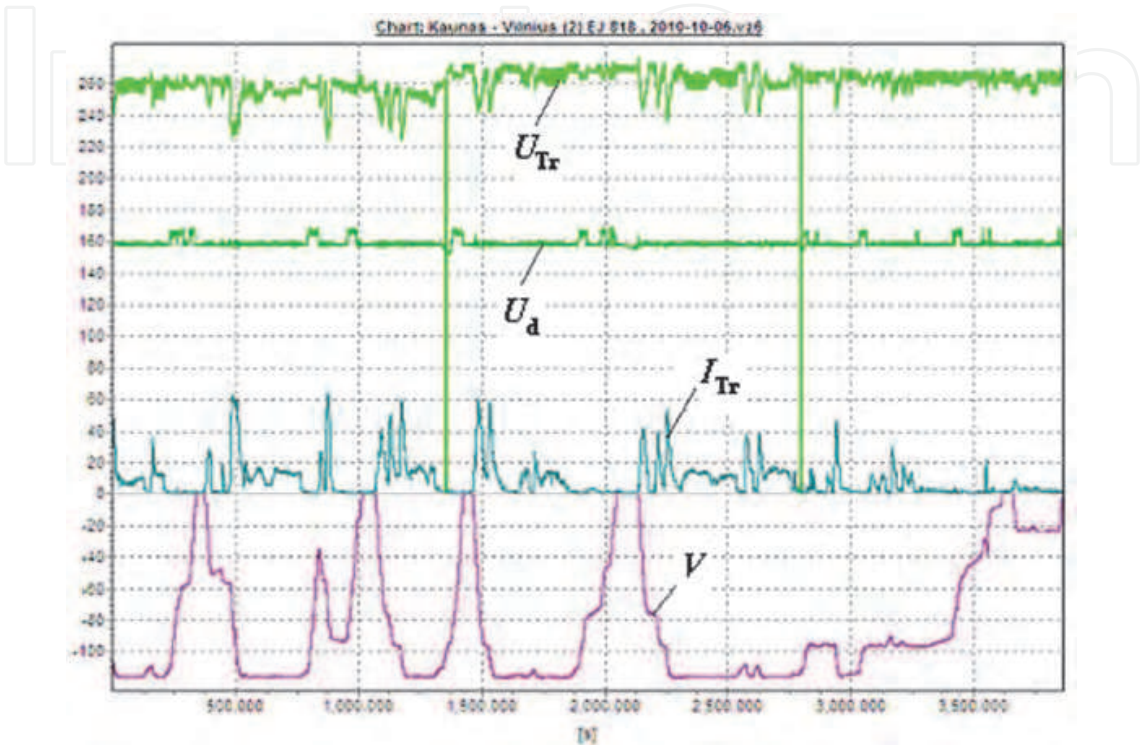
$$\eta_{regen} = \frac{P_{regen}}{P_{br}} = \frac{I_{bat} \cdot U_{bat}}{k_m \cdot m \cdot a \cdot V}, \quad (10)$$

JSC *Lithuanian Railways* has acquired four new-generation double-deck electric trains type EJ-575. In order to evaluate consumption of energy of the new generation double-deck electric trains type EJ-575, the authors carried out the practical research. The aim of the research is to determine why the electric trains type ER-9M (without energy saving system) and EJ-575 (with energy saving system), running in the same section, consume different amounts of electrical energy. Practical research, and statistical comparisons of results are carried out.

13. Practical researches of train EJ-575 energy management

In order to determine the double-deck electric train EJ-575 energy-management principles and to measure the dynamic electrical and mechanical parameters, the practical experiments were performed. The following channels of parameters measurement are predicted for determining the quantity of energy for traction and electrodynamic braking: the primary traction transformer winding of instantaneous current I_{Tr} , the primary traction transformer

must be multiplied by 100, flattening voltage U_d values must be multiplied by 10; single-carriage asynchronous traction motor of the train EJ-575 (of 1, 2 wheelsets) variation of speed is charted by marking n_1, n_2 , and shows the instantaneous values of train speed, km/h. The values of dynamic parameters, measured with personal computer during the practical research are given in Fig. 25.



I_{Tr} – diagram of primary traction transformer winding current variation (A); U_{Tr} – diagram of contact network voltage variation(V); flattening voltage U_d variation diagram (V); V – diagram of speed variation of the train (km/h); t – time (s)

Fig. 25. Parameters values of the double-deck electric train EJ-575 energy-management in traction-electrodynamic braking modes:

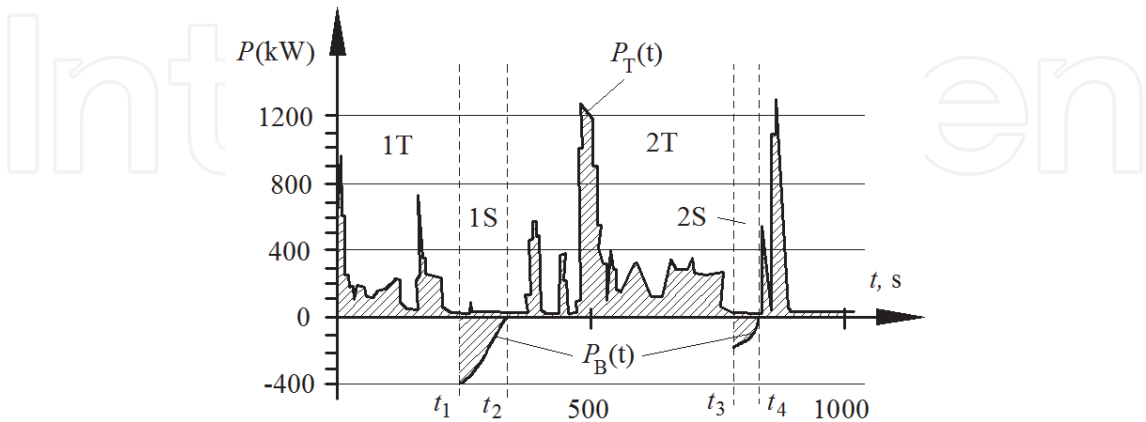
14. Results of practical research on energy control in EJ-575

Variation range of instantaneous active power P used in traction cycles 1T and 2T is up to 2×1250 kW (two separate windings of traction transformers). Variation range of instantaneous active power P in electrodynamic braking cycles 1S–2S is 25–60 kW. During electrodynamic braking, the amount of energy is used only for power supply to ancillary devices. The electrodynamic braking of the train is carried out using kinetic energy. In traction and electrodynamic braking cycles, the amount of consumed contact network energy $P(t)$ converted into useful work is described by the respective areas delineated by curves. The amount of energy is determined by integrating the respective cycles, following the given formulas (Bureika 2008; Dailydka, Lingaitis ... 2008):

$$W = \int_0^t P dt ; \tag{11}$$

$$W = \int_0^{t_1} P dt + \int_0^{t_2} P dt + \int_0^{t_3} P dt + \dots + \int_0^{t_i} P dt . \tag{12}$$

The diagrams showing variation of contact network energy $P(t)$ and electrodynamic braking $P(t)$ energy consumed in electric double-deck train EJ-575 are given in Fig. 26.



0- t_1 – traction cycle 1T; t_1 - t_2 – electrodynamic braking cycle 1S; t_2 - t_3 – traction cycle 2T; t_3 - t_4 – electrodynamic braking cycle

Fig. 26. Diagrams showing variation of contact network energy $P(t)$ and electrodynamic braking $P(t)$ energy consumed in electric double-deck train EJ-575:

Variation range of contact network energy $P_T(t)$ consumed in traction cycles 1T and 2T is represented in traction cycles 0- t_1 and t_2 - t_3 ; Variation range of electrodynamic braking $P_B(t)$ energy is given in cycles t_1 - t_2 and t_3 - t_4 . The amount of electrodynamic braking $P_B(t)$ energy converted into useful work is described by the respective areas delineated by curves in cycles t_1 - t_2 and t_3 - t_4 .

15. Results of research

Comparison of research results on electrical energy consumption in electric trains ER-9M and EJ-575 in 2010 is presented in the diagrams below (Fig. 27, Fig. 28). They are given following the statistical data of JSC *Lithuanian Railways*.

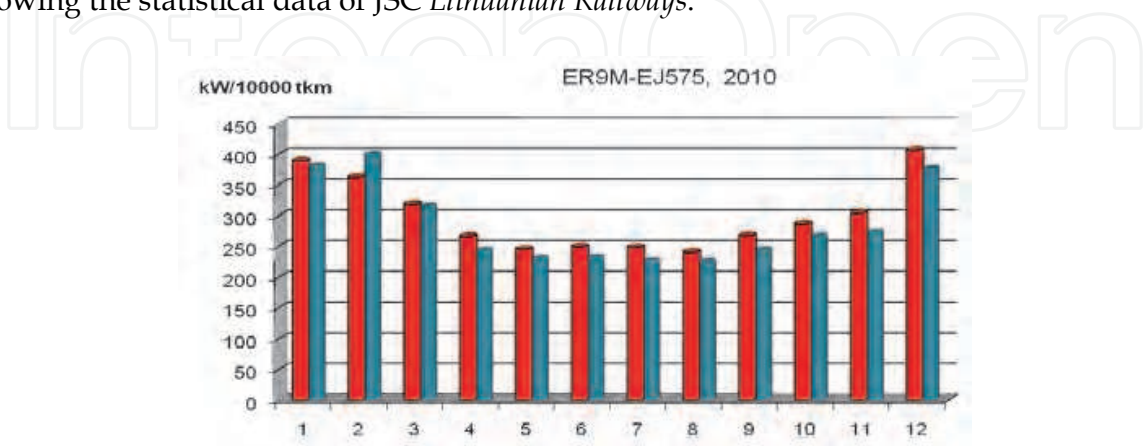


Fig. 27. Electrical energy input (kW/10000 tkm) of electric trains ER-9M with DC traction motors and EJ-575 with AC traction motors in 2010

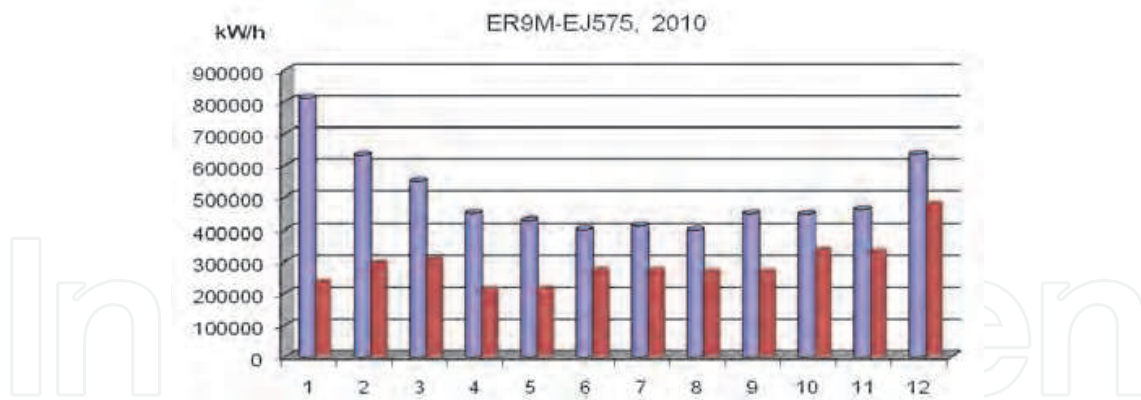


Fig. 28. Electrical energy input (kW/km) of electric trains ER-9M with DC traction motors and EJ-575 with AC traction motors in 2010

16. Conclusions

1. Electrodynamic braking is the main braking technique used for modern electrically-driven locomotives.
2. The use of supercondensers in the locomotives with electric drive expands the regenerative braking range to full stopping. This creates the conditions for full use of kinetic energy of the train.
3. Using supercondensers enables replacing the diesel motors of powerful locomotives and ships.
4. Supercapacitors were chosen to act as energy buffer.
5. The use of regenerative braking of electric locomotives for 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 regenerative braking forces can be obtained in a wide range, with a possibility to return energy to energy supply in a high-speed range and to store energy in a low-speed range.
6. All diesel electric powered locomotives should use hybrid traction technology.
7. Hybrid traction technology locomotives can use regenerative braking of high-speed and a low-speed range.
8. The energy used by hybrid traction technology locomotives is reduced by 25–30 %.
9. The offered regulation algorithm allows obtaining various types of flat characteristics enabling asynchronous traction motor to be extensively used in traction, recuperation and dynamic braking modes of operation.
10. A circuit scheme of using hybrid traction technology with energy storage tender and catenary-free operation was proposed.
11. It is possible to use the regenerative braking power in diesel electric locomotives for starting engine, acceleration, and operation mode.
12. Energy savings and power supply optimization possibilities were proposed.
13. The electrodynamic braking system installed in EJ-575 enables to stop the train without friction braking.
14. The electrodynamic braking system installed in EJ-575 enables a complete use of kinetic energy of the train in the braking cycles without contact energy network.
15. The use of kinetic energy of the train saves 25–30 % of electrical energy used for traction.

16. Flattening voltage U_d in ER-9M is step-controlled and for this reason, the currents of DC traction motors and energy losses during starting are great.
17. Due to the step-controlled flattening voltage U_d of traction motors in ER-9M, braking alternates in a step manner, i.e. unevenly; thus the passengers experience discomfort and automatic coupling is affected by dynamic forces.
18. Kinetic energy of the train is not used for braking in ER-9M. The train is braked using friction, which increases operational expenses.
19. The speed of asynchronous traction motors of EJ-575 is evenly controlled by alternating power supply voltage and values of frequency.

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Energy Management Systems

Edited by Dr Giridhar Kini

ISBN 978-953-307-579-2

Hard cover, 274 pages

Publisher InTech

Published online 01, August, 2011

Published in print edition August, 2011

This book comprises of 13 chapters and is written by experts from industries, and academics from countries such as USA, Canada, Germany, India, Australia, Spain, Italy, Japan, Slovenia, Malaysia, Mexico, etc. This book covers many important aspects of energy management, forecasting, optimization methods and their applications in selected industrial, residential, generation system. This book also captures important aspects of smart grid and photovoltaic system. Some of the key features of books are as follows: Energy management methodology in industrial plant with a case study; Online energy system optimization modelling; Energy optimization case study; Energy demand analysis and forecast; Energy management in intelligent buildings; PV array energy yield case study of Slovenia; Optimal design of cooling water systems; Supercapacitor design methodology for transportation; Locomotive tractive energy resources management; Smart grid and dynamic power management.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Lionginas Liudvinavičius and Leonas Povilas Lingaitis (2011). Management of Locomotive Tractive Energy Resources, Energy Management Systems, Dr Giridhar Kini (Ed.), ISBN: 978-953-307-579-2, InTech, Available from: <http://www.intechopen.com/books/energy-management-systems/management-of-locomotive-tractive-energy-resources>

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