locomotive kinetic energy, energy storage battery,
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LOCOMOTIVE KINETIC ENERGY MANAGEMENT

Summary. The paper addresses some basic theoretical and engineering problems of electrodynamic braking, presenting methods of regenerative braking returning energy to contact network or the energy storage batteries. The paper presenting the non-traditional structural schemas of the starting of DC/DC, AC/DC, AC/AC power systems locomotives 800 kW-6000 kW diesel engines using the energy storage batteries (block of supercapacitors).

УПРАВЛЕНИЕ КИНЕТИЧЕСКОЙ ЭНЕРГИЕЙ ЛОКОМОТИВОВ

Аннотация. В статье рассматриваются новые возможности экономии энергии, полностью используя кинетическую энергию. Отображены возможности рекуперации энергии: электроподвижного состава в контактную сеть, на тепловозах с электропередачей, в накопительные батареи. Предложены нетрадиционные системы управления кинетической энергии DC/DC, AC/DC, AC/AC DC/DC структур локомотивов для запуска тепловозных дизельных двигателей мощностью от 800 kW до 6000 kW от накопительных батареи созданных на базе „супер конденсаторов“.

1. INTRODUCTION

Currently in the world, as the energy resources are running out, new energy-saving methods are trying to be found, a new approach in the field of management of locomotive power is being developed. One power-management policy is dominating in the locomotives of traditional structures. The energy diagrams of locomotive traction motor operating modes (Fig. 1) shows two theoretical locomotive power management policies: from the primary energy source into the wheel-sets (WS) or from the wheel sets WS into the primary energy source – contact network or the energy storage batteries. It is very important to create the two-way energy management systems in locomotives.

2. LOCOMOTIVE ENERGY MANAGEMENT DIRECTIONS

Train kinetic energy E is determined from the formula:

$$E = mg(1+Km)\int_0^t v dt + Kv^3 + \frac{m}{2}\left(v_p^2 + v_k^2\right) \quad (1)$$

where:
m – train mass, kg,

g – acceleration of gravity, m/s^2,
Km – coefficient of rotation mass,
v –locomotive velocity, m/s,
K – aerodynamic resistance coefficient,
v_p – initial velocity, m/s,
v_k – final velocity, m/s.

The energy diagrams of locomotive traction motor operating modes are given in Fig. 1.

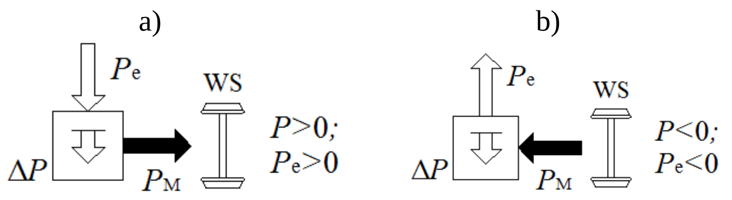


Fig. 1. The energy diagrams of locomotive traction motor operating modes: in the a) – traction mode; in the b) – regenerative braking mode
Рис. 1. Энергетические диаграммы тягового двигателя локомотива: a) – в режиме тяги; b) – в режиме рекуперативного торможения

In the engine mode, the electrical energy is used from the primary energy network (contact network or traction generator). The power taken from the network, W, is distributed as follows:

$$P_e = P_1 + \Delta P \quad (2)$$

where:
P_e – the power taken from the network,
P_1 – the power taken by the traction motor to rotate,
ΔP – the power, used in engine to compensate the losses.

Locomotive electrical braking methods

During the regenerative braking, the traction motor, which is operating in the generator mode, returns for the network the part of stored kinetic energy of mechanical system. Balance of power is expressed by:

$$P_M = P_e + \Delta P \quad (3)$$

where:
P_M – mechanical power of motor shaft,
P_e – the electrical power given for the primary network.

Dynamic braking, when the motor rotates by inertia (disconnected from the network), but the armature additionally is connected by resistance, where it depletes its own (generator) power. 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_o of torque-speed characteristic $n = f(M)$, which is required in regenerative braking, cannot be satisfied (see Fig. 2).

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_{in} exceeds network voltage, the armature current is reversed and electromagnetic braking moment is developed (see Fig. 2). 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 catenary system.

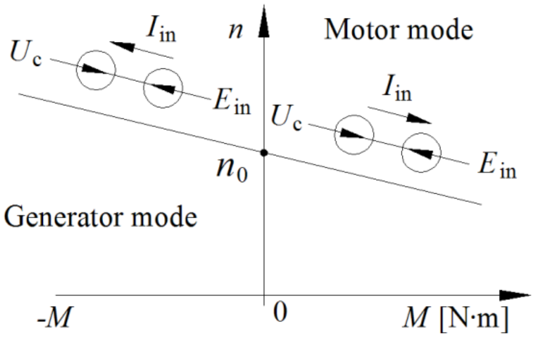


Fig. 2. Torque-speed characteristic of shunt-wound excitation motor's braking and traction modes: n_0 is motor's ideal no-load speed; U_c is catenary voltage; I_{in} is armature current of traction motor

Рис. 2. Механическая характеристика двигателя независимого возбуждения в режиме тяги и рекуперации; n_0 скорость холостого хода тягового двигателя; U_c – напряжение контактного провода; I_{in} – ток якоря тягового двигателя

3. 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 supercapacitors are very high. Single module capacities are 3000 F, at the tension 2,7 V and even more powerful. [1,2,9]. All this has given an impulse to the various scientific researches. General view of supercapacitor is given in Fig. 3.

Fig. 3. General view of supercapacitor

Рис. 3. Общий вид супер конденсатора

Comparative characteristics of the supercapacitors and accumulators are given in the Tab. 1.

Table 1

Characteristics of accumulator and supercapacitor

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

The charge – discharge time of conventional accumulative batteries is very long, because chemical reaction depends on time. The charge – discharge time of supercapacitors is only few seconds. In addition, their period of duty is incomparably longer.

4. NON-TRADITIONAL MANAGEMENT SYSTEM OF LOCOMOTIVE KINETIC ENERGY OF DC/DC POWER SYSTEM

The electric drive of diesel locomotive of traditional DC/DC power system does not create the theoretical and practical possibility of using regenerative braking [3]. Fig. 4 shows the structural schema of locomotive kinetic energy direction management system. It is very important to create of DC/DC power system locomotive bi-direction energy control system. Locomotive energy direction is controlled by signals Y1 and Y2.

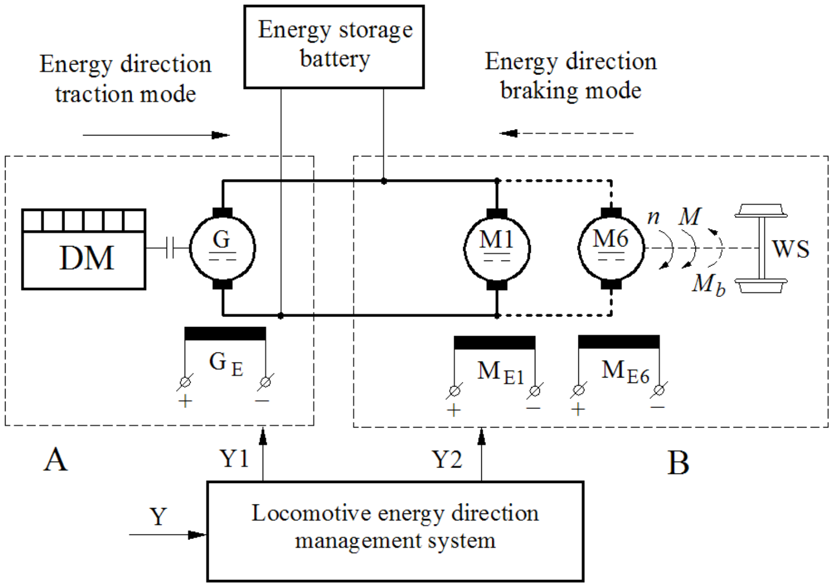


Fig. 4. The structural schema of energy direction management system of locomotive of DC/DC power system: DM – diesel engine; G – DC traction generator; G_E – separately excitation winding of DC traction generator; M1-M6 – DC traction motors; $M_{E1...}$ M_{E6} – separately excitation windings of DC traction motors; G_E – separately excitation winding of DC traction generator; n – traction motor rotor speed; M – electromagnetic moment; M_b – electrodynamic braking moment; WS – wheel-sets

Рис. 4. Система управления направления энергии DC/DC структуры локомотива: DM-дизельный двигатель; G – DC тяговый генератор; G_E – обмотка независимого возбуждения DC тягового генератора; M1,..M6 - DC тяговые двигатели; $M_{E1...}$ M_{E6} – обмотки независимого возбуждения DC тяговых двигателей M1, M2; Y, Y1, Y2 – сигналы управления; M – электромагнитный момент; M_b– электродинамический тормозной момент; n – скорость ротора тягового двигателя; WS – колёсная пара

The authors propose to create a non-traditional management system of locomotive kinetic energy of DC/DC power system (Fig. 5) [4, 5]. DC/DC power systems in the management of the locomotive kinetic energy use the electronic key K, which consists of IGBT transistor and a diode connected in parallel. To control the electronic key K i.e. „open“ or „close“ by the signal Y. By using the provided system, appears the possibility to fully use the kinetic energy of the train unit to stop the train without mechanical (friction) braking and along with it to charge the energy storage battery. The stored energy can be used for supply of the traction motors in the traction mode, for supply of additional equipment, or to use the stored energy for the diesel motor starting.

5. TRADITIONAL DIESEL LOCOMOTIVE MOTORS STARTING SYSTEMS

Usually the power of DC/DC locomotives is 800 kW-4000 kW. These locomotives do not need special DC electrical machinery-starters. The function of the starter is provided by the traction generator which is operating in the motor mode (Fig. 6 marked with M) AC/DC. The traditional starting system of AC/DC, AC/AC locomotive diesel motor is provided in Fig. 6b.

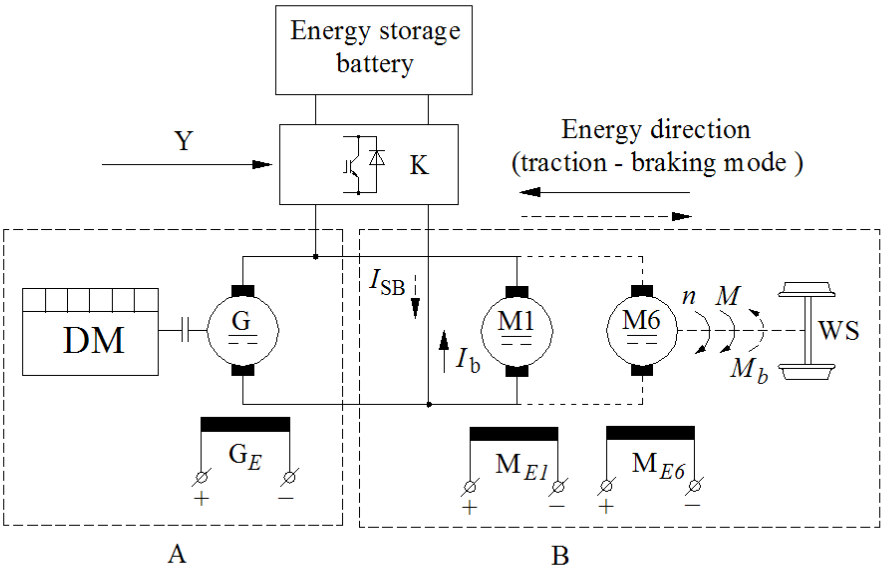


Fig. 5. The structural schema of non-traditional management system of locomotive kinetic energy of DC/DC power system; I_b – regenerative braking current; I_{SB} – storage battery current; K – semiconductors key; Y – drive signals; *M* – electromagnetic moment; M_b – electrodynamic braking moment; WS – wheel-sets

Рис. 5. Нетрадиционная система управления кинетической энергии DC/DC структуры локомотива: I_b – ток рекупеpативного торможения; I_{SB} – ток накопительной батареи; K – электронный ключ управления; Y – сигнал управления

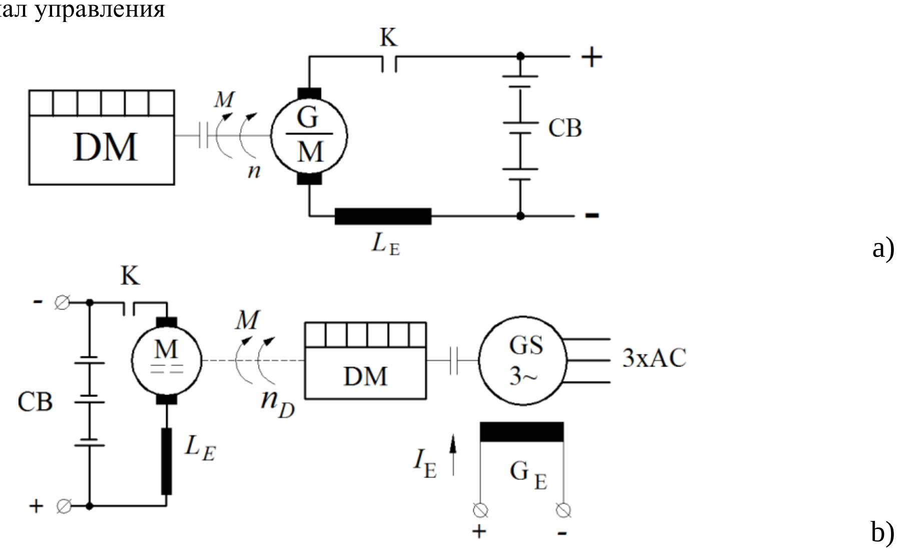
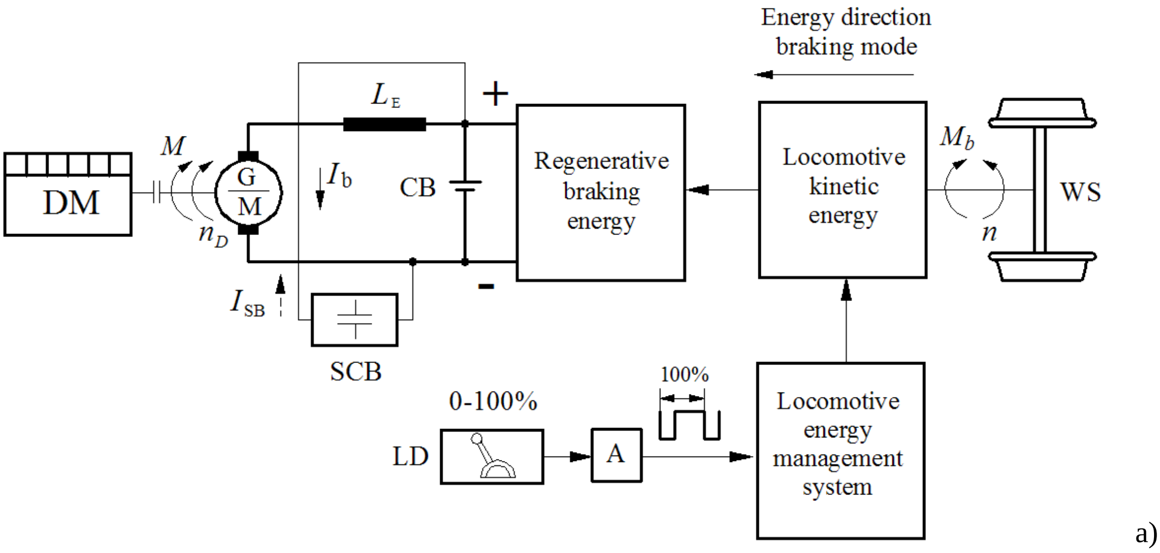


Fig. 6. The traditional starting schemas of DC/DC, (a) AC/DC, (b) AC/AC locomotive diesel motor: G/M – DC electric machine (generator or motor mode G/M); K – contactor. GS – synchronous traction generator; L_E – excitation windings

Рис. 6. Схемы локомотивов с традиционными системами запуска дизельных двигателей (a) AC/DC, (b) AC/AC: G/M – электрическая машина постоянного тока: генератор – G, двигатель – M; GS –синхронный тяговый генератор; L_E – обмотка возбуждения

6. NON-TRADITIONAL STARTING SYSTEMS OF DC/DC AC/DC, AC/AC POWER SYSTEMS OF LOCOMOTIVES DIESEL MOTOR

The authors propose to create a non-traditional management system [6, 7, 8, 10] in DC/DC locomotives of 800 kW-4 MW power for the starting of diesel motor in accordance with provided structural schemas Fig. 7a AC/DC, AC/AC Fig. 7b. The diesel engines are used for creating of primary energy, which power is up to 6000 kW. JSC *Lithuanian Railways* uses diesel engines, which power is up to 3000 kW. Using conventional systems of starting, from alkaline or acid accumulators, starting of such engines is very complicated because it requires powerful batteries of accumulators. The locomotives TEP-60 and TEP-70, which powers diesel engines is up to 3000 kW 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 authors and Vilnius locomotive depot experts have been researching how to extend the life of battery, reduce their weight, improve the conditions of diesel engine starting up. The new management system of locomotive kinetic energy proposed by the authors enables to charge supercapacitors in the regenerative braking cycle, the stored energy of which would be „protected" for future use. The stored energy will be stored until the electronic key K will be „opened" by the control signal Y. The system offered by the authors allows to change the traditional starting schemas of locomotive diesel motors, to reduce the weight of traditional batteries, battery capacity Ah, the energy costs for the charging the traditional batteries, since it significantly reduces the currents in CB circuit, the basic energy needed for the starting of the diesel motor is used from the supercapacitor unit.



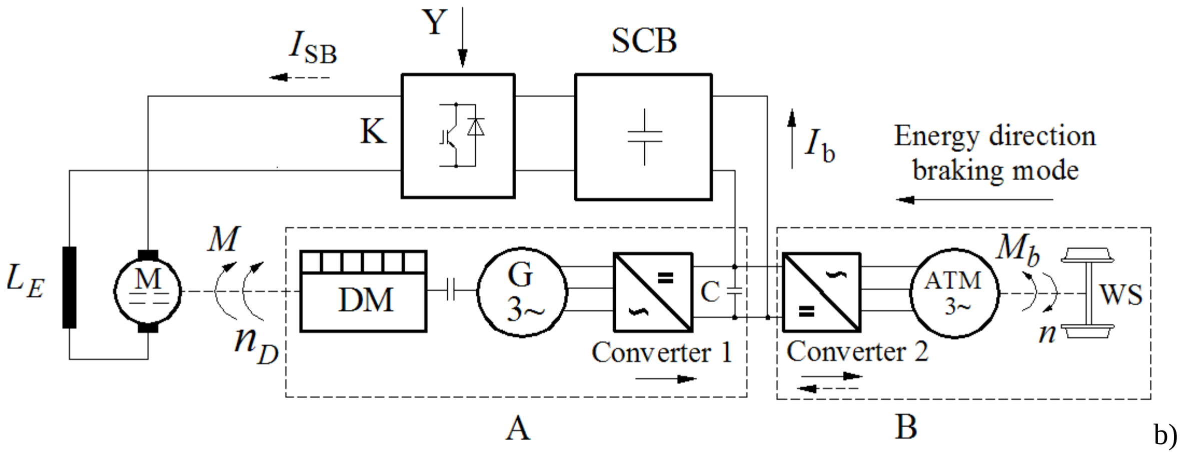


Fig. 7. The non-traditional structural schemas of the starting of DC/DC, AC/DC, AC/AC locomotives diesel: LD – locomotive controller; A – analog to digital converter; ATM – asynchronous traction motor, SCB – block of supercapacitors; Converter1 – undirection converter (rectifier); Converter 2 – bidirection converter (inverter- rectifier)

Рис. 7. DC/DC, AC/DC, AC/AC структур локомотивов нетрадиционные системы запуска дизельных двигателей: LD – ручка управления локомотива; А – аналоговый цифровой преобразователь; ATM – асинхронный тяговый двигатель; SCB – блок супер конденсаторов; Converter 1 – преобразователь энергии (выпрямитель); Converter 2 – преобразователь энергии (инвертер-выпрямитель)

7. THE RESULTS OF THE RESEARCH ON NEW ENERGY ACCUMULATION ELEMENTS – USING OF THE SUPERCAPACITORS IN STARTING UP OF DIESEL ENGINES

In Fig. 8 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 550 Ah, without SCB and the curve 2 of current run, when the diesel engine is started using accumulative batteries of smaller capacity (110 V x 160 Ah) and the block in parallel connected supercapacitors. Using the conventional system of current starting up in chain of accumulators is up to 3700 A. Using the conventional system of current starting up in chain of accumulators suggested by the authors is up to 1200 A. The time of Diesel engine starting up, using the conventional system is 40-50 seconds, and using a complementary system is 7-10 seconds.

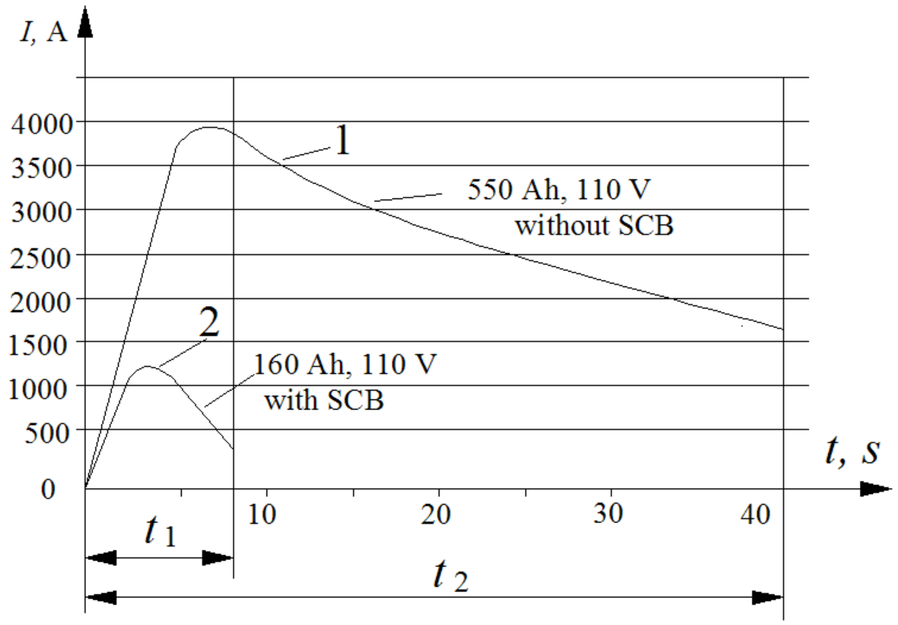


Fig. 8. The diagrams of starting up of the TEP-60 diesel engines starter in chain of current accumulators:1 – battery current without SCB, when traction generator operates in a starter mode; 2 – battery current with SCB, when traction generator operates in a starter mode

Рис. 8. Диаграммы тока пуска дизельного двигателя локомотива ТЕР-60: 1 – ток пуска без блока супер конденсаторов SCB; 2 – ток пуска с блоком супер конденсаторов SCB

8. CONCLUSIONS

1. Electrodynamic braking is the main braking technique used for modern electrically-driven locomotives.
2. The use of super condensers 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 super condensers 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.
6. Hybrid traction technology locomotives can use regenerative braking of high-speed and a low-speed range.
7. The energy used by hybrid traction technology locomotives is reduced by 25–30%.
8. It is possible to use the regenerative braking power in diesel electric locomotives for starting up to 800–4000 kW diesel engine, acceleration, and operation mode.

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