OPPORTUNITIES TO ENHANCE EFFECTS OF REGENERATIVE BRAKING OF DC ELECTRIC LOCOMOTIVES

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ABSTRACT

Regeneration system is mounted on all electric locomotives designed for driving freight trains. There has been a tendency of its use in combination with dynamic brake on passenger locomotives and electric trains.

The objective of the authors is to analyze regulatory and protection functions of electrical equipment and its operation in regenerative mode, using analytical method, mathematical calculations, simulation and comparative method.

Regenerative braking should be considered as the most effective means of reducing energy consumption in electric traction. Therefore, its scope should be expanded, including its use for returning of kinetic energy of the train to electric traction network. The authors present a methodology for calculating the energy when an electric locomotive moves downhill, analyze individual components of the energy balance, indicate possibility of increasing the efficiency of the locomotive in regenerative behavior. An analytical review of regulatory and protection functions of electrical equipment was carried out and has shown that in regenerative behavior a set of these functions is much broader than in traction. Electric equipment, implementing regeneration, should be improved using new technologies (static converters, onboard microprocessors, high-speed protection). It is necessary to keep the achieved level of functional reliability and maintain proven schematics, including cross-cyclic excitation of traction electric motors.

Keywords: railway, electric locomotive, direct current electric braking, recovery, traction electric motors, short circuit.

Background. *Regenerative braking is an essential means of energy saving in electric traction [1], it can convert mechanical energy of the train (potential or kinetic) in electrical and return it to electric traction network. Such a conversion is carried out in accordance with the characteristics of energy balance when switching electric traction motors in generator mode (Pic. 1). Regenerative braking system is mounted on all electric locomotives for freight traffic and also on new passenger locomotives.*

Objective. *The objective of the authors is to analyze regulatory and protection functions of electrical equipment and its operation in regenerative mode.*

Methods. *The authors use analytical method, mathematical calculations, simulation and comparative method.*

Results.

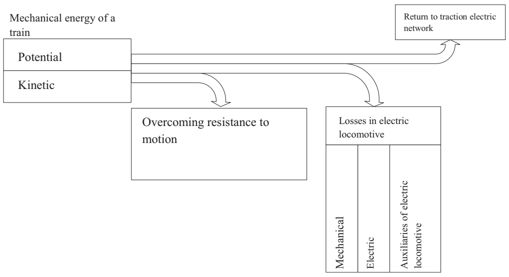
1.

The main purpose of regenerative brakes is maintaining a constant speed of train on hazardous descents, i. e. on sections with descending gradient i > (4÷4,5)‰ [2].Wherein potential energy is realized:

$$E_1 = (P+Q)H = \frac{i(P+Q)l}{1000}, \qquad (1)$$

where $(P+Q)$ *is weight of a train (locomotive and cars);* H *is height difference of initial and final points of a hazardous descent; l is length of a hazardous descent.*

Part of the potential energy is used to overcome the resistance to motion of the train [3]:



Pic. 1. Energy balance of an electric locomotive at regeneration.

$$\Delta E_W = (W_O + W_c)l = \left[w'_O P + w''_O Q + w_c(P+Q)\right]l, \qquad (2)$$

where w'_O, w''_O *indicate specific basic resistance to motion of a locomotive and cars;* w_c *is specific additional resistance to motion of a locomotive and cars from curves.*

Value ΔE_W *should not be considered as a loss of energy, since it corresponds to the costs of the movement of the train. Calculations by formulas (1) and (2) are usually carried out at a constant speed of motion on hazardous descent. This corresponds to the practice of driving trains and requirements of traffic safety.*

If an electric locomotive is considered as a converter of mechanical energy at the input ($E_1 - \Delta E_W$ *) into electrical* E_2 *at the output, its coefficient of efficiency can be represented as*

$$\eta = \frac{E_2}{E_1 - E_W} = \frac{E_2}{E_2 + \Delta E_e}, \qquad (3)$$

and losses in the electric locomotive ΔE_e *will be the sum of three components (see Pic. 1). The greatest influence on the value of the efficiency amounts to electric losses, which in regenerative mode are higher than in traction (for nominal capacity of 0,86 and 0,92 respectively). This is easily explained: traction motors implement regenerative mode when they are separately excited, which requires the inclusion of additional smoothing and damping elements into power circuit.*

2.

Regeneration is implemented by much more complicated technique than the traction mode, which uses traction electric motors (hereinafter- TEM) of series excitation. In case of regeneration excitation windings (hereinafter- EW) of traction motors are powered by a separate motor-generator with capacity of 5–6% of the total capacity of all TEM of the electric locomotive. Separate excitation has certain advantages, but in this case, that is, multi-engine traction motor drive powered by catenary system, there are several problems to ensure stability and functional reliability that cannot be considered as solved.

Table 1

Limitation of operation and protection of TEM in traction and regeneration

N	Parameter	Indication	Traction	Regeneration
1.	Voltage at current collector	U	–	+
2.	Current of armature windings	I_{AW}	+	+
3.	Excitation current	I_E	–	+
4.	Protection against SC:			
	– in electric locomotive (internal SC)	SC1	+	+
	– in catenary (external SC)	SC2	–	+
5.	Equalization of load of parallel circuits of TEM	ΔI_{TEM}	–	+

Therefore, it is advisable to consider the achieved level of technical solutions at the example of a typical 4-axle section of electric locomotive with connection of TEM 1–4 with the use of grouping scheme P. Generator B is connected to excitation windings EW1- EW4 by the cyclic circuit, also called circuit-of Tikhmenev- Ptitsyn [4]. It has three excitation windings, two of which are in the circuit of armature windings 1–4; they are designed for the total current of TEM and produce counter-excitation of generator B. In addition, there is a separate excitation winding H. Here current from the power supply control circuit 50 V is controlled by the driver or automatic control system [5]. Due to such a scheme of switching of generator B the following tasks are realized:

- *differential compounding of TEM in generator mode and extenuation of transient processes in case of surges in catenary system;*
- *load balancing of parallel circuits of armature windings 1–4.*

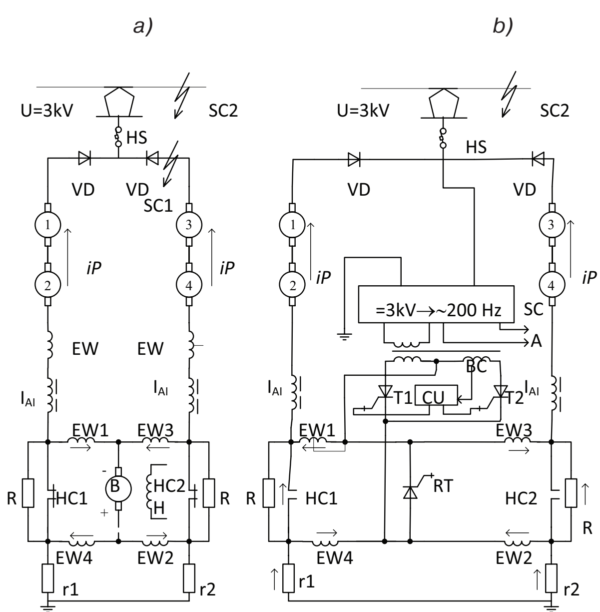
A particular problem in case of regeneration is short-circuit protection (against internal SC1 and external SC2 short-circuits). In the first case the protective function is identical to the traction and braking modes; it is traditionally realized with high-speed switch HS [6]. To an external short-circuit the electric locomotive in traction mode responds with demagnetization of TEM with subsequent disconnection of HS on the electric locomotive and the substation. If SC2 occurs in regeneration, the fault current increases sharply in circuits of windings 1–4, but wherein HS is not activated because it is polarized and responds only to the current of internal SC1. With external SC2 the current in armature windings increases rapidly with intensity

$$\frac{di_P}{dt} = \frac{U}{2l_A + l_{EW} + l_{AI}}. \qquad (4)$$

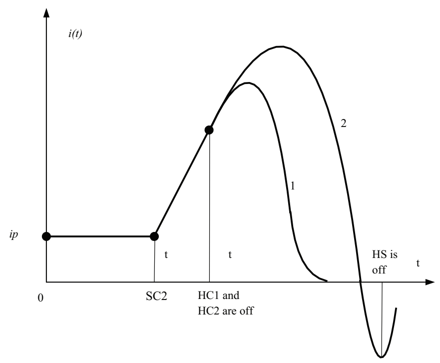
Active resistances in the circuit are not considered due to their small value. Their intensity is limited to values of 150–200 A/ ms, which is achieved by additional inductivities l_{AI} which are included in the circuits of armature windings.

Protection against SC2 is provided by disconnection of high-speed contractors HC1 and HC2 for about 5 ms [4]. In this case, the fault current will flow through resistors R and the voltage drop on them will be applied to EW1-EW4. Hence there is rapid reversal of the current in excitation windings (EW) and resetting to zero of electromotive forces of TEM. As a result, the emergency process of external SC2 quickly fades. Regenerative circuit functions similarly circuit in case of SC1.

Thus, control and protection functions of the electric locomotive in regenerative mode are much



Pic. 2. Switching of TEM in regenerative mode: a) physical rectifier B, normal mode of regeneration; b) static converter SC, shutdown mode of SC2.



Pic. 3. Variants of developing a process SC2.

more complicated than in traction, as shown in Table 1. This should be considered when developing a new generation of electric locomotives, in which cross-field exciter B must be replaced by a static converter SC (Pic. 2, b). It is based on a stand-alone inverter and is designed to supply auxiliaries A of the electric locomotive. Power supply of excitation windings EW1-EW4 is performed by static converter by means of transformer Tr and full-wave rectifier on thyristors T1 and T2 with control unit CU. This idea is implemented on electric locomotives VL15S, 2ES4K and 2ES6K.

Provided regulatory functions are carried out in the presence of SC with higher quality using back coupling BC for all parameters listed in Table 1. There is however a problem with the protection against SC2, thus disconnection of HC1 and HC2 will not lead to a reversal of the current in the windings EW1-EW4, as thyristors T1 and T2 do not pass a reverse current. Therefore, it is necessary to install in the rectifier a reversible thyristor RT, which turns on simultaneously with disconnection of high-speed contactors.

Other variants of regeneration are also possible with a static converter for supplying excitation windings. And it is possible to significantly improve quality indicators of TEM generator mode and output of the mechanical energy of the train into network.

3.

Particular attention should be paid to the functions of protection against an external short circuit. In particular, it is advisable to further investigate this process as applied to modern conditions, when substantially increased both capacity of electric locomotives (of 12-axle it increased up to 10 MW), and capacity of traction power supply system.

Conventionally, we can assume that the emergency process of external SC2 is as follows (Pic. 3):

- *at the time t_1 SC2 occurs and current i_p increases rapidly, thyristors T1-T2 immediately turn off and RT turns on;*
- *at the time t_2 HC1 and HC2 turn off, and the growth of i_p slows down.*

Further development of the process depends significantly on a number of factors (remoteness of the electric locomotive from the place of SC2, protection operation at the substation, etc.). Pic. 3 shows two types of processes: curve 1 occurs when SC2 is disconnected by substation protection and curve 2 occurs with preservation of voltage in the circuit and disconnection of HS.

Practices of operation of DC electric locomotive with regeneration proved the effectiveness of considered solutions using rotary converters for power supply of excitation windings of TEM. When switching to static converters it is necessary to keep worked-out functions of regulation and protection of electrical equipment.

Conclusions.

1. Regenerative braking should be considered as the most effective means of reducing energy consumption in electric traction. Therefore, its scope should be expanded, providing for return of the kinetic energy of the train to electric traction network.

2. Electric equipment, implementing regeneration, should be improved using new technologies (static converters, onboard microprocessors, high-speed protection). It is necessary to keep the achieved level of functional reliability and maintain proven schematics, including cross-cyclic excitation of TEM.

REFERENCES

1. Gapanovich, V. A. Energy savings for rail transport. Textbook [*Energosberezhenie na zheleznodorozhnom transporte: Uchebnik*]. Moscow, ID MISiS publ., 2012, 620 p.

2. Kantor, I. I. Physical profile of a track and traction of trains [*Prodol'nyj profil' puti i tjaga poezdov*]. Moscow, Transport publ., 1984, 207 p.

3. Osipov, S.I., Osipov, S.S., Feoktistov, V. P. Theory of electric traction [*Teorija jelektricheskoj tjagi*]. Moscow, Marshrut publ., 2006, 436 p.

4. Trakhtman, L. M. Electrical braking of electric rolling stock [*Elektricheskoe tormozhenie elektropodvizhnogo sostava*]. Moscow, Transport publ., 1985, 204 p.

5. Inkov, Yu.M., Feldman, Yu.I. Electric rolling stock with electrical braking. Educational guide [*Elektropodvizhnoj sostav s elektricheskim tormozheniem: ucheb. posobie*]. Moscow, UMCZhDT publ., 2008, 412 p.

6. Zakharchenko, D. D. Traction electric equipment [*Tjagovye jelektricheskie apparaty*]. Moscow, Transport publ., 1991, 247 p.

7. Inkov, Yu.M., Litovchenko, V. V., Nazarov, D.V., Feoktistov, V. P. Selection of Parameters for Dual-System Freight Electric Locomotive. World of Transport and Transportation, 2014, Vol.12, Iss. 6, pp. 34–46.

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