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TO A QUESTION OF AN ESTIMATION OF POSSIBILITIES AND EFFICIENCY OF VARIOUS KINDS OF ELECTRIC BRAKING OF INDUSTRIAL ELECTRIC LOCOMOTIVES

Introduction. Industrial electric locomotive transport (ELT) consumes 14 - 18 % from total amount of electric energy consumed by these enterprises [1].

For the purpose of improvement of energy efficiency of ELT in recent years preproduction models of new traction electrotechnical complexes of industrial electric locomotives were created, tested and implement at the domestic enterprises [1, 2].

Relevance of researches. Introduction in practice of modern high-efficiency systems of traction electric drives of electric locomotives on the basis of IGBT-converters of electric energy cannot be solved with sufficient level of efficiency without the answer to a question: what type (way) of braking is necessary for applying?

The purpose of researches. Substantiation of possibilities of application of those or other types of electric braking and development of circuitry engineering solutions of power efficient structures of traction electric drives of industrial two-axial ore mine electric locomotives of average capacity.

Research materials. Electric braking is a basic type of braking in industrial electric locomotives, but along with it the pneumatic and parking (manual) mechanical brake are used in an electromechanical complex.

Known in the general theory of the electric drive following types of braking can be used as electric braking in traction electric drives of a direct current with series excitation of electric locomotives:

- rheostatic braking (electrodynamic);
- opposite connection;
- regeneration braking.

In all cases traction motors operate in a generator mode due to kinetic or potential energy of moving locomotive rake. Generated in this case energy is extinguished in rheostats (electrodynamic braking and opposite connection) or enters in a trolley system (regeneration braking).

At electrodynamic braking which is a basic type of TED braking in produced by domestic industry manufacturing (ore mine) electric locomotives, traction motors are disconnected from a trolley system and closed at the brake resistor (it as well the starting) by resistance r_T.

Voltage at motor terminals at brake current I_T of electric machine $U_T = I_T r_T$ determines the greatest possible speed of an electric locomotive, as at rheostatic braking:

$$\omega_T = \frac{U_T + I_T r_T}{c_e \Phi} = \frac{E}{c_e \Phi}, \qquad (1)$$

where: ω_T – speed of rotation of a traction electric motor at the moment of the braking beginning, radian/sec;

U_T – voltage at terminals of traction electric motor, V;

i_T – current of traction electric motor, A;

r_T – braking resistance;

$r_{дв}$ – resistance of armature circuit with all windings of an electric motor, Ohm;

c_e – constructive constant of electric motor;

Φ – magnetic flux;

E - emf of engine.

Obviously, during braking at high speed and with the big current the voltage at motor terminals strongly increases and can become dangerous for motor, that in turn imposes necessity of application of corresponding restrictions.

According to (2)

$$i_{дв} = \frac{E - U}{r_{дв}} \qquad (2)$$

regeneration braking is possible only when emf of electric machine will be larger than voltage of a trolley system, i.e. $c_e \omega \Phi > U$.

But series excitation motor in motorizing loses its magnetic flux with growth of speed and it cannot naturally move to operation in a generator mode.

Therefore during regeneration braking it is necessary to use independent excitation of windings of direct current TEM from the special generator. Limits of speed regulation in this case are set by limits of an excitation current regulation and by allowed according to commutation conditions relation between mmf of excitation and mmf of armature reaction.

From the point of view of simplicity of circuit engineering solutions of TED, the electrodynamic kind of braking looks more preferable than the recuperative.

However, the inefficiency, being the known drawback of electrodynamic braking , remains its negative factor in its traction variant as well

The recuperative type of braking looks at first sight much more economically and power efficient. Let's analyse this type of braking for actual conditions of present mines and ore mines by the example of Krivorozhsky iron-ore combine.

The kinetic energy accumulated by moving weight of locomotive is equal:

$$W = \frac{m \cdot V^2}{2}, \text{ J}, \tag{3}$$

где: m – weight of locomotive, kg;
V – motion speed, m/s.

At that, as is known, weights and speeds of movement are various for empty and for loaded rakes [3].

In iron-ore mines for transportation of mined rock the electric locomotives of type К-14 and mine cars ВГ-4, with 10 mine cars in rake are used.

The weight of empty rake in that case is equal:

$$m_{пор} = (P + Q_{пор}) \cdot k_j \cdot 10^3 = (14 + 4{,}2 \cdot 10) \cdot 1{,}1 \cdot 10^3 = 61{,}6 \cdot 10^3 \text{ kg}, \tag{4}$$

where: P – weight of locomotive 14 ton,
$Q_{пор}$ – weight of 10 empty mine cars at 4,2 ton,
k_j – the factor considering rotating elements, for empty rake - 1,1, for loaded rake - 1,05.

The weight of loaded rake, at load-carrying capacity of mine car at 10 ton, will be equel:

$$m_{гр} = (14 + 4{,}2 \cdot 10 + 10 \cdot 10) \cdot 1{,}05 \cdot 10^3 = 163{,}8 \cdot 10^3 \text{ kg}. \tag{5}$$

Empty rakes move up-hill that promotes their braking. On conditions of restriction of a brake way to 40 m speeds of movement to 20 km/h or 5,55 km/s are permitted.

In that case kinetic energy of rake can reach

$$W_{пор} = \frac{m_{пор} \cdot V_{пор}^2}{2} = \frac{61{,}6 \cdot 10^3 \cdot 5{,}55^2}{2} = 950 \text{ kJ}. \tag{6}$$

Loaded rakes move down hill that complicates their braking. On conditions of restriction of a brake way to 40 м speeds of movement to10 km/h or 2,78 km/h are permitted. In that case kinetic energy of rake can reach

$$W_{гр} = \frac{m_{гр} \cdot V_{гр}^2}{2} = \frac{163{,}8 \cdot 10^3 \cdot 2{,}78^2}{2} = 632 \text{ kJ}. \tag{7}$$

As researches testify, at rake movement during tour along main haulage way 1 braking of empty rake and 2 braking of loaded rake are required on average.

Then energy which is required to extinguish is equal

$$950 + 632 \cdot 2 = 2214 \text{ kJ}. \tag{8}$$

It is necessary to notice, that real speeds of movement less maximum speeds according to braking conditions, the considerable part of kinetic energy - about 20 % - is absorbed by natural resistance to movement, skilled machinists use slowing-down for decrease in speed, especially at movement with "empties". Considering these factors, energy which can be used for recuperation, will be much less - no more

$$2214 \cdot 0{,}8 = 1771 \text{ kJ}. \tag{9}$$

Then this energy through the mechanical transmission, the motor and the converter can be given to a trolley system. Considering total efficiency of these devices equal to 0,9 - we will obtain

$$1771 \cdot 0{,}9 = 1594 \text{ kJ or } 0{,}44 \text{ kW·h}. \tag{10}$$

That is, according to (10), during 1 tour it can be given to trolley system only 0,44 kW·h due to recuperation of braking energy. Considering, that during 1 tour the electric locomotive consumes from a network nearby 18 kW·h, we see, that the economy of the electric power is equal to 2,4 %, i.e. efficiency of recuperation is insignificant, that can be explained be the low speeds of movement, especially speeds of loaded rakes - to 10 km/h.

Besides, for implementation of energy recuperation the essential complication of a control system of an electric locomotive and also providing of consumption possibility of regenerated energy are required.

For an illustration of the told we will consider schemes of power chains of an electric locomotive with possibility of braking energy recuperation and without recuperation - only with dynamic braking.

On fig. 1 the scheme of power chains of the electric locomotive is shown allowing to use both dynamic and recuperative braking.

Recuperative braking is carried out at switched on line contactor on a scheme input, also is continuously switched on thyristor VS3Q of brake mode. Regulation of process of recuperative braking is carried out by power transistors VT3E and VT4E by pulse-width modulation so that motor emf will exceed a voltage in trolley system. The detailed description of operation of the scheme in all modes is presented in [1].

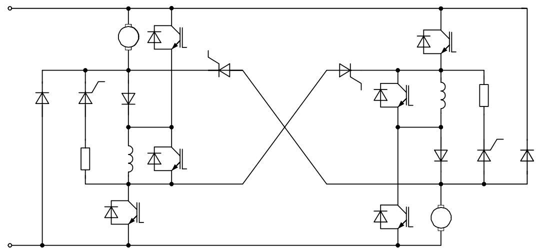

Fig. 1 The scheme of the coupled traction electric drive with possibility both dynamic, and recuperative braking

On fig. 2 the scheme of the traction electric drive of the ore miner electric locomotive is showed, providing only electrodynamics braking that has allowed to simplify the scheme essentially. (+) P

As we can see, the quantity of operated power elements is reduced twice - 5 instead of 10, that rather essentially simplifies both power, and the control scheme of a traction drive of an electric locomotive.

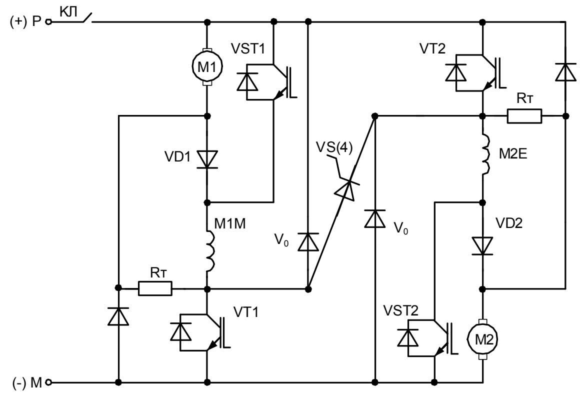

Fig. 2 Scheme of the traction electric drive of ore mine locomotive

In motorizing it is provided two-band voltage control at TD by regulation of VS2, VT1, VT2.

Field decay is not used, as for ore mine electric locomotives there is no need to increase speed above natural characteristic of TD.

In a brake mode the thyristors VS1, VS2 are open switching the scheme in a mode of dynamic braking. In difference from the classical scheme of cross braking in the given scheme the brake effort of each engine is regulated independently, that allows to receive higher total brake effort. (-) M

On underground mines with the big productivity in mining operations the locomotive rakes with increased weight can be used by application of the coupled electric locomotives or several electric locomotives in rake operated by multiple-unit control. From the point of view of estimation of braking energy recuperation efficiency it changes nothing. At increase in weight of rakes their quantity accordingly decreases and relative value of economy of the electric power remains same, as well as for single electric locomotives, i.e. insignificant.

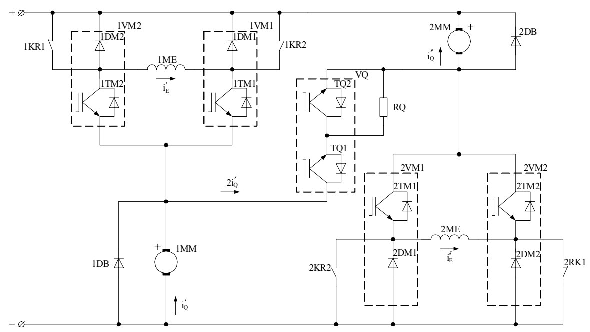

Fig. 3 Basic scheme of the two-block combined traction electric drive

In this variant it is applied two-block variants of TED-structures [1,2].

Power efficient two-block TED-structure with IGBT-converters for electric locomotives was developed by authors and has passed preliminary approbation in laboratory conditions (Fig.3).

The main difference of given TED-structure is that it operates in an one-block variant (one electric locomotive in rake), is easily transformed in two-block variant (two electric locomotives in rake structure with multiple-unit control), that is rather important for conditions when the fast reconfiguration of variants of locomotive rakes driving is necessary.

Besides it the given system unlike a number of others contains smaller quantity of elements.

Transistors TQ1 and TQ2 are not involved in a traction mode and blocks operate independently from each other. In a brake mode in a zone of high speeds of an electric locomotive the transistors TQ1, 1TM1 and 2TM1 are energized contoniously, TQ2 is disconnected and transistors 1TM2 and 2TM2 operate in a mode of pulse-width modulation. At energized 1TM2 and 2TM2 transistors the currents flow in circuits:

$$\begin{tikzcd}
1MM \arrow[r] & TQ1 \arrow[r] & RQ \arrow[r] \arrow[dr] & 2TM1 \arrow[r] & 2ME \arrow[r] & 2KR1 \\
 & & & 1MM \arrow[urr] & &
\end{tikzcd}$$

и

$$\begin{tikzcd}
2MM \arrow[r] & 1KR1 \arrow[r] \arrow[dr] & 1ME \arrow[r] & 1TM1 \arrow[r] & TQ1 \arrow[r] & RQ \\
 & & 1TM2 \arrow[urr] & & &
\end{tikzcd}$$

At de-energized 1TM2 and 2TM2 transistors the excitation windings are not shunted and currents in them increase. In process of decrease in speed the motors emf tries to decrease, and in order to avoid it for maintenance i_Q the impulse of conducting state of 1TM2 and 2TM2 transistors is reduced, that promotes increase in currents of excitation i_E. At completely de-energized 1TM2 and 2TM2 transistors and the further decrease in speed the operating in pulse mode transistor TQ2 is entered. Due to it the pulse shortening of brake resistor RQ occurs that leads to maintenance of a brake current i_Q at the set level practically to a full stop of an electric locomotive.

Thus, from the description of the scheme operation (fig. 3) follows that choppers VM combine in themselves functions of regulation of traction and brake currents, field decaying and reversing of direction of engines excitation current that guarantees a minimum of quantity of semi-conductor devices.

Conclusions. 1. Level of efficiency of recuperative braking of traction electric drives of industrial (ore mine) electric locomotives in difference from the main kinds of the electrified types of transport is insufficient for practical realisation of this type of braking in underground conditions of operation.

2. For ore mine electric locomotives it is necessary to consider as an expedient kind of electric braking the electrodynamic.

3. The variant of two-block structure of the traction electric drive for prospect of modernisation of miner electric locomotives TED is offered. In a basis of developing of these schemes the author puts a principle of multifunctionality of use of IGB-transistors which has allowed to create the compact schemes containing minimum quantity IGBT and providing highest emf of device.

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