сеть при уменьшении потока возбуждения двигателей. В граничной точке этого режима, то есть при E=U, следует перейти на импульсный режим по схеме рис.1, б.

ВЫВОДЫ

1. Мотор-вагонные электропоезда пригородного сообщения являются перспективным видом подвижного состава, но их тяговые электроприводы используют устаревшие технические решения, что приводит к значительным пусковым и тормозным потерям электроэнергии.

2. Для сферы производства новых электропоездов рекомендуется тяговый электропривод с бесколлекторными электродвигателями.

3. При модернизации электропоездов эксплуатируемого парка в процессе капитального ремонта целесообразно использовать импульсное регулирование, что позволяет существенно снизить потери энергии на тягу.

4. Предложенную методику расчета регулировочных и пульсационных характеристик систем импульсного регулирования рекомендуется использовать для сравнительного анализа вариантов выполнения импульсных преобразователей при учете требований их электромагнитной совместимости с тяговыми электродвигателями.

ЛИТЕРАТУРА

1. Иньков Ю. М., Ротанов В. Н., Феоктистов В. П., Чаусов О. Г. Преобразовательные полупроводниковые устройства подвижного состава/Под ред. Ю. М. Инькова. – М.: Транспорт, 1982. – 263 с.

2. Солодунов А. М., Иньков Ю. М., Коваливкер Г. Н., Литовченко В. В. Преобразовательные устройства электропоездов с асинхронными тяговыми двигателями. – Рига: Зинатне, 1991. – 351 с. ●

DEVELOPMENT OF TRACTION DC ELECTRIC MOTORS OF ELECTRIC TRAINS

Inkov, Yury M. *– D. Sc. (Tech), professor of Moscow State University of Railway Engineering, Moscow, Russia.*

Feoktistov, Valery P. *– D. Sc. (Tech), professor of Moscow State University of Railway Engineering, Moscow, Russia.*

Shabalin, Nickolay G. *– D. Sc. (Tech), professor, director of Kirov branch of Moscow State University of Railway Engineering, Kirov, Russia.*

ABSTRACT

Trains with electric motorized coaches prevail in commuter passenger traffic in the areas surrounding large regional centers. The article studies current state of electric commuter trains and analyzes stages of their development including modernization with maintaining of DC traction motors and transition to trains of a new generation equipped with asynchronous motors. Conclusions and comments are aimed at practical implementation.

ENGLISH SUMMARY

Background. *Electric trains consisting of motor and trailer cars are widely used for the carriage of passengers in commuter and local traffic. They are powered by DC and AC catenaries with voltage of 3 kV and 25 kV respectively. The core of the train park is DC trains – about 75% of their total number. This is due to the fact that most of the major cities are located in the zone of DC electrification of railways; here electric trains are operated in the most intensive mode (average daily mileage is about 500 km, series of cars – 10–12 cars, including 5–6 motor cars, block speed is 40–50 km / h with a maximum of 100–120 km / h).*

Significant difference in block and maximum speeds is explained by frequent stops of commuter trains; the average distance between stops is 5–7 km, so that there are significant starting and braking energy losses, as well as its high discharge intensity – usually more than 35–40 W • h / ton kilometer gross, loss ratio reaches 30–35%.

Energy costs in operation system of electric trains reach 40% of total expenditure, that, given the constant increase of tariffs by 12–20% per year, brings to the forefront the problem of energy saving.

Now a clear trend is marked out. The oldest types of electric trains are ER2 and EM2 with DC traction motors with series with wattage of 150 kW at a resistor- contactor regulation with switching groups of traction electric motor and without electrical braking.

On the subsequent series of electric trains, including the type of the currently produced ED4M, advanced traction electric motors are used with wattage of 250 kW without switching of groups, preserving resistor- contactor control, which significantly increased the starting losses. To compensate this effect, regenerative-resistor braking is provided for, but regeneration is possible at speeds below 40 km / h, and then there is a smooth passage to resistor braking and pneumatic shoe type braking. Since in normal mode, a train after slowing-down brakes at the speed of 50–60 km / h or less, the regeneration efficiency is low, this is fixed by the counters of energy, returning into network (typically 1–2% of consumption).

Electric trains of EM2I electric type with pulse control are in operation; in 1960–1975 years on the former Baltic and October Roads trains of ER2I and ER12 types, and high- speed train of ER200 type were in operation. I.e.. there is sufficient experience of non-resistor regulation of traction electric motors [1].

A new stage in the development of traction electric motors is associated with the use of asynchronous traction electric motors [2]. Electric trains of ET2A type with domestic inverter equipment and of ED6 type of Japanese firm «Hitachi» passed a full range of tests.

Objective. *The study aims at comparing different generations of traction electric drives or stages of development. This comparison should be made on energy, operational and economic criteria for separate spheres of electric car-building and overhaul (modernization) of electric trains. To solve this problem, the authors pose the task of generalizing the known methods for calculating pulse converters, adapting them to the possibilities of new power semiconductors of key elements, in particular to increase in frequency.*

Methods. *The study is based on comparative analysis of power consumption, operation and economic features of commuter rolling stock and on mathematical computation using differential and algebraic equations.*

Results.

Stages of development of traction electric drives, highlighted by the authors, are shown in Table 1.

Stage 1 *is the most worked-out and is characterized by the lowest costs in the production stage. Electric wagon works produce till now by the orders of OJSC «Russian Railways' trains with DC traction electric motors and resistor- contactor regulation. In the context of commuter traffic starting losses reach 14–18% of the energy consumed. Regeneration efficiency is low due to the limited scope of its application, i. e. because of the low speed of braking start.*

At this stage it is possible to implement individual measures to reduce energy losses; tests of electric train of ED4E type with switching groups of traction electric motors were carried out, which provided reduction of starting losses and extended the range of regeneration. However, nominal voltage of traction electric motors had to be raised from 750 to 1500 W, which greatly complicated its design. Another measure is associated with the use of an additional grouping of eight serially connected traction electric motors of two motor cars, as it was made with electric train of ER200 type.

Stage 2 *offers a more radical solution of the energy saving problem. In case of pulse control, starting losses are almost completely eliminated and regeneration becomes possible to speed of 8–10 km / h. The cost of DC voltage transformers tends to decrease while increasing reliability. Particular importance has the possibility of realizing stepless control, which allows the use of modern automatic control system.*

Stage 3 *best contributes to the solution of all problems; commutator traction electric motor is replaced by brushless asynchronous one, but with a more complicated system of frequency control. The concept of this electric train of ED6 type assumes a reduction in the number of motor cars in a train while increasing capacity on their axis. But the factor of increasing the cost of the electric drive with asynchronous traction electric motor under the conditions of unprofitability hinders the transition to such an option.*

Assessing the stages of development of traction electric drives, preliminary conclusions can be drawn. As for the production of the new trains, electric drives with brushless electric traction motors are consistent with the world`s practice, and along with asynchronous types other types of traction electric motors should be considered – synchronous with permanent magnets and inductor types. The most elaborated version is asynchronous traction electric motor, in favor of which speaks the completion of the rolling stock of Moscow Metro with trains «Rusich». For commuter trains similar solution cannot be considered ready for mass production, but with development of power semiconductor technology and development of power transistors production sphere should focus on implementation of Stage 3.

The problem of modernizing in-service rolling stock in the process of planned overhauls is also important. The most acceptable variant is pulse control (stage 2), because it is possible to use the existing traction electric motors and motor truck as a whole. It minimizes the cost of modernization and provides the same energy savings, as at stage 3.

Electric trains have been operated in commuter traffic for at least 40 years, and new technology of overhaul with extension of resource contributes to it. The additional costs for modernization using pulse control get regained in 3–4 years due to energy savings.

The task of modernizing electric trains is relevant for OJSC «Russian Railways», since energy program provides for the reduction of specific energy consumption for all modes of transport, particularly commuter one, having the highest specific energy consumption. To achieve the solution of this problem, known methods of calculating pulse converters should be generalized, adapting them to the possibilities of new power semiconductors of key elements, in particular to increase in frequency.

Generalized method should include all modes of operation of traction electric motor – motor, regenerative and resistor braking (Pic. 1). They are realized by the same elements of the converter system – DC voltage transformers and the diode VD, which are switched depending on the mode. In case of resistor braking resistor R is used at full capacity of traction electric motor (see Pic. 1, c).

To switch from traction mode to braking mode excitation winding is reversed in order to keep the direction of the current i in the excitation winding (OB) and the direction of electromotive force of capstan (Я). The direction of the current $I_я$ in the capstan Я changes and there is a change of direction of rotational moment M in the same direction of rotation of the armature.

Pulse control system operates at start-up and braking of trains in transition mode with the acceleration or deceleration of about 0, 8 m/s². However, since time constants of mechanical and electromagnetic processes in traction electric drive differ by 2–3 orders of magnitude, then the process of pulse control can be considered quasi-stationary. On this basis, it is assumed that in each of the intervals kT (Pic. 2) of a pulse cycle with period T electromagnetic process is described by differential equations, corresponding to the second Kirchhoff's law. These equations are presented in Table 2 (line I).

To solve these equations, the assumption is usually taken that the magnetic flow of traction electric motor in the quasi-stationary regime is perfectly smoothed, i. e. cΦ (I) = const and hence e~E. Consequently, the value E is defined by the average value of current I , which is shown in Pic. 2 by the dashed line. Thus, in the differential equations the change can be made

$$e \approx E = c\Phi(I)\,n. \qquad (1)$$

In addition, due to the insignificant impact of active resistance r of windings of traction electric motor, it is useful to introduce a similar assumption

$$ri \approx rI. \quad (2)$$

Particular attention should be paid to the inductance l of circuit of traction electric motor that for pulse mode is usually determined as

$$L = (L_0 + K_Д \; L_M) + L_{ср}, \qquad (3)$$

where L_0, L_M – respectively, leakage inductance and magnetizing inductance of traction electric motor;

$L_{ср}$ – inductance of the smoothing reactor (if present);

$K_Д$ – damping coefficient.

If traction electric motor has a capacity of 150–250 kW, the parenthetical expression takes on a value 35–55 mH for f = 450–950 Hz at $K_Д$ = 0,5–0,6. For higher frequencies, the influence of the skin effect increases, which is equivalent to an increase in active resistance of circuits of eddy- currents and growth $K_Д$.

When these assumptions are taken, differential equation for each respective interval of a ripple cycle is achieved by representation of results in an exponential function. In such a case, adapting of solutions on the boundaries of intervals is required, that is performable, but leads to complex dependencies, which are uncomfortable for practice, for example, in determining the scope of ripple and its extreme value.

Given the specificity of traction electric drives, including limiting ripple amplitude and prospects for improving the operating frequency of DC voltage *transformers, the authors provide a method for solving differential equations based on the assumption of linearity of the current i change in the time function t. This assumption corresponds to the diagram $i(t)$ in Pic. 2; it can be expressed analytically:*

$$\frac{di}{dt} = \frac{\Delta I}{kT} \text{ (DC voltage transformer is on); (4, a)}$$

$$\frac{di}{dt} = \frac{-\Delta I}{(1-k)T} \text{ (DC voltage transformer is off). (4, b)}$$

Substituting these expressions in the corresponding differential equations in Table 2, a system of linear algebraic equations (line II) is obtained. Its solution gives expressions for regulating $I(k)$ and oscillatory $\Delta I(k)$ characteristics, which are presented in an analytical form in a line III.

The analysis of regulating characteristics shows that for traction and regeneration modes dependence $I(k)$ is linear with E = const. But since the value of $I(k)$ depends on n and I, then in tasks of automation of traction electric drives regulating characteristics of the drive are considered when n = const, because mechanical processes are slow. Thus there is a dependence of E (I) with n = const. Usually traction electric motor of an electric train at the start and stopping braking works with maximum current limited by wheel- rail adhesion. This corresponds to the deep saturation of a magnetic system of traction electric motor, i. e. weak dependence of the magnetic flow $c\Phi(I)$ and hence electromotive force from current.

Thus, the regulating characteristics $I(k)$ for traction and regeneration are linear. They are non-linear for resistor braking and in designing of traction electric drive they can be calculated as a two-parameter dependence $I[k,n]$ according to formula $I(k)$ with account of $c\Phi(I)$. But it is important for these dependencies to be smooth and for non-linearity in the presence of back-coupling to have no significance.

Oscillatory characteristics $\Delta I(k)$ are more significant, as current ripple determines performance of traction electric motors. Electric trains with pulse control, which are in operation, are functioning at current ripple of up to 8%, but at bench tests increase in sparking in the brush contact was fixed as compared to the DC mode without ripple. It is advisable to reduce the allowable ripple level up to 4–5%.

To calculate the oscillatory regime it is necessary to determine the extreme value of ΔI by differentiating the oscillatory characteristics and equating the corresponding derivative to zero, i. e.

$$\frac{d(\Delta I)}{dt} = \frac{d}{dt}\left[\frac{UTk(1-k)}{L}\right] = \frac{UT}{L}(2k-1) = 0, \qquad (5)$$

whence it follows

$$k(\Delta I_{max}) = 0{,}5; \ \Delta I_{max} = \frac{UT}{4L}. \qquad (6)$$

According to this formula for traction electric drive of electric train of EM2I type it is possible to obtain relative value of ripple amplitude 100 $\frac{\Delta I_{max}}{I_{max}}$ =8,5%. To reduce ripple it is advisable to increase the frequency f, which is possible if DC voltage transformers are produced on the base of IGB-transistors. They do not require forced commutation and have a voltage drop in the power circuit significantly lower than thyristors normally used in DC voltage transformers.

Separately, there is a question about sustainability of pulse control. Requirement for sustainability is that (see Pic. 2) if in the interval kT, i. e.when DC voltage transformer is on, current i always increases $\frac{di}{dt} > 0$, then in the interval (1 – k), i. e. DC voltage transformer is off, the relation $\frac{di}{dt} < 0$ has to be satisfied. Otherwise current inevitably increases, i. e. the system becomes unmanageable. Analysis for the formulas when DC voltage transformer is off in Table 2 (lines I, II) shows that by the traction mode the system is always stable, since under any conditions

$$\frac{di}{dt} \sim (-E - rI) < 0. \qquad (7)$$

In regenerative mode, stability is not provided in the zone of high velocity when

E > (U+rI). *(8)*

Therefore, in this zone, i. e. at E> U, the regeneration with continuous energy output in electric traction network should be used with a decrease in the excitation flow of motors. At the boundary point of this mode, i. e. at E = U, there should be passage to the pulsed mode according to the scheme Pic. 1b.

Conclusions.

1. Motor-car electric commuter trains are a perspective type of the rolling stock, but their traction electric drives use outdated technical solutions, which lead to significant starting and braking losses of power.

2. For the sphere of production of new electric trains, traction electric drive with brushless electric motors is recommended.

3. During modernization of operated electric trains it is advisable to use pulse control in the overhaul, which can significantly reduce the energy loss in traction.

4. It is recommended to use the proposed method of calculating the regulating and oscillatory characteristics of pulse control systems for comparative analysis of embodiments of pulse transformers taking into account the requirements of electromagnetic compatibility with traction electric motors.

Key words: motor car trains, traction electric motor, pulse control, DC voltage transformer, brushless electric motor, power saving.

REFERENCES

1. Inkov, Yu.M., Rotanov, V.N., Feoktistov, V.P., Chausov, O. G. Transforming semiconductor devices of rolling stock [*Preobrazovatel'nye poluprovodnikovye ustroystva podvizhnogo sostava*]. Ed by Inkov Yu.M. Moscow, Transport publ., 1982, 263 p.

2. Solodunov, A.M., Inkov, Yu.M., Kovalivker, G.N., Litovchenko, V. V. Transforming devices of electric trains equiped with asynchronous traction engines [*Preobrazovatel'nye ustroystva elektropoezdov s asinhronnymi tyagovymi dvigatelyami*]. Riga, Zinatne publ., 1991, 351 p.

Координаты авторов (contact information): Иньков Ю. М. (Inkov Yu.M.), Феоктистов В. П. (Feoktisotv V. P.) – + 7 495 6842390, Шабалин Н. Г. (Shabalin N. G.) – + 7 8332 602594.

Статья поступила в редакцию / article received 28.11.2013
Принята к публикации / article accepted 26.01.2014