



SELECTION OF PARAMETERS FOR DUAL-SYSTEM FREIGHT ELECTRIC LOCOMOTIVE

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ABSTRACT

The paper presents a classification of parameters of electric locomotives with comments about existing restrictions and a block diagram of a dual-system electric locomotive. Variants for formation of a train of freight electric locomotives (multiple locomotive section) are shown based on a flexible type, taking into account different groups of parameters.

The authors underline that locomotive's reliability is assessed by a number of parameters but availability index is most important. This index is calculated for a given period of time between overhauls and is now considered to be normally equal to 0,95. The authors consider this value effective for future as well.

ENGLISH SUMMARY

Background. Classification of electric locomotives' parameters with account of existing restrictions is given in Table 1. In fact, many of them are very slow to change in terms of any changes in future, or are secured by applicable regulations and operating experience. Analysis of rail transport development, meanwhile, allows us to justify basic parameters for a long term, which is associated primarily with the objective to establish a normative service life (working life).

First electric locomotives had a working life of 50 years, and then it was reduced to 30–35 years, due to obsolescence of equipment, mainly electrical. However, it could be replaced during factory repairs. In addition, overhaul was widely used with prolongation of a working life for 15 years (hereinafter-OPWL). Now OPWL is carried out for electric locomotives CHS2 and VL10. These factors must be taken into account when justifying the working life time.

It will be especially difficult to take into account a variety of operating conditions, given the fact that the entire network of railways with electric traction should be serviced by a minimum number of types of electric locomotives, ideally – by one type. The important thing here is that originally a dual-system electric locomotive should be taken as sample type, since both electric traction systems (3 kV DC and 25 kV AC) will remain in future. The experience of foreign and domestic electric locomotive construction (EP10, EP20, 2ES5) shows that modern electrical engineering based on asynchronous traction motors is capable of providing a release of freight electric locomotives with a capacity of up to 1200–1300 kW / axle. And the design of dual-system electric locomotive must take into account the possibility of production on its basis of single-system AC and DC electric locomotives, as on the basis of EP10 variants EP2 and EP3 were produced.

Objective. The objective of the authors is to investigate parameters of electric locomotives; to provide their classification; to show possibility of formation of a train of freight electric locomotives based on a flexible type.

Methods. The authors use mathematical and engineering design method, analysis, descriptive method, comparison.

Results.

Options of flexible type

The problem of universal electric locomotive, that is adaptable to different conditions of freight traffic, is solved on the basis of flexible type (Table 2). It is possible to form a multiple electric locomotive section on the basis of a different number of similar sections. Between end sections which have control cabins, one or two homotypic sections (VL11, VL80S) or booster sections without control cabins completely unified with end sections (2ES5K) can be put. The use of booster sections is characteristic of the U.S. railways (for diesel traction). This gives certain advantages as booster is cheaper than a section with control cabin by 15–20%, but there are also disadvantages. They are related to the situation when 3-section electric locomotives are relocated to other depots, where it is necessary to re-shape them in 2-section electric locomotives.

Ultimately, the decision on boosters for prospective electric locomotives depends not only on economic considerations, but also on the stability factor of freight flows in time and space. Therefore, when choosing a type it is necessary to take into account the forecast of the main cargo-industries (metallurgy, heavy engineering, logging). In any case, to consider options of flexible type we should pay attention to a set of existing conditions.

Option on the basis of 4-axle sections has been actually already implemented with absolutely identical sections (VL11, VL80S) and the use of booster sections in the middle of the tractive connection (2ES5K). In this case, the possible number of axes of electric locomotive is 8, 12, 16. Options with 8 and 12 axes are widely used, that is, two or three sections. 12-axle locomotives 2ES5 with booster section are also widely used (Trans-Siberian and Baikal-Amur (BAM) mainlines). As we have noted due to the largest increase in traffic within those mainlines, the need for them will be stable.

Option on the basis of 6-axle sections ensures the formation of 2-section 12-axle electric locomotives (VL85, VL15). It is possible to add the third section (18 axes), but here we get a restriction on the strength of coupler which is of 120 tf. Therefore, in order to increase traction in mountain areas it is necessary to use boosting with substitution of an additional electric locomotive to the tail end of the train that is usually done on the Trans-Siberian main line.

The development programs of JSC «Russian Railways» provide the introduction of composite trains with formation schemes ECEC (E – electric locomotive, C – composite train of freight cars) weighing up to 2-6000 t or weighing up to 3-6000 t. To implement the idea of composite trains in most cases it will be sufficient to use 8-axle electric locomotives with distant control via radio channel (SMET-R), which was tested on Moscow-Ryazan branch on trains E2CE where 2C is 12 th. tons.

Table 1

Classification of parameters of electric locomotives

Parameters of a prospective freight electric locomotive		
1. Constant on the physical nature (adhesion coefficient, temperature range)	2. Relatively constant (car fleet, automatic coupling, track, electric power supply)	3. Varying (number of axes, sections, nominal value of power, traction, speed)

Table 2

Classification of possible solutions for flexible type

Base section of electric locomotive		
4-axle 2-2	6-axle 2-2-2 or 3-3	4- and 6-axle sections
Only sections with control cabin		
Sections with control cabin and booster sections		

If on mountain sections ($i = 16-25\%$), this weighted norm will be featured, 12-axle locomotives are required. That is the scope of the locomotives on the basis of 6-axle sections (VL85 and VL15) is retained in the long term for the mountain areas, which exist on most locomotive runs on Trans-Siberian mainline and BAM, as well as on the Ural mountain passes. But at the same time plants have to produce two types of DC electric locomotives and two types of AC electric locomotives or two types of dual-system electric locomotives, which will be reflected in their price.

Option on the basis of joint use of 4 and 6-axle sections is also considered in some researches on a flexible type. And it is possible to form sections of electric locomotives with a number of axes 8 (4 + 4) 10 (4 + 6) 12 (6 + 6) 14 (4 + 4 + 6) 16 (6 + 6 + 4), 18 (6 + 6 + 6), for all these cases type step is 2. However, this option is complex in terms of production, repair and maintenance.

Option based on 8-axle section is not included in the classification in Table 2 due to its rather rare implementation on locomotives, though 8-axle execution is used for freight cars. As for locomotives, the only example of a serial execution is diesel locomotive TEP-80 with axial formula (2 + 2.2 + 2); more than 100 units were produced. Kolomna factory produced two electric locomotives EP200 with the same axial formula. There are no foreign precedents except for the project of «Skoda» plant (electric locomotive CHS12 implemented only in brassboard).

For freight locomotives, this option is not reasonable because of the impossibility of forming a flexible type of multiple locomotives' section.

Thus, for a long term it is necessary to recommend an option on the basis of 4-axle sections.

Constant parameters (group 1)

Going back to Table 1, according to the classification parameters of prospective freight electric locomotive are divided into constant, relatively constant and varying. Constant parameters, referring to their relationship to the physical nature include adhesion coefficient and temperature range.

Adhesion coefficient reflects processes in the contact zone of the wheel and the rail. It largely depends on the shape of contacting surfaces, the wheel speed (more accurately, the speed of displacement of the contact area), the compression force in the area, etc. Influence of dirtying of the contacting surfaces is significant, including their watering. Theoretically, this ratio can be measured only on a laboratory bench where it is possible to set pressing force of wheels on the rail, the speed of displacement of the contact area, dirtying of the contacting surfaces, the shape of the rail head and the working surface of the wheel.

In reality, on the electric locomotive we have traction coefficient K_T , i. e. the ratio of maximum traction force on the rim of the wheel to the weight of the locomotive:

$$K_T = \frac{F_{\kappa-\max}}{P}; K_{i-\text{adh}} = \frac{F_{i-\text{WS}}}{q_{i-\text{WS}}}; K_T < K_{\text{adh}},$$

where K_T is traction coefficient;

$K_{i-\text{adh}}$ is adhesion coefficient for the i -th axle;

$F_{\kappa-\max}$ is maximum tangential traction force of the locomotive;

P is weight of the locomotive;

$F_{i-\text{WS}}, q_{i-\text{WS}}$ is maximum traction force of the wheel set and its load on rails.

Decrease in K_T in relation to K_{adh} is related to the change of axial loads (quality of locomotive weighting, dynamic redistribution of wheels load when driving due to irregularities of the track and because of overturning moment under the action of forces of traction and braking). Here are also noticeable the impact of dirtying of the contact zone, the oscillations in the spring suspension, transverse forces – for example, in the curved sections of track. However, in the instructions of the former Russian Ministry of Railways and of JSC Russian Railways, as well as in the academic literature and even often in scientific journals usually only the term «adhesion coefficient» is used, deeming at the same time «traction coefficient». For example, in the rules of traction computations (1985) different formulas for adhesion coefficient are shown, including

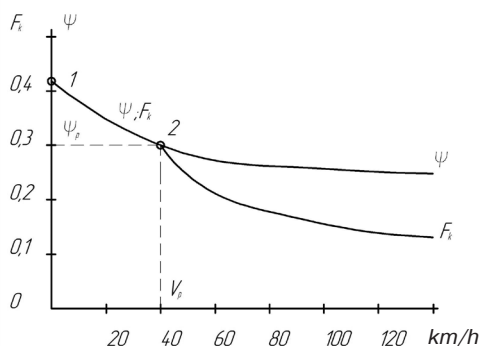
$$\psi = \frac{1}{A + BV},$$

where A, B are constant coefficients, obtained by approximation of the results of the tests; V is speed of an electric locomotive.

The results obtained by this formula are higher for AC electric locomotives as compared to DC electric locomotives. This is due to flat characteristics $F(V)$ and $I(V)$ of alternating current as electric traction motors are connected in parallel.

On prospective electric locomotives it is advisable to use asynchronous traction motors, which have more hardening characteristics than commutator motors. In addition, the traction drive systems have mandatory systems of automation and protection against skidding and sliding of wheels. With this in mind, as well as with account for the results of the tests we can take (Pic. 1) the value of the estimated coefficient of adhesion when starting ($V = 0$, point 1) to be $\Psi_s = 0,4$, and at rated speed V_p , i. e. when driving on the ruling gradient, as equal to $\Psi_p = 0,28-0,32$ [9]. This value depends on V_p and the value of V_p is associated with a nominal capacity of the electric locomotive N_n by ratio





Pic. 1. Determining electric locomotives' parameters for featured modes: 1 – getaway of a train; 2 – movement of a train on a ruling gradient.

$$N_n = F_p \cdot V_p = \psi_p \cdot P \cdot V_p,$$

where F_p is traction force on calculated gradient; P is weight of the electric locomotive.

From the formula it follows that with the increase in electric locomotive power, which is proportional to the traction motor power N_n , V_p increases similarly and ψ_p decreases slightly. In the area to the right of point 2 there is a point of calculated (nominal) mode. In operated electric locomotives (VL11, VL85) $N_n = 800\text{--}900\text{ kW}$ and $V_p = 43\text{--}48\text{ km/h}$. Accordingly, in case of asynchronous traction motor $N_n = 1100\text{--}1200\text{ kW}$ can take $V_p = 55\text{--}60\text{ km/h}$, but the reduction of ψ_p will be offset by improvement of antiskid properties, so that taking into account all factors $\psi_p = 0,28\text{--}0,32$.

The value of V_p , especially on ruling gradients has a great influence on the value of carrying capacity of locomotive run. Therefore an increase in V_p is beneficial in terms of train traffic.

Temperature range reflects actual operating conditions within the entire range of railway network with 1520mm gauge. When outside temperature is from $-50\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$, this range is important for choosing the element base of equipment and insulation type of high-voltage circuits and windings of electrical machines.

There are no fundamental difficulties in solving such a problem, but a number of positions require attention. These include:

- Increasing the reliability of insulation of traction electric motors by automatic control of blower motors with a continuous regulation of their performance in the air;
- Improving the resistibility of the most stressful steel structures at low temperatures (cold resistance), first of all it concerns the bogie frames and axles of wheel sets;
- Improvement of the climate control for the driver's cab in the whole range of ambient temperatures.

Relatively constant parameters (group 2)

Constancy of these parameters is determined not by their physical nature, but by the decisions taken as for the design of subsystems of rail transport. More stable parameters defining the interaction of electric locomotive with track structure are:

- 1520 mm gauge;
- Dimensions of the rolling stock (on lines with electric drive only dimension 0-T is used);
- Profile of the working surface of the rail head, which determines profile of the rolling surface of the wheels of electric locomotive;
- Load capacity of each axle of electric locomotive on rails – now for freight electric locomotives it is 25 t /

axle, but in program documents of JSC «Russian Railways» 28 t / axle is provided for certain most loaded areas;

- Ruling gradients for different locomotive runs, and in the design phase all sections are divided into six categories with maximum descending gradients of 10–20 per mille;

– The minimum radius of curved sections of the track it is taken equal to 300 m, that has an impact on the design of undercarriage of electric locomotive.

Freight car fleet determines the following parameters of the locomotive:

- Maximum traction force, depending on the automatic coupler is 120 tf (stress limit is 200 tf). Development of future-oriented couplers focuses not on the increase in its strength, but on the improvement of dynamics at sharp changes of longitudinal forces;

– Design speed of the majority of freight cars is 120 km / h, thus determining the design speed of freight locomotives. There is a tendency to increase the design speed of certain types of cars, such as container platforms, but their share in the car fleet does not exceed 1,5%. In the future, it will be possible to exploit express container trains, as in the EU, but they will have a short length (up to 40 cars) and, accordingly, the weight of not more than 2000 tons. Therefore, special passenger-freight or passenger locomotives should be used;

– The rate of axial load, as already mentioned, is related to the track structure

– The main share of freight cars has a limit axial load of 25 t / axle, which is an additional argument for justification of similar standards for electric locomotives.

Power supply of electrified railways affects the concept of prospective electric locomotive as follows: it should be dual-system that at the present level of development of power electronics and control systems is quite feasible. Switching of electric locomotive from one system to another is possible in process, during the passage of neutral insert in a contact network – this will significantly simplify operation of splicing stations (Vyazma, Vladimir, Mariinsk and others. – a total of 20 stations) and allow to extend locomotive runs. Given that a creation of a flexible type locomotive is provided, it is appropriate to adopt as a basic traction module for dual-system electric locomotive an equipment set of two-axle bogie with each axis individually driven by its own traction motor. At the same time design modularity should not be limited only to mechanical part. This principle should be extended to the electrical equipment.

The traction unit, except for two asynchronous traction motors, should include a traction converter, providing individual axis control by traction motors, as well as auxiliary converter used when running with a catenary of both DC and AC. In contrast to traction converters of dual-system electric train «Sapsan», for electric locomotive EP10 it is proposed to use secondary windings of traction transformer and inductor of 100-hertz resonant filter as an input filter inductors when running on catenary DC, as it was provided by the main circuit of traction drive of an electric train «Sokol».

The power supply system is closely related to the implementation of electric braking. 25 kV AC traction substations are always ready to receive regenerative power. At the same time, asynchronous traction motors work in generator mode, autonomous voltage invertors work in mode of controlled rectifier, and controlled rectifier works in the mode of grid-controlled inverter. Under DC mode regenerative-rheostatic braking is required. In recovery mode, asynchronous traction motors and autonomous voltage invertors function, and inverter convertors reverse. If there are no receivers of

regenerative energy proximity switch turns on automatically and the power is quenched at the rheostat.

Varying parameters (group 3)

In general, these parameters are uniquely determined or limited by parameters of already considered groups 1–2. During the operation of dual-system electric locomotives the locomotive department organizes its work in accordance with the following specified parameters.

Tonnage rating is calculated by the value of ruling gradient, taking into account the average characteristics of the train, i. e. cars. Among these characteristics the main one is average axial load in the train q'' . Then the resistance to movement of the train on the ruling gradient i_p is:

$$w = w_o(V_p) + w_i = (P \cdot w'_o + Q \cdot w''_o) + (P + Q) \cdot i_p,$$

where P, Q is weight of the locomotive and the train; w'_o, w''_o are values of main specific resistivity for the locomotive and the train, wherein

$$w'_o = a_1 V_p^2 + a_2 V_p + a_3; \quad w''_o = (b_1 V_p^2 + b_2 V_p + b_3) / q.$$

These calculations are performed at the stage of interaction of customer ("Russian Railways") and manufacturer of electric locomotives, including the developer. The final stage of the calculations is considered as an integrated implementation of standardized weighted norms for extended mainlines with stable freight traffic (Trans-Siberian mainline, Moscow – Voronezh – Rostov et al.).

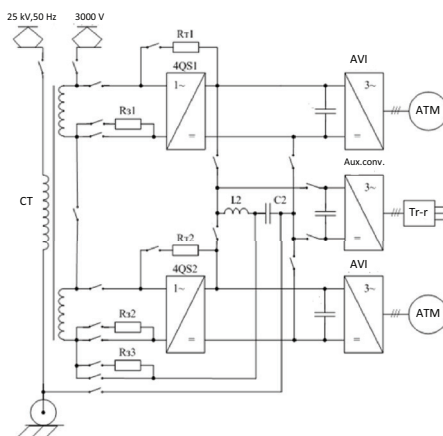
For example, the norm for Trans-Siberian mainline is 6000 t, but as relevant locomotive runs include various ruling gradients and correspondingly different individual weight norms, the uniform rules should satisfy the constraints:

- traction of a train by an electric locomotive in front of the train (8 or 12-axle electric locomotive), if necessary with the addition of pusher locomotive;
- the length of the train corresponds to the length of station tracks, at least on the section stations.

The idea of standardized weight standards has existed for about 30 years. Its implementation started on the basis of electric locomotives with commutator motors. Prospective electric locomotives with asynchronous traction motors are designed with a capacity at axle of 20% more than by collector motors. This suggests that prospective electric locomotives will not limit the implementation of uniform norms.

There is still a problem of comprehensive use of the power of multi-axis electric locomotives. The fact is that capacity of the electric locomotive is fully realized only if the weight of the train complies with the standard; but even those conditions are respected, the full power capacity can be achieved within a small range of running speeds – at V_p and slightly higher speeds. Therefore the system of section-wise regulation was implemented, which, if the current and accordingly traction force of electric locomotive are less than nominal, turns off a part of traction motors, and increases the current of the rest to maintain traction force at the level that existed before turning-off. The system of the kind under the form of control units ORML is implemented on board of electric locomotives VL80S, where it is possible to turn off the engines in pairs. Here, energy saving is performed by putting the engines into the zone of maximum efficiency, which corresponds to the nominal current.

Additional savings are achieved through regulation of performance (rotation speed) of blower motors (hereinafter - BM) of power equipment, depending on their loading. The ideal option is regulation based on the temperature of the armature or rotor



Pic. 2 Block diagram of a dual-system electric locomotive.

of traction motor, but measuring in rotating parts is very complex. Therefore, in the implemented systems BM are regulated by current of traction motors with account of the outdoor temperature. It gives energy savings of up to 16–18%.

On promising electric locomotives it is advisable to use asynchronous motors powered by autonomous inverters as BM; it allows smoothly adjusting the speed of BM. It is necessary not to reduce this frequency to less than 12–14% of the nominal value, to provide air overpressure during ventilation of traction motors (to avoid external air input into the motor).

Electric locomotives reliability is evaluated by a large number of indicators, but the main thing is availability coefficient, always indicated in the regulations of JSC «Russian Railways». It is calculated over a fixed period of time between overhauls by the formula

$$K_r = \frac{\Sigma T_{TS} + \Sigma T_{WS}}{\Sigma T_{TS} + \Sigma T_{SR} + \Sigma T_{WS} + \Sigma T_{NSR} + \Sigma T_{CF}},$$

where ΣT_{TS} is the sum of time intervals, during which the locomotive is at the disposal of traffic service, being in working condition;

ΣT_{WS} is the total time that an electric locomotive spends in the shed in working state;

ΣT_{SR} is the total time spent on the scheduled electric locomotive routine maintenance and repairs, including waiting period;

ΣT_{NSR} is duration of not scheduled emergency repairs, including waiting period;

ΣT_{CF} is the total time spent by electric locomotive in a state of complete failure outside the depot.

In the ideal case we get $\Sigma T_{NSR} = 0$; $\Sigma T_{CF} = 0$, so that availability can be affected only by increasing ΣT_{TS} and decreasing ΣT_{SR} and ΣT_{WS} . Further increase in the coefficient is possible only by improving the use of electric locomotives in transportation service and reducing the time required for maintenance and repair.

Now the availability coefficient of the ordered electric locomotives is 0, 95. This norm can be maintained for the future.

Conclusion. Run between overhauls should be increased by improving the reliability of limiting components of electric locomotive. The basic type of planned maintenance is track raising; its frequency is determined by the change of tyres of wheelsets when they reach the limit of wear. Now the appropriate run is 350–550 th. km,





but policy documents of JSC «Russian Railways» provide a task to increase it to 1–1,15 mln km. This is achieved by hardening the rolling surface of the rim (laser, plasma hardening).

Automation of electric locomotives in freight traffic is intended to be based on:

- Limitation of current of traction motors and speed stabilization according to the settings specified on the controller of the driver (microprocessor-based engine control system, developed by Russian Research and Design Institute of Electric Locomotive Building);

Keywords: dual-system electric locomotive, parameters, block diagram, flexible type, railway.

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- Automatic driving systems (System of automatic train driving and energy saving or Recorder of motion parameters and automatic driving of trains).

On-board system of technical diagnostics is required:

- To detect close-to-failure states of the most critical parts (axle-boxes, insulation of power circuits, especially traction motors);
- To register actual condition of major equipment when electric locomotive moves under full load (this information should be used in planning the next repair).

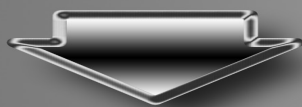
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ЭКСПРЕСС-ИНФОРМАЦИЯ

Начало эксплуатации первого в мире маршрута без подвесной контактной сети

Шейх Хамдан Бин-Мохаммед Бин-Рашид Аль-Мактум, наследный принц, председатель исполнительного комитета 11 ноября 2014 года торжественно открыл трамвайное сообщение в Дубае в присутствии высокопоставленных представителей ОАЭ и президента Альстом-Транспорт (Alstom Transport) Анри Пупар-Лафаржа.

Проект комплексной системы, реализация которого была поручена концерну Альстом дорожно-транспортным управлением Дубая (РТА), был запущен с целью развития системы интермодальных перевозок и борьбы с заторами и загрязнениями

на автодорогах. По расчетам эта первая трамвайная линия в зоне Персидского залива будет обслуживать около 27000 пассажиров в день, а к 2020 году этот показатель должен вырасти до 66000.

— Трамвай для Дубая, который мы поставили с опережением графика, отлично иллюстрирует стратегию Альстом по обслуживанию рынков на основе предоставления полного набора решений и лидирующего положения в области трамвайных систем. Благодаря нашему тесному сотрудничеству с дубайскими транспортниками жители теперь могут ездить на одном из самых совре-