

POWER SUPPLY SYSTEM WITH THREE-PHASE TRANSFORMERS FOR HSR

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ABSTRACT

The article presents a schematic diagram of a traction substation of the 2x25 kV power supply system with three-phase transformers and a vector voltage diagram for high-speed lines. Power supply systems 2x25 kV with single-phase and three-phase

transformers are compared, the power of three-phase transformers for high-speed main lines is recommended. And all this taking into account the new special technical conditions that are worked out for the design, construction and operation of Russian HSR.

Keywords: railway, high-speed railway, traction substation, 2x25 kV power supply system, three-phase transformer, single-phase transformer, special technical conditions.

Background. High-speed passenger transportation is profitable and pays for itself, bringing direct economic benefits to the state, as well as development of the regions along which the main lines pass and a certain status in the world community.

In our country, the first high-speed rail (HSR) Moscow–Saint Petersburg has been launched and is functioning. It is electrified with a direct current of 3 kV. Unfortunately, practice shows that a lot of problems arise in the operation of a DC-electrified high-speed railway. First of all, this is a serious «drawdown» of voltage on the current collector of electric rolling stock (ERS) in the middle of the feeder zone and, as a consequence, the necessity of using bulky volt-adding devices in traction substations, and even forced speed limits in certain areas. But for this main line, the type of current was not chosen, but only existing traction substations were modernized.

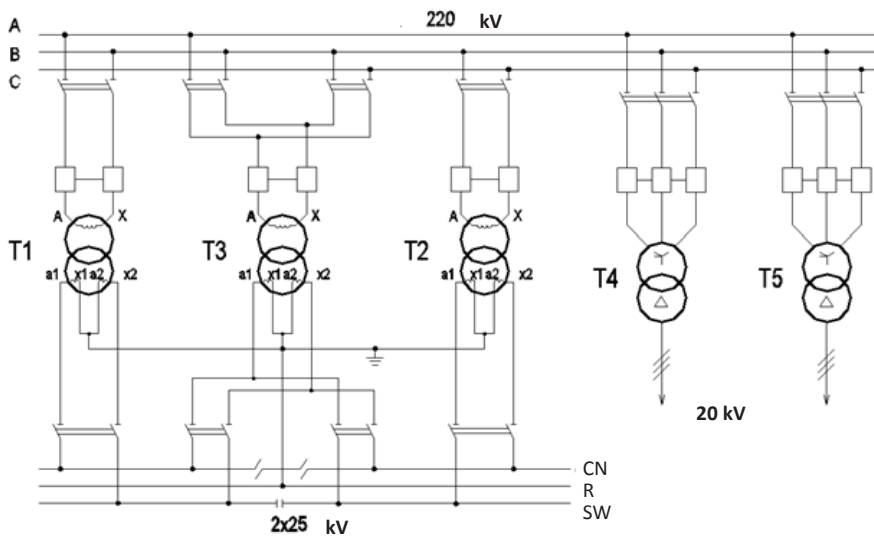
The experience of electrification of high-speed main lines in Japan showed that with an electric train power of about 16 MW, it is most advisable to use an autotransformer power supply system, which we called 2x25 kV traction power (2x2 kV TSP). If in Japan on the first high-speed main line Tokyo–Osaka with a power supply system of 25 kV this distance was about 20 km, with continuation of electrification of the main line using the system 2x25 kV the distance increased to 50 km [1].

At the moment, work is underway to design the HSR-2 Moscow–Kazan–Yekaterinburg and the

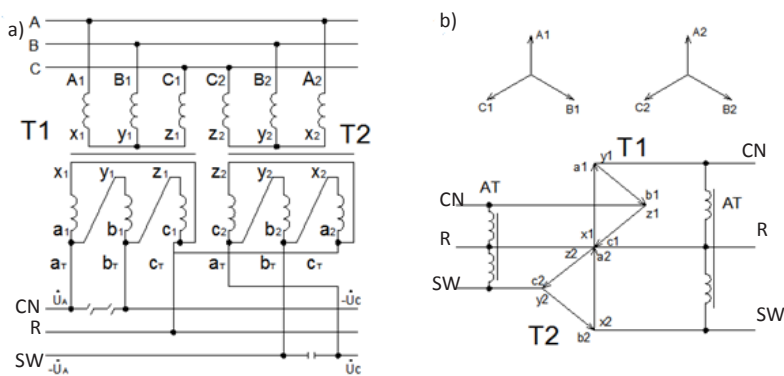
investment justification for the HSR-3 Moscow–Adler is made. In the absence of early design Russian documents regulating the requirements for the construction and operation of specialized railway lines with the speed of passenger trains of up to 400 km/h, at the request of JSC «High-speed main lines» Petersburg State Transport University (PSTU) and a number of other organizations under the leadership of professor A. T. Burkov developed «Special technical conditions» Railway power supply of Moscow–Kazan–Yekaterinburg section. Technical standards and requirements for design and construction» (hereinafter referred to as STC). The STC specifies that the design should consider options for traction substation schemes using single-phase, three-phase power transformers, transformers with a balancing effect, devices for improving the quality of electricity.

In justification of the investment of HSR-2 it is proposed to build a power supply system from the DC section (Moscow–Noginsk) and the 2x25 kV alternating current section (Noginsk–Kazan), which is recommended by STC.

The article is devoted to the choice of a rational variant of the scheme of transformers of traction substations of the power supply system 2x25 kV of the main line. The question arose not by chance. Based on the results of traction calculations made by JSC «Lengiprotrans» at the stage of investment justification, it was recommended to use single-phase



Pic. 1. Schematic diagram of traction substation with single-phase transformers.



Pic. 2. Schematic diagram of the traction substation of the power supply system 2x25 kV with three-phase transformers (a), on the right – vector diagram of voltages (b).

traction transformers with a capacity of 48 MVA, which does not meet the STC's requirement to choose equipment from a number of nominal values established by the standard. In addition, none of the domestic factories produces single-phase transformers of this power.

Objective. The objective of the authors is to consider power supply system with three-phase transformers, which can be applied on HSR.

Methods. The authors use general scientific and engineering methods, comparative analysis, scientific description, mathematical calculations.

Results.

1.

As a rule, in our country, single-phase transformers with a split secondary winding are installed in traction substations for supplying the traction network of the 2x25 kV system [2]. There is an experience of using three-phase transformers in the 2x25 kV system on the Privolzhskaya railway and earlier on the BAM.

Pic. 1 shows the scheme of a traction substation with single-phase transformers, taking into account the recommendations of the STC: 100 % redundancy of power transformers and supply of non-traction consumers from two additional three-phase double-wound transformers with a higher voltage of 220 kV and a secondary voltage of 20 kV. Such a scheme is also considered in justifying the investment of HSR-2. The primary windings of two transformers T1 and T2 are connected to an open triangle. The additional transformer T3 is reserved. Two three-phase transformers T4 and T5 are provided for supplying three-phase consumers for redundancy purposes. In the figure, CN is the contact network, SW is the supply wire, and R is the rails.

A significant drawback of the circuit with single-phase transformers was the unreliable operation of voltage-controlled load devices (VCL). The speed of the train depends on the voltage on the current collector of ERS. In STC, the minimum value of voltage on the current collector is not less than 21 kV. Nominal voltage in the traction network, at which traction calculations are performed, 25 kV. Reducing the voltage on HSR to the minimum allowed leads to a loss of ERS power by 15 % and to a decrease in the average technical speed by 7–8 % [3].

One of the means to provide the necessary voltage level in the traction network, including through changing the voltage on primary buses of traction substations, is automatic voltage regulation (ARPV) on transformers of traction substations. In the first

year of operation of the 2x25 kV power supply system with single-phase transformers at the Vyazemskaya power supply distance of Moscow Railway, at one of the substations the fine voltage regulation windings failed that perform stepwise voltage regulation. As a result, they had to be shunted [4].

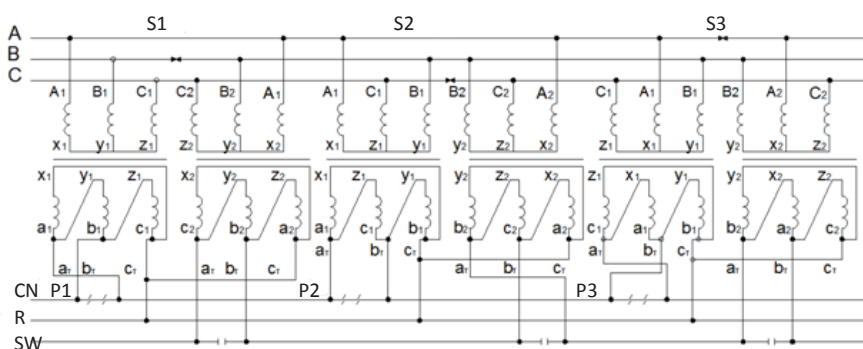
The VCL device at the traction substation Mukhtolovo of Gorky Railway failed. At the substation Sergach only odd positions of such a voltage regulator work. At the request of the authors, a response was received from the CET of JSC Russian Railways that ARPV in the 2x25 kV system is not used because of its unreliable operation.

Unreliable operation of VCL devices is caused by the following reasons. According to the insulation conditions, these devices, designed to regulate the number of turns in the neutral of the primary three-phase winding, are included in the two sections of the split low-voltage secondary winding on the side of the rails. With a low voltage, the currents flowing through only two phases of the circuit sharply increase. In this case, significantly larger current flows through the switching device connected to the contact network than through the device connected to the supply wire, because of the greater resistance of the loop feeding the wire-rails, to which the resistance of the linear autotransformers is subsequently connected. In addition, the reliability of the VCL devices, especially on the low side, when powering the traction load is significantly affected by more frequent short circuits in the traction network compared to the stationary power. A greater frequency of short circuits is caused by the influence of foreign bodies (parts of wagons, birds), damage to ERS, malfunction of current collectors, weather conditions (thunderstorms, strong wind), faults in the contact network.

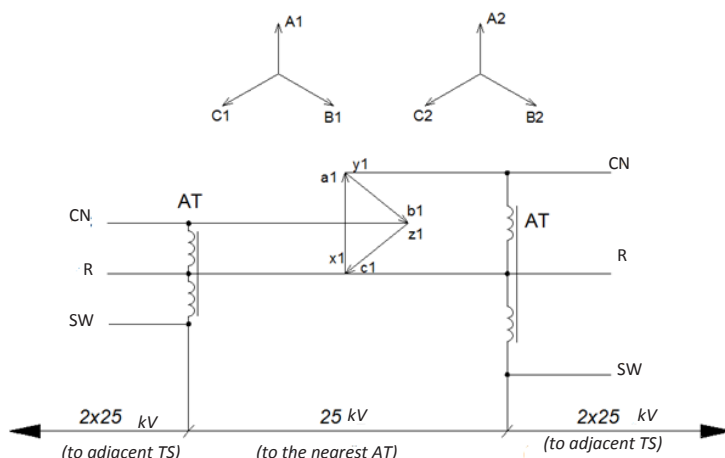
These circumstances led to the fact that in the 2x25 kV system with single-phase transformers automatic regulation of voltage under load, according to the Moscow and Gorky Railways, is not practiced. However, in [3] it is recommended to automatically maintain the voltage on the current collector to improve the power supply system of the HSR by adjusting the voltage on the bus bars of the traction substations.

2.

When developing the first traction substations of the 2x25 kV system for the Baikal-Amur Mainline, MIIT, VNIIZhT and Transelectroproekt proposed a connection scheme for substation transformers, which can be called (by analogy with the Scott and



Pic. 3. Scheme of phasing of three substations (S1-S3) with standard three-phase transformers in the 2x25 kV system.



Pic. 4. Schematic diagram of the operation of the traction substation of the 2x25 kV system in emergency mode.

Woodbridge schemes) the Chernov scheme, using three-phase transformers with the winding group U / D – 11, produced serially for the traction power supply system of 25 kV [5].

In this scheme, shown in Pic. 2a, two phases of the secondary windings of two three-phase transformers are connected in series, one of which has a winding group U / D-11, and the other is a U / D-1 connection group. In this case, one transformer is connected to the contact wires to the right and to the left of the traction substation, and the second to the wires of both the right and left arms of the power supply. The U / D-1 connection group is formed by the double-labeling of two terminals of a standard transformer. The beginning of the secondary winding «a» is connected to the end of the secondary winding «z».

Vector diagrams of primary and secondary voltages are shown in Pic. 2b, where autotransformers (AT) are additionally indicated.

In order to balance the load of the phases of the supply network, as provided in the STC, alternating the connection of the least loaded substation phases to the high-voltage line (phasing scheme) should be alternated. In this case, the connection diagram of the transformers connected to the contact wires is the same as in the TSP 25 kV. The phasing scheme of the transformers connected to the supply wires is obtained automatically, as shown in Pic. 3.

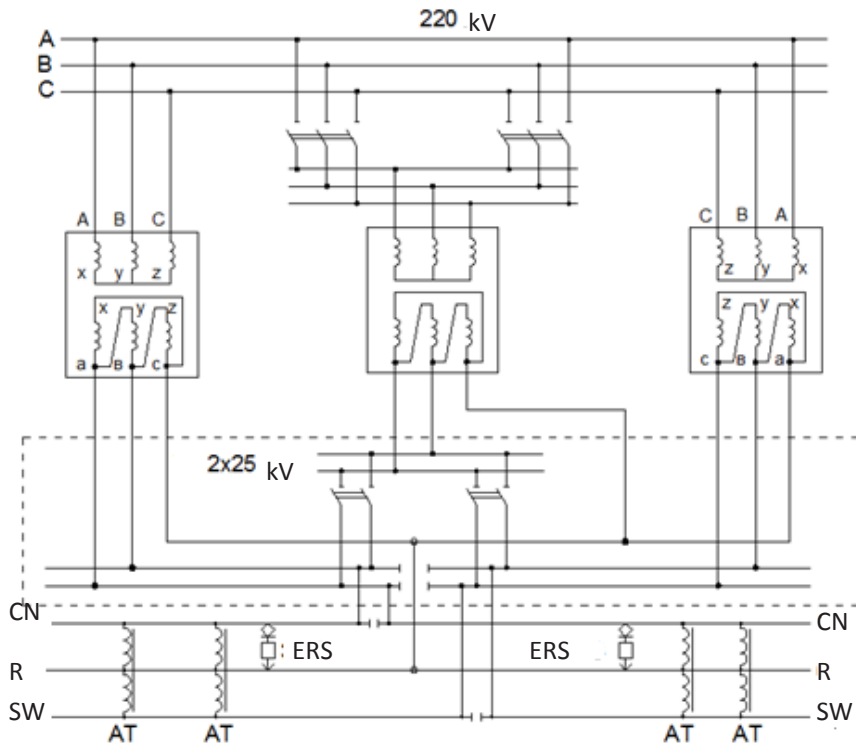
The scheme of the traction substation with three-phase transformers, connected in series, yielded to

the circuit with single-phase transformers because it was originally proposed as a circuit with two three-phase three-winding transformers. The reservation was to be carried out as follows. In case of failure of the transformer connected to supply wires, the contact network is powered from both sides of the substation to the nearest autotransformers according to the TSP 25 kV (Pic. 4).

The nearest autotransformer to the substation increases the voltage to 50 kV, and as a result, on the whole section, a 2x25 kV system with a two-way power supply of the traction network operates behind it to the next traction substation. If a transformer connected to the contact wires fails, it is replaced by a transformer connected to the supply wires, by means of operational switching. During the operative switching, the traction network will continue to be powered from two substations.

When implementing STP 2x25 kV with single-phase transformers at the Baikal-Amur Mainline departed from the idea of a two-transformer substation. To reserve any of the single-phase transformers, a backup is installed. Two three-phase transformers are provided for the supply of three-phase consumers on the territory of the traction substation. As a result, if the power of one traction transformer is sufficient to supply the traction load of the power supply, at least five transformers are installed at the substation.

A departure from the idea of a two-transformer traction substation in the 2x25 kV system made it



Pic. 5. Schematic diagram of connection of a backup traction transformer in STP 2x25 kV with three-phase transformers.

possible to offer installation of a third (backup) traction transformer in a system with three-phase transformers [6]. The redundancy scheme is shown in Pic. 5.

A 2x25 kV system with three-phase transformers was supposed to electively connect the Kochetovka–Rtishchevo line to the South-East Railway. To this end, in 1987, Khargiprotrans completed the project of electrification of this line for 2x25 kV STP with three-phase transformers at four traction substations: Nikiforovka, Rasskazovo, Kirsanov, Vertunovskaya. The project was approved and received funds. But in connection with the deteriorating economic situation in the country was not implemented. In recent years, we have returned to the electrification of this line, and Transnelectroproject has already issued a project with five traction substations.

The 2x25 kV system with three-phase transformers makes it possible to simply organize the passage of high-speed railway of large cities (Vladimir, Nizhny Novgorod, Cheboksary, Kazan) based on the existing 25 kV traction power system with three-phase transformers. At the same time, a branch for passenger trains with a speed of up to 200 km/h on a main line with the old 25 kV system is possible.

3.

At HSR professor A. T. Burkov proposed an original way to reduce voltage losses in the traction network by introducing a package schedule for the movement of high-speed trains with an interval of at least the train travel time along the longest inter-substation zone, which ensures only one train on one track between traction substations [3]. In this case, at medium distances between substations in Japan and France, respectively, 50 and 55 km, the inter-train interval is 9–12 minutes. Such an interval substantially

reduces the peak load of traction network wires, transformers of traction substations, loss of electricity in all elements of the power supply system and improves the quality of electricity on the tires of traction substations. With this arrangement of train traffic, the peak load of the substations will be a one-armed, when two oncoming trains are located between two substations, and two-armed – when the oncoming trains are on opposite sides of the substation.

When implementing the interval of the package traffic schedule proposed in [3], the use of Scott and Woodbridge symmetrizing transformers in the 2x25 kV system on HSR, mainly due to the single-armed load of the traction substations, practically does not give them an advantage in reducing the negative sequence currents in the supply network. The reverse result is possible while ensuring the requirements of the STC on the need for parallel operation of traction substations. If for single-phase and three-phase transformers due to the alternation of phase loads from parallel operating substations, the currents of the reverse sequence of power supplies from the loads of different substations are folded vectorially at an angle of 120° , then for single-armed loads the currents of the reverse sequence of power supplies from balancing transformers are added arithmetically with a shift of 180° from the loads from one and the other side of the traction substation. Only when the loads are equal on both sides, which is possible on the HSR in single cases, a balancing effect is realized.

In [3] it is clearly shown that in the scheme for the 2x25 kV Scott Woodbridge system the transformer is not connected to the rail. And then on the 50 kV side, the main equipment is required for this voltage class.

Table 1

Comparison of capital costs for transformer equipment of traction substations STP 2x25 kV

Circuit design	Transformer type	Cost of transformer, rel. units	Quantity, pcs	Total, rel. units
Substation with 3 single-phase and 2 three-phase transformers	ORDNZh-25000/220	1	3	4,313
	TDN-10000/220	0,656	2	
Substation with 5 three-phase transformers	TDNZh-25000/220	0,937	3	4,123
	TDN-10000/220	0,656	2	

In Russia there is no such class of voltage. The implementation of the scheme is possible only with the use of the main equipment of the 110 kV class, which is much more expensive. In order to use equipment of 35 kV class in RU2x25 kV in our country, transformers are connected to rails, which determines the unequal load of windings of transformers connected to the contact network and the supply wire.

The proposal of professor A. T. Burkov allows us to simply estimate the necessary power of three-phase transformers in a 2x25 kV system on the HSR. Analysis of the main parameters of high-speed trains [3] shows that the maximum capacity of 18,24 MW is possessed by the train, produced in Japan in 1995. Based on this, to estimate the power of the three-phase transformers in the 2x25 kV system, the maximum power of the electric train is 20 MW, consuming 727 A current from the windings of the transformer of the traction substations. We will take into account that in the case a train is located between autotransformers, a three-phase transformer connected between the contact wire and the rail is loaded with 10 % more than the transformer connected between the supply wire and the rails [7]. The latter is determined by the greater resistance of the unsplit supply wire and the autotransformer connected in turn with it. As a result, the load of the power arm, connected to the most loaded transformer between the contact wire and the rail, from one train will be 400 A (55 % of the train current) with unilateral power supply of the traction network. In the future, under the load of the power arm is understood the load coming from the transformer, connected to the contact wires.

Let's estimate the possibility of using 20 MW of electric power for two successive three-phase transformers with a capacity of 40 MVA at unilateral power supply of the traction network. The estimation is carried out for the most loaded transformer.

A standard three-phase transformer with a capacity of 40 MVA with a secondary winding voltage of 27,5 kV has a rated winding current of 485 A. Since the whole current of the supply arm (in contrast to a single-phase transformer) does not fall on the winding of a three-phase transformer, but 2/3 of it, nominal current of the phase is achieved with a single-armed load of 727 A, which is equal to the current of the train at its power of 20 MW. With the same load on both sides, the nominal current of the two most loaded phases of the transformer is achieved at currents of 550 A on each arm.

With the arrangement of two trains with currents of 400 A on either side of the substation, the currents of the two most loaded phases will be less than their nominal values.

In case two trains are located between substations, two options for their mutual arrangement should be considered. The easier option is when trains are between autotransformers. Then a single load from two trains 800 A will exceed the nominal current of the most loaded phase of the transformer by 10 %. The maximum short-term peak of a single-armed load of the most loaded phase of the transformer will be when the oncoming trains are on one side directly from the traction substation. This causes a single-armed load from two trains. Between the series-connected transformers it is distributed inversely with respect to the resistance of the transformer connected to the contact wires and the total resistance of the circuit consisting of the resistance of the contact network—rails to the nearest autotransformer, the resistance of the AT itself, the loop resistance, powering wire—rail to the nearest AT, resistance of the transformer, connected to supply wires. Since the resistance from the train to the side of the transformer connected to the supply wires is much larger, a significant part of the load of the two trains will have to be connected to the contact wires.

As shown in [7], the two closest to the AT substation will transmit 15 % of the load of each train to the transformer between the supply wire and the rail. As a result, the one-stage load of the transformer connected between the contact network and the rail will be 70 % of the sum of the two trains, which will exceed by 40 % the nominal current of the most loaded phase. The duration of this peak is seconds, since the oncoming train will go to another feeder zone, and the second train will reach the nearest AT station. The considered case will not affect the temperature of the windings and the aging of insulation, since it is unlikely and occurs when two other phases of the transformer are underloaded with the most loaded phase in the common oil bath.

It should be borne in mind that these overloads will only be for a 40 MVA transformer connected between the contact network and the rails at the capacity of electric trains of 20 MW, when there are two trains between the substations in case the traction network is supplied from one substation. With the capacity of electric trains of 12 MW there will be no overload, as in the case of unilateral power supply.

With two-sided feeding of the traction network, the transformer will not be overloaded and with two 20 MW trains, when they are between autotransformers. In case of simultaneous presence of two 20 MW trains on one side, a short-term transformer overload is possible directly at the substation and with a bilateral power supply of the traction network, but less than 40 %. This overload is briefly permissible for





the transformer, even if three phases are simultaneously overloaded. Note that with three-phase transformers, the probability of unidirectional feeding of the traction network is 2 times less than in single-phase transformers.

If necessary, the overload of the transformer connected to the contact network with two trains on one side of the substation can be eliminated by increasing the load of the transformer connected to the supply wire by reducing the resistance of the traction network between the series-connected transformers. This can be done by splitting the supply wire in the section between the substation and the nearest AT, installing a longitudinal compensation at the substation in the circuit feeding the wire-rails, and also reducing the distance from the substation to the nearest AT.

Thus, the power of two three-phase transformers of 40 MVA connected in series is sufficient to supply high-speed trains up to 20 MW with an interval between them no less than the train travel time along the longest inter-station zone.

By order of the authors, the manufacturer of the transformer equipment of CJSC Energomash (Yekaterinburg)–UralElectrotyazhMash estimated the relative cost of the ORDZh-25000/220 transformers; TDN-10000/220; TDNZh-25000/220. Since at the moment the plant does not produce single-phase transformers of the ORDZH type with a capacity of more than 25 000 kVA, as a unit is taken a known cost of a single-phase transformer with a capacity of 25 000 kVA. Proceeding again from the known cost of three-phase transformers, their cost is determined in relative units. Since in both schemes 2x25 kV can be executed in the same way, using domestic equipment, then two schemes are compared only for the cost of transformers. Two transformers TDN-10000/220 are necessary for supplying non-traction consumers to traction substations in both cases. The results of the relative cost estimation of transformers of traction substations STP 2x25 kV are given in Table 1.

The results in the table show that with the same cost of transformers for supplying non-traction consumers, the variant with single-phase transformers is somewhat more expensive than the three-phase variant with the same power of the power transformers. It should be noted that a single-phase transformer with a proposed capacity of 48 MVA will be more expensive than a three-phase 40 MVA.

Conclusions.

1. Considering the size of our country and population distribution in comparison with Japan and countries of Western Europe, as well as the population of Russia in comparison with China, it is not advisable to design a power supply system for the HSR with an interval of 5 minutes for the next 25 years (transformer service life). It is more rational and economical for Russia to design the power supply system of the HSR to start from the proposed

scheme for organizing train traffic, when the interval of passing trains is determined by the time of the train travel through the longest inter-station zone. Depending on the speed of the train, this interval will be 9–14 minutes.

2. Taking into account a number of significant advantages of the considered scheme with three-phase transformers and especially reliable operation of VCL devices of three-phase transformers, the authors propose for the system of electric power supply of high-speed main lines of Russia a scheme with two working commercially available for the traction power supply system 25 kV with three-phase transformers of 40 MVA, connected in series, and one backup transformer of the same power. At the same time, if in an ordinary 25 kV system the installed capacity of transformers at substations is 80 MVA, then it will become 120 MVA at the HSR, which corresponds to the world practice.

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