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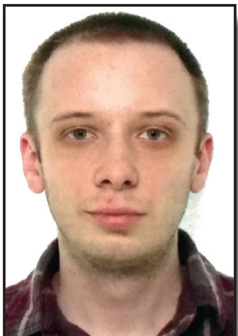
Technical and Economic Specifications of a New Type of Smoothing Reactors



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ABSTRACT

The technical and economic indicators of introduction of new type of smoothing reactors are calculated considering the features of the operating conditions of traction power supply systems of direct current 3,5 kV. Based on the data provided by operating and installation organizations, an assessment was made of cost indicators of catenary system repairs. The main financial items were formed, on the basis of which the calculation of net income and net present value was carried out in order to determine the payback period of investment costs.

The payback period based on the calculations (a little more than three years for equipment related to fixed assets with an assigned service life of twenty-five years) indicates a high level of investment attractiveness of a new type of smoothing reactor. The suggested method allows calculations using a large number of physical and operational parameters that affect the economic performance of the device.

Keywords: railway transport, net present value, present value, payback period, investment, traction substation, catenary system, overhead line, catenary system burnout, reactor with low ohmic resistance, investment costs.

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Introduction. At present, at traction DC substations on Russian railways, depending on the rectifier unit used, smoothing reactors of RBFAU-6500/3250 type with various inductances are installed in the traction current return circuit [1, p. 282]. The inductance of the reactor can vary from 1,5–12,5 mH through switching of windings or the number of sections connected in series, based on the conditions for ensuring electromagnetic compatibility [2, p. 211].

At the same time, all equipment of traction substations must be resistant to overloads, being unloaded the main part of the operating time, because the average effective value of the traction current can be 4 or more times different from its peak values, due, for example, to the start of electric rolling stock (ERS). Overload resistance or installed capacity margin determines the high cost of capital costs and the relatively low coefficient of use of this equipment [3, p. 124].

The introduction of RZhFA-6500 reactor at the traction power supply facilities can significantly reduce losses, thereby reducing the cost of centralized purchase of electricity from a wholesale supplier. Besides, the results of mathematical modeling suggest that the use of RZhFA-6500 significantly reduces the thermal and electrodynamic effects of short-circuit currents on power equipment, switching devices and current-carrying parts of traction substations, as well as overhead wires. In almost 100 % of cases of occurrence of arc short circuits, it is possible to avoid burning and annealing of the wires of the catenary system [4].

The *objective* of the study was to develop a methodology and evaluate the cost indicators of catenary system repairs, calculate net income and net present value in order to determine the payback period of investment costs when introducing a reactor of a certain type.

The authors used general scientific and economic research *methods*, engineering analysis.

Evaluation of economic efficiency and return on investment

As indicators of economic efficiency, the authors assumed:

• net income as the difference between the volume of revenues and the volume of investment costs;

• net present value as the difference between the volume of revenues for the periods (years) of the operational phase reduced to the start of the event in accordance with the discount rate used in the calculations and the amount of investment costs;

• payback period as a point in time when the total amount of revenues becomes equal to the volume of investment costs;

• discounted payback period as a point in time when the total amount of revenues brought to the point at which the event begins becomes equal to the volume of investment costs;

• profitability index.

To assess the effectiveness of investments, discounted cash flows are used that reflect cash inflows and outflows during the project implementation. The cash balance for each period is adjusted taking into account the reduction factor:

$$\alpha_t = \frac{1}{(1+E)^t}\ , \qquad (1)$$

where E is discount rate for projects in the field of railway transport (for the purposes of calculation it is taken equal to 0,1);

t – number of the calculation step.

The net present value (NPV) for the accounting period, reduced to the starting point at the discount rate, which is determined by the formula [5, p. 23]:

$$NPV = \sum_{t=0}^{T}(P_t - Z_t)\alpha\ , \qquad (2)$$

where P_t is cash inflow in the year t;

Z_t – cash outflow in the year t, excluding depreciation deductions, but including investments;

α – reduction factor.

The following groups of cash receipts are included in P_t cash inflows, mainly for operating activities:

• effect obtained due to implementation of the proposed measure;

• depreciation deductions.

The following groups of expense items are included in cash outflows Z_t:

• costs of construction, installation and commissioning;

• ongoing operating costs;

• investments for purchase of equipment;

• profit tax;

• property tax.

Calculations of tax payments on property are performed according to the formula [6]:

$$N_u = \varphi \cdot \sum_{i=1}^{n}\sum_{t=1}^{T}(K_{ti} - DD_{ti} \cdot t_{ti}) , \quad (3)$$

where K_{tj} – capital investments in implementation of the i-th technique or technology for the calculation period up to year 1, rub.;

$i = 1, 2, ..., n$, where the number of new equipment with different service life within the framework of the project under consideration;

DD_{ti} – depreciation deductions for the i-th technique or technology in the year t, rub.;

t_{tj} – years of the calculation period for the i-th technique or technology,

$t_{tj} = 1$ during commissioning of the i-th fixed assets;

ϕ – property tax rate (2,2 %/100).

Profit tax T is calculated by the formula:

$$T_p = (P_{(t)} - Z_{m(t)}) \cdot p, \quad (4)$$

where $Z_{m(t)}$ – current expenses in the year t, including depreciation, rub.;

p – profit tax rate (p = 20,0 %/100).

When evaluating the result $P_{(t)}$ from sale of products, when the valuation is associated with cost savings, profit tax is calculated according to the formula:

$$T_p = (Z'_{m(t)} - Z_{m(t)}) \cdot p, \quad (5)$$

where $Z'_{m(t)}$ – current expenses for the «no project» option in the year t, rub.;

$Z_{m(t)}$ – current expenses for the «with the project» option in the year t, rub.

The profitability index [7] shows the value in rubles of income that falls on each invested ruble of investments:

$$PI = \frac{\sum_{t=0}^{T}(P_t - Z_{mt})\alpha_1}{K_1\sum_{t=0}^{T}\alpha_1}, \quad (6)$$

where K – capital investment at the t-th step;

$Z_{m(t)}$ – current expenses excluding capital investments and depreciation deductions;

α – reduction factor in the year t.

The payback period of investments or return on investment represents the period from the start of the project, beyond which the integral effect becomes positive. The payback period determines time after which the initial investment is reimbursed at the expense of net proceeds, calculated from the base point in time. To determine the payback period, equation is used:

$$\sum_{t=0}^{T\ payback}(P_t - Z_{mt})\alpha_1 = \sum_{t=0}^{T\ payback} K_t \cdot \alpha_1 , \quad (7)$$

where P_t – cash inflow at the t-th step;

K_t – capital investments at the t-th step;

Z_{mt} – current expenses without account of capital investments and depreciation deductions;

α – reduction factor at the step t.

The formation of costs for construction, installation and commissioning is based on the cost of delivery of a serial sample of RZhFA-6500, expected at the level of 11 151 000 rub. including VAT, volumes and estimated cost of work performed by a specialized installation company at the traction substation facility of JSC Russian Railways [8, section 3]:

- rental of a crane (8 hours): 12 000 rub. VAT included;
- cost of labor of installers-riggers based on the volume of 32 man-hours at a tariff rate of 600 rub. per standard hour, total: 19 200 rub.;
- cost of labor of electricians based on the volume of 16 man-hours at a tariff rate of 625 rub. per standard hour, total: 10 000 rub.;
- amount of deductions to extra-budgetary funds on wages of installers will be 8 760 rub.;
- total cost of installation of RZhFA-6500 will be 49 960 rub. VAT included.

The dismantling of an old type reactor RBFA-U-6500/3250 includes its disconnection from live parts, removal and disposal of non-ferrous metal windings, in connection with which the cost of performing these works can be calculated using the following formula:

$$C = P_{ut.f.m.} M_{n.f} - M_{eq} P_{ut.n.f} + 30\ \%, \quad (8)$$

where $M_{eq.}$ – mass of dismantled equipment (kg);

$M_{n.f.}$ – mass of non-ferrous metal contained in the equipment (kg);

$P_{ut.n.f.}$ – price of utilization of 1 kg of non-ferrous metal (rub. with VAT);

$P_{ut.f.m.}$ – price of utilization of 1 kg of ferrous metal (rub. with VAT);

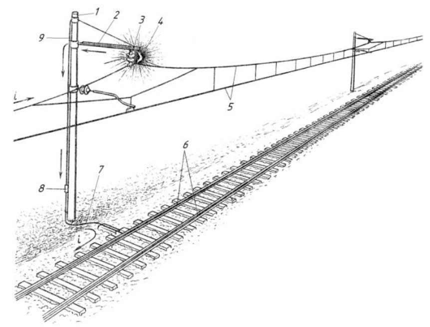
30 % –allowance for dismantling and removal.

Using the expression (8) we determine the cost of construction, installation and commissioning in numerical terms, which will be:

(5500 kg • 110 rub.) – ((7800 kg • 9,5 rub.) + 30 %) = 580 670 rub.

Consequently, from each utilized reactor of RBFA-U-6500/3250 type, an income can be obtained of 580 670 rub. VAT included.

The formation of current operating costs within the framework of the adopted financial model is associated with the periodic check of



Pic. 1. Insulator flashover and arc on the messenger wire:
1 – support, 2 – cross-arm, 3 – insulator, 4 – arc, 5 – catenary system: messenger wire and contact wire, 6 – rails, 7 – cable for group grounding of the supports, 8 – spark gap, 9 – bus connecting metal parts mounted on a support.

the state of electrical insulation and inductance parameters of a new type of reactor blocks. With respect to expert assessment, the costs of verification activities will not exceed 2 % of the cost of RZhFA-6500, that is, 150 000 rub. per year VAT included.

The calculation of the volume of investments for purchase of equipment, as well as the calculation of taxes associated with performing verification operations, are not given, because they are not decisive in this context and are carried out according to the internal standards of companies connected by a single technological process.

To assess reduction of electric energy losses during introduction of a new type of reactors JSC Transenergo – a branch of JSC Russian Railways provided data on the average daily value of the traction current of Grigoryevskaya, which is one of the constantly loaded traction substations of DC railway network, the value was 2757,81 A. Therefore, the power loss of electric energy in operating reactors such as RBFA-U-3250/6500 per day:

$\Delta W_{RBFA\ day} = (I_{av.\ day} K_{ef.})^2 R_{RBFA} \cdot h = (2757{,}8 \cdot 1{,}2)^2 \cdot 0{,}006 \cdot 24 = 1577{,}08$ kW • h,

where $I_{av.day}$ is average daily current of the substation (according to 2015 data);

K_{ef} – current efficiency coefficient (average value selected);

R_{RBFA} – active resistance of RBFA type reactor;

h – number of hours in a day.

In reactors of RZhFA-6500 type with aluminum windings with a cross section of 2970 mm² the power loss of electric energy per day will be:

$\Delta W_{RZhFA\ day} = (I_{av.\ day} K_{ef.})^2 R_{RZhFA} \cdot h = (2757{,}8 \cdot 1{,}2)^2 \cdot 0{,}0015 \cdot 24 = 394{,}27$ kW • h,

where R_{RZhFA} – active resistance of RZhFA type reactor.

In terms of the year, the losses will be:

$\Delta W_{RBFA\ year} = \Delta W_{RBFA\ day} \cdot k \cdot 365 = 1577{,}08 \cdot 1{,}25 \cdot 365 = 719542{,}66$ kW • h,

where k is correction factor taking into account the increased heating of RBFA reactor

$\Delta W_{RZhFA\ year} = \Delta W_{RZhFA\ day} \cdot k \cdot 365 = 394{,}27 \cdot 1 \cdot 365 = 143908{,}55$ kW • h.

The weighted average purchase price of electricity at Sverdlovsk railway for 2018 is 3,83 rub. per 1 kW • h [9]. Then the cost of electricity losses is:

$\Delta C_{RBFA} = \Delta W_{RBFA\ year} \cdot 3{,}83 = 2755848{,}39$ rub.;

$\Delta C_{RZhFA} = \Delta W_{RZhFA\ year} \cdot 3{,}83 = 551169{,}75$ rub.

The damage from burnout of the contact wire can vary greatly depending on each specific case, but for evaluative calculations, we consider the simplest and most frequent case of thermal damage to the contact wire.

Using the Statistical Emergency Analyzer, or the SEA instrument, developed by the team of the Department of Transport electric power engineering of Russian University of Transport and installed on one of the traction substations of the railway St. Petersburg–Moscow, statistical data were collected in real time mode, which showed that 90 % of short circuits cases were caused by faults at the electric rolling stock (ERS). At the same time, the total number of shutdowns per year per double switch of one of the feeders of the catenary system is about 100 (on this line), and this number per a depot supply feeder is about 500, that is 5 times higher. In 30–40 % (the average figure for network of railways [10, p. 110]) of cases, the shutdown was caused by an arc short circuit (see Pic. 1). For the feeder of the railway depot, this percentage is much higher.

We take the average estimated number of short circuits per traction substation feeder per year to be 35. In this case, contact wire burnout occurs in 6–8 % of cases (which can also be related to automatic recloser, for calculation we take 7 %), in total 2,5 cases of short circuit per year for each feeder result in a burnout of

Table 1

Type of an accident	Frequency, 1/year	Damage per a case, mln rub.	Risk, mln rub./year
Contact wire burnout	10	0,16	1,6
Significant accident caused by short circuit	0,3	1	0,3
Total:			1,9

the contact wire. The minimum number of feeders at traction substations of main railways is 4 pcs [11, p. 169], therefore, all feeder zones fed by a traction substation account for 10 cases of contact wire burnouts per year.

Fault removal following contact wire (CW) burnout at main track necessitates stopping of traffic along the affected track, and first the train dispatcher needs to organize movement along one track in both directions, then the shunting diesel locomotive must maneuver (tow) the train to the adjacent track to free up the site for recovery works [12, p. 289]. After that, the team of catenary repairmen starts repair work, which on average takes about 1 hour (in the simplest case).

According to the data provided by JSC Transelektromontazh, it is possible to calculate the amount of costs required to eliminate one CW burnout:

- work of a railcar: 800 rub./h;
- inspection of the anchor section and adjustment: 27206 rub./km (in case of 2 CW);
- cost of a running meter of a contact wire is 222,5 rub.;
- present value is indicated using 2000 prices; for their conversion into 2018 fourth quarter prices (period of calculations), an index of 3,63 should be used;
- length of the anchor section on the Russian railway network is of 1600 m (1,6 km), in some (extreme) cases it is of 1800 m (1,8 km).

For calculation, we take 1,6 km:

$P = (1,6 \cdot 27206+800+(2 \cdot 222,5)) \cdot 3,63 =$ 162532 rub., excluding costs of violations of schedules of trains and maneuvers.

Total damage per year at all feeder zones fed by one traction substation is $P = 162532 \cdot 10 =$ 1625320 rub. ≈ 1,6 mln rub.

About 3 % of the total number of short circuits across the entire railway network have severe and extremely serious consequences, the damage from which is difficult to be assessed. For example, non-disconnection of a dead short circuit by a high-speed circuit-breaker (a contact wire and a rail are connected without forming an electric arc) leads to the need to replace a part of the contact wire within the haul at the short circuit point, which is also done through stopping movement in this section and replacing the high-speed circuit-breakers) [13, p. 103]. Direct damage from such cases is about 1 mln rub. (the cost of one set of feeder circuit-breakers, which must be replaced, is 800 000 rub. without taking into account damage to conductor lines and related equipment). More serious accidents are also possible, which occur much less frequently (once per 5–10 years throughout the Russian Railways network), but no one can completely exclude the probability of their occurrence. These accidents are associated with the complete failure of the traction substation equipment (e.g. Moscow–Mytishchi section, spring 2005). Such accidents entail severe consequences in violation of the train schedule (losses only with regard to the equipment of the traction substation can amount to 10 to 30 mln rub., depending on its type and installed capacity, data provided by JSC Mosgiprotrans). For an optimistic assessment of direct damage caused by accidents to a typical traction substation and all feeder zones it feeds, we will refer to Table 1.

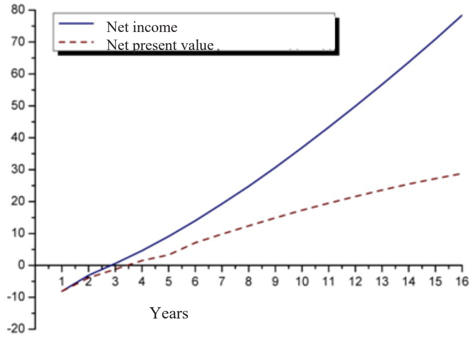
The use of a reactor of RZhFA-6500 type instead of obsolete one in the traction current return circuit will significantly reduce the damage caused by thermal and electrodynamic effects of short-circuit currents, as well as the risk of feeder circuit-breakers failure thanks to twice bigger limitation of the rate of change of current and its steady-state value. A 100 % reduction in the risks of developing emergencies and related damage provides additional savings of 1,9 mln rub. excluding damage associated with violation of the train schedule. At the same time, the total savings per a single traction substation due to a reduction in electricity losses (2,314 mln rub./year) and a reduction in damage from short circuits (1,9 mln rub./year) will be of ≈ 4,2 million rub./year.

Based on the results of assessment of total damages in monetary terms, implied by design and operation features of the catenary system resulting in highly frequent short

Table 2

The effect of introducing a new reactor model at a single traction substation

Net income, rub.	78 369 490
NPV (rate 10 %), rub.	28 796 956
Internal rate of return (IRR), %	57 %
Payback period, years	2,8
Profitability index	4,6



Pic. 2. The graph of return on investment costs.

circuits, and using the expressions (1)–(7) presented above, the payback periods of investment costs for implementation of RZhFA-6500 at traction substations of the JSC Russian Railways network were calculated. The calculation results have a graphical (Pic. 2) and the numerical representation shown in Table 2.

The total effect of introduction of RZhFA-6500 can be determined under the following assumptions:

1. The length of DC sections on the Russian railway network is ~ 23 000 km.

2. The number of DC traction substations (based on 1 substation per 15 km of track) is ~ 1500.

3. The number of reactors at the substation is 1.

Thus, the total savings of JSC Russian Railways when introducing RZhFA-6500 at all DC traction substations can amount to 4 200 thous. rub. • 1,500 = 6,3 bln rub./year with a payback period of slightly less than three years.

Conclusion. The calculations showed that introduction of a new type of reactor with low ohmic resistance and with a payback period of about three years has a high investment attractiveness. Besides, its introducing provides previously unattainable technical effects related to safety of train traffic and the fault tolerance of power equipment and live parts. Despite the fact that many of the concomitant effects cannot be directly estimated, the comparative operational efficiency of RZhFA-6500 turned out to be quite high. Updating the results obtained can be carried out based on the results of the pilot operation of the device.

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