Improvement of the system of contactless automatic regulation of voltage of converter traction units of traction substations

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Abstract. The article discusses the problem of increasing the energy efficiency of the 3 kV DC traction power supply system on the railways of the Russian Federation. As one of the ways to amplify it, the authors consider a system of contactless automatic voltage regulation under load of converting units of traction substations, where reactor controlled devices serve as the regulatory body. As one of the directions for improving the system, the use of thyristors in the design of a controlled device is proposed. The article presents the functional diagrams of contactless automatic voltage control systems with thyristor-reactor and thyristor controlled devices, shows the external characteristics of the converter unit with these systems. To calculate the economic efficiency when introducing contactless automatic voltage control systems with reactor, thyristor-reactor and thyristor controlled devices, a methodology has been developed based on calculating the savings in reduced costs, as well as the payback period when replacing a contactless automatic voltage control system under load with a reactor controlled device by a system with thyristor-reactor and system with thyristor.

1. Introduction
Improving the energy efficiency of electrified railways is one of the most important tasks for ensuring the competitiveness of the transportation process. To this end, in accordance with the strategy for the development of railway transport in the Russian Federation until 2030, the railways of our country provide for an increase in passenger train speeds of up to 250 .. 300 km/h, organization of circulation of freight trains of increased mass and length and connected trains.

However, the existing system of 3 kV DC traction power supply can no longer cope with such tasks and when skipping the indicated categories of trains in a number of electrified sections, a decrease in the voltage at the collector bow is lower than the permissible values necessary for normal operation of an electric locomotive. In order to maintain the voltage level within acceptable limits in the traction power supply system, various methods of its amplification are used, one of which is the use of transformers with voltage regulation devices under load (on-load tap-changer). Voltage regulation using such devices is carried out by changing the transformation ratio of the transformer [1-3].

The reactor on-load tap-changers included in the contactless automatic voltage control (CAVC) system provide high voltage quality, smooth regulation of the transformation ratio and high reliability of the equipment due to the absence of mechanical switches and contactors in their design [4].
The system includes one uncontrolled UR1 and one controlled CR2 reactors connected to the taps of the primary winding of the converter transformer (CT), and an automatic voltage control box «SHAUN 5», which provides voltage regulation due to the magnetization and demagnetization of the controlled reactor CR2. The voltage regulation in the transformer is carried out by magnetizing the core of CR2, and the role of UR1 is reduced to limiting the circulating current.

Functional scheme of the contactless automatic voltage regulation system with controlled and uncontrolled reactors CR1-UR2 is shown in Figure 1.

![Functional scheme of the contactless automatic voltage regulation system with controlled and uncontrolled reactors CR1-UR2](image)

The disadvantages of the CAVC system include significant weight and size parameters, the high cost of reactors associated with the use of electrical copper and steel; and most importantly, significant losses of electricity in reactors.

2. Description of contactless automatic voltage control systems with thyristor-reactor - CAVC-TRSD and thyristor - CAVC-TSD on-load tap-changers

To increase the technical and energy parameters of the CAVC system, promising directions for its further development are the use of semiconductor devices in the design of the on-load tap-changer. One of the directions is the development of thyristor-reactor switching device (TRSD) [5, 6], where CR2 is replaced by a thyristor switch, and the role of UR1 is to limit the circulating current, the second is the development of a thyristor switching device (TSD), where CR2 and UR1 are replaced by thyristor switches, which eliminates the use of current-limiting resistances. Figure 2 shows the functional diagrams of a contactless automatic voltage control system with a thyristor-reactor on-load tap-changer - CAVC - TSD and a thyristor on-load tap-changer - CAVC - TSD.

The object of regulation in these systems is a converter unit (including a converter transformer and a rectifier unit). The thyristor-reactor on-load tap-changer is used as a regulatory body in the CAVC - TRSD system, and the on-load tap-changer in the CAVC-TSD system. The automatic controller is the «SHAUN 6» automatic voltage control box.

Systems provide contactless voltage regulation in the range of 14%. The calculated external characteristics of the conversion unit with the CAVC - TSD and CAVC - TSD systems are shown in Figure 3.

Characteristics 1, 2 correspond to two extreme operating modes of the CAVC - TRSD and CAVC - TSD systems. The regulation zone is between characteristics 1 and 2.

The systems provide automatic voltage stabilization on the tires of traction substations at the levels of 3500 V, 3600 V and 3700 V. (characteristics 3, 4 or 5, Figure 3).

In the CAVC - TRSD and CAVC - TSD systems, the TRSD cabinet and the TSD cabinet are located near the converter transformer and whose main purpose is to switch the primary windings of the converter transformer under load in accordance with the received control signal from the «SHAUN 6»
cabinet. The control signal from the «SHAUN 6» cabinet, through optical isolation, comes to the on/off keys, according to which they form a signal to the control electrodes of the thyristor keys TK. Power supply for the keys is carried out from the transformer's own needs of the traction substation.

Figure 2. Functional diagrams of a contactless automatic voltage control system: a - with thyristor-reactor on-load tap-changer - CAVC - TRSD; b - with thyristor on-load tap-changer - CAVC - TSD; 1, 2, 3, 4 – on/off keys.
**Figure 3.** The calculated external characteristics of the conversion unit with the CAVC-TSD and CAVC -TSD systems: 3 - 6 – stabilized characteristics; 1, 2 – falling characteristics.

The «SHAUN 6» box has seven measuring channels for generating working information signals.

The first channel provides communication with a voltage sensor (VS), which is connected to the buses of the rectifier unit and provides the conversion of the value of the rectified voltage $U_d$ into a working information signal. Information about the level of rectified voltage from the VS comes to the microcontroller of the cabinet «SHAUN 6», which compares the measured voltage value with a given stabilization level. Based on the comparison result, the «SHAUN 6» box generates a control signal and sends it to the TRSD cabinet or the TSD cabinet.

Three measuring channels provide the connection of the voltage transformer of the traction substation with the box «SHAUN 6», in order to determine the intervals of the zero phase voltage of the converter transformer.

To facilitate the switching of thyristor switches TRSD, the control signal is transmitted from the box «SHAUN 6» at the moment of zero voltage value of the supply network.

The remaining three measuring channels provide the connection between the current transformers of the traction substation and the box «SHAUN 6», in order to determine intervals of the zero phase current value of the converter transformer. To facilitate the switching of TSD thyristor switches, the control signal from the «SHAUN 6» box is transmitted at the moment of zero value of the current of the supply network.

The cost [7-9] of the considered automatic voltage control systems is presented in table 1.

| Type of system | CAVC | CAVC -TRSD | CAVC -TSD |
|----------------|------|------------|-----------|
| System on-load tap-changer elements | Controlled CR2 and uncontrolled UR1 reactors | Thyristor switch | Uncontrolled reactor | Thyristor switch |
| The cost of the elements of the on-load tap-changer, rubles | - | 527 190 | 7 000 000 | 1 054 380 |
| The cost of the on-load tap-changer, rubles | - | 7 527 190 | 1 054 380 |
| The cost of the on-load tap-changer with a construct, rubles\(^a\) | 22 000 000 | 8 054 380 | 2 108 760 |

\(^a\) The cost of the construct is taken equal to the value of the thyristor switches.

To compare economic efficiency when implementing the CAVC, CAVC -TRSD and CAVC -TSD systems, one that requires a minimum of reduced costs is selected. The calculation of the savings of reduced costs allows you to compare the economic efficiency of capital investments.

Reduced costs are calculated according to the following formula:

$$3_{RC} = \sum_{t=0}^{T} \left[ \frac{K_t \cdot (1-j)^{(t-T_0)+\sum \Delta P \cdot T_{year} \cdot C_{ap}}}{(1+E)^{t}} \right]$$  \hspace{1cm} (1)

$T$ - calculation horizon, year;
$j$ - share of tax deductions from profit, 0.2;
$E$ - discount rate, 0.1;
$Z$ - risk adjustment (equals 0.03 – when investing in infrastructure and reliable equipment);
$K_t$ - capital expenditures, rubles;
$C_{ap}$ - equipment price, rubles
$T_0$ - life time, 25 years;
Cap - average price of 1 kW·h electricity;  
T_year - hours per year – 8760 years;  
\( \sum \Delta P \) - energy losses in the CAVC, CAVC -TRSD or CAVC -TSD system, kW  
Losses of electric power in the reactors of the CAVC system, taking into account the load factor of the traction substation:

\[
\sum \Delta P_{CAVC} = n(\Delta P_1 + K_L \Delta P_{SC} + P_C), \tag{2}
\]

- \( n \) – number of working at traction substation converters units;  
- \( \Delta P_{SC} \) – loss of short circuit power of the controlled reactor CR2, kW;  
- \( \Delta P_1 \) – idle power loss of the controlled reactor UR 2, kW;  
- \( P_C \) – control power equal to 10 kW  
Loss of electric power in the TRSD of the CAVC -TRSD system, taking into account the load factor of the traction substation:

\[
\sum \Delta P_{TRSD} = n(\Delta P_{I-UR} + K_L \Delta P_{SC-UR} + K_L S(U_{TO} I_1 + I_1^2 r_T) + P_{CS}) \tag{3}
\]

- \( \Delta P_{SC-UR} \) – loss of short-circuit power of an uncontrolled reactor UR, kW;  
- \( \Delta P_{I-UR} \) – loss of idle power of uncontrolled reactor UR, kW;  
- \( U_{TO} \) – thyristor threshold voltage, V;  
- \( r_T \) – thyristor differential resistance, Ohm;  
- \( S \) – number of thyristors in series;  
- \( P_{CS} \) – control power equal to 1 kW  
Losses of electric power in TSD of CAVC -TSD system taking into account the load factor of the traction substation:

\[
\sum \Delta P_{TSD} = n(K_L(U_{TO} I_1 + I_1^2 r_T) S + P_{CS}) \tag{4}
\]

The load factor of the traction substation is:

\[
K_L = \frac{I_{TS}}{I_{d_{\text{ru}}}}, \tag{5}
\]

- \( I_{d_{\text{ru}}} \) – rated rectified current of the converter unit, A;  
- \( I_{TS} \) – average annual current of the traction substation, determined by the formula:

\[
I_{TS,YEAR} = \frac{A_{\text{TR YEAR}} + A_{\text{NS,YEAR}}}{U_{dcr} T_{YEAR}} \tag{6}
\]

- \( A_{\text{TR YEAR}} \) – electric energy consumption for traction in one year, thousand kW·h;  
- \( A_{\text{NS,YEAR}} \) – electric energy consumption for traction needs substations thousand, kW·h;  
- \( U_{dcr} \) – preset stabilization level, V  

3. Results

In accordance with the above calculation method, the reduced costs of the CAVC, CAVC -TRSD or CAVC-TSD systems were calculated, the results of which are presented in the form of graphs of the dependence of the reduced costs on the load factor of the traction substation. Graphs of the dependence of the reduced costs of the CAVC, CAVC -TRSD and CAVC -TSD systems on the load factor of the traction substation are presented in Figure 4.

When replacing the CAVC system with the CAVC -TSD system, the payback period in an approximate version can be determined from expression 7, and when replacing the CAVC -TSD system from expression 8 [10]:

\[
\eta_{year} = \frac{K_c + \Phi - K_{cap} \cdot 700 000}{\sum C_{AA,CAVC} \cdot \sum C_{AA,TRSD}}. \tag{7}
\]
\[ \eta_{\text{year}} = \frac{K_\text{scp} + \Phi}{\sum C_{\Delta \text{CAVC}} + \sum C_{\Delta \text{TSD}}}; \]  

(8)

- \( K_{\text{scp}} \) – the cost of scrap electric copper, scrap electrical steel and spent transformer oil, steel tanks of reactors, rubles;
- \( \Phi \) – the cost of installing new, dismantling old equipment and transportation costs, rubles;

The graph of the payback period \( \eta_{\text{year}} \) versus the load factor of the traction substation \( K_h \) when replacing the CAVC system with the CAVC-TRSD or CAVC-TSD system is presented in Figure 5.

In approximate calculation, the coefficient \( K_{\text{scp}} \) taken equal to the coefficient \( \Phi \).

**Figure 4.** Graphs of the dependence of the reduced costs of the CAVC, CAVC -TRSD and CAVC -TSD systems on the load factor of the traction substation.

**Figure 5.** The graph of the payback period \( \eta_{\text{year}} \) versus the load factor of the traction substation \( K_h \) when replacing the CAVC system with the CAVC-TRSD or CAVC-TSD system.

4. Conclusions

In accordance with the calculation results presented in Figure 4 and 5, and also due to the fact that under operating conditions, the value of the load factor of the traction substation is in the range of 0.3 - 0.5 relative units:

- the reduced costs for the implementation of the CAVC system are 33–35 million rubles, the CAVC-TRSD system is 11.5–12.5 million rubles, the CAVC-TSD system is about 3 million rubles;
- The payback period when replacing the CAVC system with the CAVC-TRSD 1 system is 1.5 years, and with the CAVC-TSD system 1.5 - 2 years;
Currently, according to the scheme in Figure 2, a, the CAVC-TRSD system is being designed.

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