Adaptive power supply system in plot with artificially complex profile

Mirjalil Yakubov*, *Muborak* Sagatova, *Sayfuddin* Norjigitov, and *Saidaziz* Saydivaliev

Tashkent State Transport University, Tashkent, Uzbekistan

Abstract. The paper deals with the issues of energy saving in the railway section, which has a tunnel with a double longitudinal slope, which limits the capacity of trains due to a decrease in the rated voltage by more than 10%, which negatively affects thermal and transient electromechanical processes. The practicality of voltage regulation using the existing installation of series compensation is shown; it is proposed to use an additional installation of parallel reactive power compensation, with automatic voltage regulation of the power transformer under load. The principle of self-tuning adaptive regulation is applied, establishing the optimal power supply mode according to the criterion of minimum losses, which has high reliability and cost indicators of traction power supply.

1 Introduction

With an increase in the volume of passenger and freight traffic, and a large length of the contact system, there are often irregularities in the feeder zone of the track, the presence of artificial structures in the form of long tunnels, there are often cases when traction asynchronous motors of electric trains due to a decrease in voltage and the presence of a longitudinal inclination of the track find themselves in conditions of limited bandwidth. These conditions are characterized, first of all, by significant voltage drops, which lead to prolonged transportation.

Here is brief technical information about the "Kamchik" tunnel built in 2016 on the "Angren-Pap" railway section of the Republic of Uzbekistan. This is a category III single-track railway from "Angren" to "Pap", with a maximum speed of 90 km/h. The total length of the tunnel is 19268.5 m, and its maximum depth is 1260 m. The tunnel has a double slope, that is, 20 ° length (11430 m) of the tunnel slope from west to east and 10.765 ° length (7770 m) of the descent.

The presence of a double slope of the tunnel reduces and increases the transition time of the electric rolling stock, leading to a decrease in voltage of 25 kV, exacerbating thermal transients and electromechanical processes.

Currently, the contact network is powered by the "Orzu" traction substation, which has a power transformer TDTNZh-40000/220/27.5/10. Its suction feeder is connected to a reactive power longitudinal compensation unit. Installation of parallel compensation of reactive compensation was not foreseen by the project. At present, these factors have led to

*Corresponding author: mirjalil.yakubov@mail.ru

 https://doi.org/10.1051/e3sconf/202340102037

the restriction of passenger and freight traffic through the tunnel with more than 2500 tons. There are power losses of traction power supply, reaching up to 10-12%. In addition, there is asymmetry and non-sinusoidal voltage and current, which aggravate normal modes and reduce the resource consumption of traction motors of electric rolling stock [6,9]. Cargo transportation with a volume of more than 2,500 tons is carried out through the "Kamchik" tunnel separately, which increases the time of cargo transportation and additional energy losses.

2 Methods

At the present stage of increasing the generation of electrical energy in the Republic of Uzbekistan, with the introduction of government regulations, requirements for the use of methods and technical means of energy saving, which consist in reducing the time of transportation, reducing losses in traction power supply and improving the quality of electrical energy, the following methods are used for this: the existing installation of longitudinal and the use of an additional installation of transverse compensation, the use of automatic regulation of the output voltage of the power transformer under load. When regulating the voltage of a power transformer, it is advisable to apply the principle of algorithmic adaptive regulation to save its resource [1-3]. In particular, their joint regulation should be provided depending on the value of the traction load, which varies along the length of the contact network line in the tunnel [7, 8] of the specified traction power supply system, fed by only one substation, "Orzu". The set parameters of longitudinal and transverse compensation should be selected, taking into account the non-symmetry of the parameters of the existing traction power supply system [12-16]. The matrix method is used to calculate the parameters.

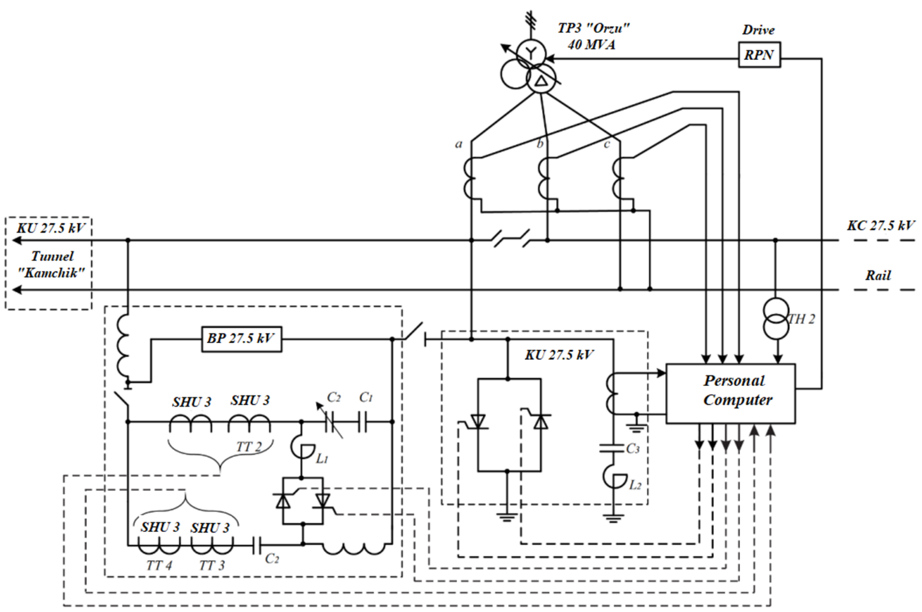

Fig. 1. Scheme of an adaptive traction power supply system with longitudinal and transverse reactive power compensation.

3 Results and discussions

Consider a mathematical model of electrical supply and supply of the required power with one traction substation "Orzu" with a power transformer equipped with automatic voltage regulation of the power transformer under load. We also consider the parameters of the adjustable installation of longitudinal capacitive compensation and the use of an additional device for transverse reactive power compensation to increase the capacity of the electric locomotive through a tunnel with a complex profile. For this, it is advisable to use the principle of adaptive voltage regulation [1, 2, 13] and limit the switching frequency of automatic voltage regulation of a power transformer under load to save its resource. For the operation of such a system, it is necessary to apply a calculated logic block (Fig. 1)

The basis of the calculated logic block of voltage regulation is a mathematical model that sets the following mode of allowable power according to the condition:

$$\Delta P(\Delta U)_i \le \Delta P_0 \quad (1)$$

$$U - U_{k_{max}} \le 0, \quad U - U_{k_{min}} \ge 0. \quad (2)$$

where $\Delta P(\Delta U)i$ is losses of active power at i -change of voltage mode by ΔU; ΔP_0 is active power of the total losses of the power three-phase transformer of the traction substation ΔS_{TTP}, including the power of external power supply, as well as power losses in the traction network $\Delta \underline{S}_{ts}$ in matrix form [4,11] equal to:

$$\Delta \underline{S} = \Delta \underline{S}_{TTP} + \Delta \underline{S}_{TS} \quad (3)$$

$U_{k_{min}}$ is minimum voltage at the substation feeder; $U_{k_{max}}$ is maximum voltage at the substation feeder.

Further, we will express the equations in matrix form oriented to the use of computers [1, 2, 13].

The power components in (1) and (3) are expressed in terms of the voltage supplied to the traction power transformer, taking into account the diagonal matrix of its phase resistances $\mathrm{Z}_{\Delta}^{\partial}$ with the star-delta connection scheme:

$$\Delta \underline{U} = \Delta \underline{Z}_{\Delta} \mathrm{C} \cdot \underline{I} \quad (4)$$

where C is the matrix of connection between the winding currents of the traction power transformer and the currents of the traction network; $\underline{I}$ is column vector of currents of the traction network and transformer loaded by the traction network; $\Delta \underline{Z}_{\Delta}$ is $3N \times 3N$ diagonal matrix of power transformer resistances in a star-delta circuit.

Here and below, the traction power transformer and the traction network are expressed in terms of diagonal resistance matrices, the first incidence matrix, the block-diagonal matrix of the connection between the power transformer currents and load currents based on the given traction power supply scheme (Fig. 1).

Considering that the currents in the traction winding connected in a "triangle" $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$ through the currents of the traction load and the overhead line, two rail wires $\underline{I}_a$, $\underline{I}_b$, $\underline{I}_c$ are expressed as:

$$\underline{I}_A = \frac{1}{3}(2\underline{I}_a - \underline{I}_b - \underline{I}_c)$$
$$\underline{I}_B = \frac{1}{3}(-\underline{I}_a + 2\underline{I}_b - \underline{I}_c) \quad (5)$$
$$\underline{I}_C = \frac{1}{3}(-\underline{I}_a - \underline{I}_b + 2\underline{I}_c)$$

and the matrix-column of currents of the traction transformer I is written as:

$$\underline{\mathrm{I}} = \mathrm{C} \cdot \underline{\mathrm{I}}_{\mathrm{T}} \qquad (6)$$

where $\underline{I}_T$ is the load current matrix of the power transformer.
The power loss in the power transformer is written as:

$$\Delta \underline{S}_{T\mathrm{p}} = (\mathrm{C}\underline{I}^*{}_{T\mathrm{p}})^T \cdot \underline{Z}_\Delta^\partial \cdot C\left(\underline{I}^*{}_{T\mathrm{p}}\right) \qquad (7)$$

where $(\underline{I}^*{}_T)^T$ is transposed sum of conjugated column matrices 3N currents of a three-phase transformer; Incident matrix for connecting a single-phase traction network to a three-phase power transformer.

Taking into account the rules of operations on matrices, we can rewrite expression (7) in the form:

$$\Delta \underline{S}_{T\mathrm{p}} = (\underline{I}^*{}_T)^T \mathrm{C}^T \cdot \underline{Z}_\Delta^\partial \cdot \mathrm{C}(\underline{I}_T) \qquad (8)$$

Power losses in the traction network from the traction load ΔS_{ts} are determined by the method given in [3].

Taking into account (3)÷(7) and matrices of nodal own Z_{ii}, and mutual resistances Z_{ij}, the total power losses of the traction power supply system are written in matrix form:

$$\Delta \underline{S}_c = (\underline{I}^*{}_T)^T Z_{\mathrm{oy}}(\underline{I}_T) + \Delta \underline{S}_{ts} \qquad (9)$$

where $\underline{Z}_{oy}$ is a 3N*3N matrix of resistances of the contact network connected through a feeder to a power transformer; $\underline{Z}_{\mathrm{oy}}^*$ is matrix of reduced resistances corresponding to the changeable transformation ratio; k^∂ is diagonal matrix of relative transformer coefficients.

Formula (8) shows that the first two components of power losses in the external power supply system and in the contact network depend on the power transformation coefficient k^∂ and the changing parameters of the longitudinal-transverse compensation installation. Note that the power consumption in the contact network depends on electric locomotives' established mode of movement.

The above formulas can be considered as a mathematical model when the voltage changes to assess the active losses in the contact system $\Delta \underline{S}_c$. To calculate active power losses, which is a real component of the total power of the system under consideration, we can write [11]:

$$\Delta \mathrm{P}_\mathrm{c} = Re(\Delta \underline{S}_c) = (\underline{I}_T^*)^T \cdot R_{OY}(\underline{I}_T) + \Delta \underline{S}_{ts} \qquad (10)$$

The expression of active power losses when changing the transformation ratio of the traction power transformer k^∂, is determined using a personal computer.
The personal computer calculates the derivative, i.e., the rate of change of the active loss growth function "P" by differentiating the matrix formula (10). To do this, we use the standard matrix transformation (9):

$$P = \frac{\partial\left[(\underline{I}_T^*)^T\right] k^\partial (\Delta \mathrm{P_c}) R_{OY_1} k^\partial \left(\underline{I}_T\right)}{\partial k_i^\partial} + \frac{\partial\left[(\underline{I}_T^*)^T\right] R_{OY_2}\left(\underline{I}_T\right)}{\partial k_i^\partial} + R_{OY} k^\partial \cdot \left(\underline{I}_T\right) +$$
$$+ \frac{\partial(\underline{I}_y^{*T} \cdot R)}{\partial k_i^\partial} - 2 \times \frac{(\underline{I}_T^*)^T k^\partial}{\partial k_i^\partial} R_{OY_1} k^\partial \left(\underline{I}_T\right) + 2\frac{\partial(\underline{I}_T^*)^T}{\partial k_i^\partial} R_{OY_2}\left(\underline{I}_T\right) \qquad (11)$$

where $R_{OY}$is the real component of the resistance matrices of the output winding of the power transformer $\underline{Z}_{ts}$; R_{TC} is the real component of the Z_{TC} matrix; $\underline{I}_T^*$ is matrix of setting nodal conjugated currents.

The derivative of power losses ΔP_c (1.14) (i.e., the sensitivity of changes in power losses with voltage changes) when regulating the voltage at substation "i" is [10]:

$$P = \frac{\partial(\Delta P_c)}{\partial k_i^{\partial}} = \left[2 \times \left(\underline{I}_T^* + MZ_{kont}^{-1}T^T \times (2k^{\partial}\underline{E} + 6k^2 Z_{OY}k^2 I_T - \underline{Z}_{OY}I_T\right)\right]^{\mathrm{T}} \times \cdot R_{OY}k^2 \times \left(\underline{I}_T + MZ_{kont}^{-1}M^T \times \left(k^{\partial}\underline{E} - k^{\partial}\underline{Z}_{OY}k^{\partial}I_T - \underline{Z}_{OY2}I_T\right)\right) + \left[2\left(MZ_{kont}^{-1}M^T(\underline{E}^* - 2Z_{OY}k^{\partial}\right)\right]^{\mathrm{T}} \times R_{OY_2} \times \left(\underline{I}_T + MZ_{kont}^{-1}M^T \times \left(k^{\partial}\underline{E} - -k^{\partial}\underline{E} - k^{\partial}\underline{Z}_{OY2}k^{\partial}I_T - \underline{Z}_{OY2}\right)\right)] + \left[2 \times \left(Z_{kont}^{-1}M^T \times (\underline{k^{\partial}\underline{E} - k^{\partial}Z_{OY1}k^{\partial}}\underline{I}_y - \underline{Z}_{OY2}\underline{I}_T\right)\right] \quad (12)$$

M is the first matrix of connections of branches to chain nodes; k^{∂} is diagonal matrix relative to the coefficients of the power transformer; where $X_k = \frac{U_k}{I_{k-}}$ is reactance of the compensating device; $X_p = X_{vn} + X_{ts}, X_{vn}, X_{ts}$ is total reactance of external power supply and traction network [8.11].

Taking into account the change in voltage at the output feeder of the power transformer connected to the contact network and the rail, it can be expressed as (13, 14):

$$\underline{U}_{tk} = \underline{U}_t + \underline{I}_k \mathrm{CM}(x_p + Lx_{ts}),$$

where $\underline{U}_{tk}$ is the voltage at the installation site of the reactor L_k compensating devices before and after it is turned on.

The circuit should work as follows. Personal computer in the memory of which there is a calculation model in the form (1); (2), and (11) by the value of the total measurement information corresponding to the variable parameter of the contact network and the parameter of the capacitive compensating device, calculates the currents in the branches of the system. Node voltages are also taken into account to calculate the power $\Delta S_{TTP}, \Delta S_{TS}, \Delta S_{Tp}, \Delta S_{CT}$ based on equations (3), (8), (9). Next, the analysis for fulfilling condition (2) takes place, and the power losses are compared according to (1). In this case, the calculations are carried out considering the data of the statistical material embedded in the computer memory. The calculation is repeated using the previously accumulated static material for each step of changing k^{∂} until a control option satisfies conditions (1) and (2). According to the results of calculations, the output signal of the computer sets the command to switch the tap of the power transformer in the direction of decreasing or increasing k^{∂} and also a signal to change the parameters of the compensating devices [4, 19, 20].

4 Conclusions

1. The above system is based primarily on a theoretical concept, like any self-tuning adaptive system. It allows you to determine the system's sensitivity to variations and allows for the possibility of regulating the voltage of the traction power transformer under load. The parameters of the longitudinal and transverse compensation installations are also considered to minimize active losses in case of deviations in the transient mode of the external and traction power supply. The system also considers the assignments in the allowable uncertainty intervals, characterized by the upper and lower bounds of the guaranteed values.
2. The practicality of applying the matrix calculation of deviations of power losses of the traction network, oriented to the use of computers, is proposed. The system implements a

self-tuning method of traction power supply voltage regulation to minimize active losses and maintain the quality of electrical energy.

References

1. Spitsin A.V. Adaptive regulators with trial harmonic signal for objects with variable parameters. (2001)
2. Vanin, A. S., Valyanski, A. V., Nasyrov, R. R., and Tul'skii, V. N. Quality monitoring of electrical power to evaluate the operational reliability of power equipment and active–adaptive voltage control in distribution power grids. Russian Electrical Engineering, 87, 452-456. (2016).
3. Åström, K. J., Hägglund, T., Hang, C. C., and Ho, W. K. Automatic tuning and adaptation for PID controllers-a survey. Control Engineering Practice, 1(4), 699-714. (1993).
4. Andiappan, V. State-of-the-art review of mathematical optimisation approaches for synthesis of energy systems. Process Integration and Optimization for Sustainability, 1(3), 165-188. (2017).
5. Di Dio, V., La Cascia, D., Miceli, R., and Rando, C. A mathematical model to determine the electrical energy production in photovoltaic fields under mismatch effect. In 2009 International Conference on Clean Electrical Power (pp. 46-51). IEEE. (2009).
6. Hao, F., Zhang, G., Chen, J., Liu, Z., Xu, D., and Wang, Y. Optimal voltage regulation and power sharing in traction power systems with reversible converters. IEEE Transactions on Power Systems, 35(4), 2726-2735. (2020).
7. Li, Q. New generation traction power supply system and its key technologies for electrified railways. Journal of Modern Transportation, 23, 1-11. (2015).
8. Pochaevets. V.S. Automated control systems for railway power supply devices. (2016).
9. Yakubov, M., Turdibekov, K., Sulliev, A., Karimov, I., Saydivaliyev, S., and Xalikov, S. Improvement of the information-measuring complex for diagnostics of traction power supply objects at high-speed traffic. In E3S Web of Conferences,Vol. 304, p. 02014. (2021).
10. Yakubov M.S., Turdibekov K. Kh. Sulliev A. Kh. Improvement of the information-measurement complex for diagnostics of traction power supply. E3S Web of Conferences, Vol. 304, p. 02014 (2021).
11. Novikov, A., Glagolev, S., Novikov, I., and Shevtsova, A. Information technologies and management of transport systems development of the approach to assessing adaptation of the intersection transport model. In IOP conference series: materials science and engineering, Vol. 632, No. 1, p. 012052. (2019).
12. Sun, S., Cao, Z., Zhu, H., and Zhao, J. A survey of optimization methods from a machine learning perspective. IEEE transactions on cybernetics, 50(8), 3668-3681. (2019).
13. Shokri, A. A., and Mardaani, M. Spin-flip effect on electrical transport in magnetic quantum wire systems. Solid state communications, 137(1-2), 53-58. (2006).
14. Amiel, I., Rajput, S., and Averbukh, M. Capacitive reactive power compensation to prevent voltage instabilities in distribution lines. International Journal of Electrical Power and Energy Systems, 131, 107043. (2021).

15. Rajput, S., Amiel, I., Sitbon, M., Aharon, I., and Averbukh, M. Control the Voltage Instabilities of Distribution Lines using Capacitive Reactive Power. Energies, 13(4), 875. (2020).
16. Alenius, H., Luhtala, R., Messo, T., and Roinila, T. Autonomous reactive power support for smart photovoltaic inverter based on real-time grid-impedance measurements of a weak grid. Electric Power Systems Research, 182, 106207. (2020).
17. Sarkar, M. N. I., Meegahapola, L. G., and Datta, M. Reactive power management in renewable rich power grids: A review of grid-codes, renewable generators, support devices, control strategies and optimization algorithms. IEEE Access, 6, 41458-41489. (2018).
18. Rehman, H. U., Yan, X., Abdelbaky, M. A., Jan, M. U., and Iqbal, S. An advanced virtual synchronous generator control technique for frequency regulation of grid-connected PV system. International Journal of Electrical Power and Energy Systems, 125, 106440. (2021).
19. Suslick, K. S. Encyclopedia of physical science and technology. Sonoluminescence and sonochemistry, 3rd edn. Elsevier Science Ltd, Massachusetts, 1-20. (2001).
20. S. F. Amirov, M. S. Yakubov. Mathematical Modeling of the Reability of Ferromagnetic Current Converters with Adjustable Range for Traction Power Supple Devices. In International Journal of Multidisciplinary Research and Analysis. Vol. 05, (2022).