Prognostic Analysis of Electrical Load and Power Supply Parameters for a Newly Electrified Railway Section Supplied by a Terminal Substation

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**Abstract.** The article presents the results of calculations of current consumption, voltage losses, and energy consumption on the electrified section of the Samarkand – Urgut railway, which is powered by the Jambay traction substation. Various types of electric locomotives are considered, as well as their operation modes in single and opposing directions. Particular attention is paid to the evaluation of voltage drop at the current collectors and compliance with the requirements of regulatory documents. The obtained calculation data can be used in the development of power supply projects and optimization of traffic schedules on the section, as well as in the design of the 27.5 kV outdoor switchgear bay, selection of secondary circuits, and configuration of relay protection settings.

**Keywords:** Railway electrification, catenary system, electric locomotive, pantograph, voltage, power, traction load

# INTRODUCTION

Rail transport is one of the most important sectors of our national economy. The role of railways is significantly increasing under market conditions, as their performance directly affects the speed or delay of passenger and freight delivery, the turnover rate of capital, the cost of industrial and agricultural products, and so on. In order to meet growing demand while reducing fuel costs, newly constructed railway sections are currently being electrified. The electrification of railways in Uzbekistan began relatively late compared to a number of other countries, but from the very beginning it was accompanied by the search for effective technical solutions. The first electrified railway line was commissioned in 1971 on the Khavast–Syrdarya section, and at that stage, power supply was provided by a direct current system with a voltage of 3 kV. This system was selected in accordance with the standards of the former Soviet Union, which were particularly effective for relatively short sections with intensive traffic.

However, as the railway network expanded and the length of electrified sections increased, it became clear that the direct current system had a number of limitations — primarily in terms of significant energy losses at traction substations and the limited distance between them. Therefore, in 1985, a strategic decision was made to switch to a more efficient power supply system — single-phase alternating current with a voltage of 27.5 kV and a frequency of 50 Hz. The first section where this new system was implemented was the Keles- Jambai line.

The transition to alternating current significantly improved the energy efficiency of railway traction, allowed for longer distances between substations, and simplified connection to the national power grid [1, 2, 3]. However, from the very beginning of railway electrification — both in Uzbekistan and worldwide — one of the key technical challenges has been the quality of electrical power in the traction system. This is due to the fact that the traction load is typically single-phase, while the main power supply networks are three-phase. Such imbalance results in the appearance of negative sequence currents (NSC) [4, 5, 6, 7], equal in magnitude to positive sequence currents (PSC), which can negatively impact the stability and reliability of the power system [8, 9, 10].

Previously, single-phase commutator motors were used in rolling stock, but since the late 20th century, Uzbekistan, like many other countries, has been implementing more modern traction drives using single-phase rectifiers and three-phase inverters. These devices operate with asynchronous or synchronous traction motors, provide regenerative braking, and allow energy to be returned to the overhead line, increasing the overall efficiency of the power supply system.

Railway electrification has a noticeable impact not only on the power grid but also on other infrastructure elements: upstream power supply networks (high-voltage transmission lines), signaling, communication, and telecommunication systems. Electromagnetic interference caused by traction loads requires special solutions for shielding, grounding, and filtering. Therefore, research is also being carried out in Uzbekistan to improve power quality, reduce electromagnetic and harmonic distortions, and enhance the reliability of traction substations and rolling stock [11, 12, 13].

As part of the analysis of traction load reliability on the electrified section, the design features of locomotives operated in Uzbekistan were studied. Particular attention was given to the rigid double-helical gear transmission, which ensures smooth operation and reduced dynamic loads due to gradual meshing and axial displacement of the gears [14, 15, 16, 17].

Under high load conditions determined through traction calculations, it is especially important to consider the technical condition of the overhead contact system and its supporting structures, as these factors directly affect the reliability of power supply and the safety of train operations. Even a brief detachment of the pantograph can lead to the formation of a high-temperature electric arc, which may cause the wire to burn out and result in an emergency train stop. This electric arc forms within milliseconds, is accompanied by high-frequency magnetic interference, and its formation depends on several factors, including atmospheric pressure, ambient temperature, and the distance between the pantograph and the contact wire [18, 19, 20].

The development of Uzbekistan's railway infrastructure requires improving the efficiency of power supply to new sections. One such section is the Samarkand – Urgut line, whose electrification is carried out using power from the traction substation (TSS) Jambay. At the request of JSC “Uzbekistan Railways”, a working design project is being developed for the construction of a new electrified railway line Samarkand–Urgut. This new railway line, with a total length of 55 km, connects to the existing Tashkent–Samarkand railway line at the Jambay–Zarafshan section. The purpose of this work is to analyze the possibility of supplying the section from the mentioned TSS under various operational train traffic scenarios. The calculations allow for proper current distribution across the section and efficient scheduling of train movement.

**METHODOLOGY AND INITIAL DATA**

A properly conducted study is the key to the high-quality and efficient operation of the railway section and ensures significant savings in energy resources. The study was carried out in accordance with the assignment of JSC "Uzbekistan Temir Yullari" taking into account the recommendations of the locomotive operation department, according to which the following electric locomotives can be operated on the section:

* 3ES5K
* 3VL80s
* VL60K
* O‘Z-ELR
* O‘z-Y

However, it is not necessary to limit the analysis to only these types of locomotives, as there is a growing trend toward the use of more energy-efficient electric locomotives and electric trains produced by modern manufacturers.

On the projected section, the catenary system includes a carrying cable PBSM-95 and a contact wire MF-100. The traction rails used on the section are of type Р65. Calculations were performed based on the nominal catenary voltage of 25 kV. The maximum permissible catenary voltage should not exceed 29 kV. Such a voltage value under cantilever feeding and a nominal substation bus voltage of 27.5 kV is practically unachievable.

The parameters of electric locomotives (weight, power, speed, voltage operating range, and current consumption) are shown in Table I. A train mass of 1050 t for passenger trains and 4200 t for freight trains was assumed in the calculations.

**TABLE 1.** Main parameters of the used electric locomotives

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **Type of electric locomotive** | | | | |
| **OZ-Y** | **OZ-ELR** | **3ES5K** | **3VL80s** | **VL60K** |
| Weight (t) | 126 | 138 | 288 | 280 | 135 |
| Power (kW) | 6000 | 7200 | 9840 | 9240 | 6000 |
| Design speed (km/h) | 160 | 120 | 110 | 110 | 120 |
| Operating voltage range (kV) | 17,5-31 | 17,5-31 | 19 – 29 | 19 – 29 | 19 – 29 |
| Accepted current consumption (A) | 316 | 360 | 314 | 295 | 180 |

Note: Train weights assumed: **passenger** – 1050 t; **freight** – 4200 t.

The parameters of newly developed locomotives are usually more energy-efficient while maintaining the same traction characteristics. If modern locomotives are used, the calculations performed can fully meet their operational requirements.

The «Jambay» traction substation (110/27.5/10 kV) is a terminal-type facility, supplying two 27.5 kV feeders in the direction of Tashkent and two feeders toward Zarafshan station. It receives power from two 110 kV transmission lines feeding two 40 MVA traction transformers. In connection with the planned construction of a new 55 km electrified railway section to Urgut, it is necessary to install an additional 27.5 kV outdoor switchgear bay. To justify the selection of the required primary and secondary equipment for this new bay, a traction power calculation must be performed as part of the technical and economic feasibility study.



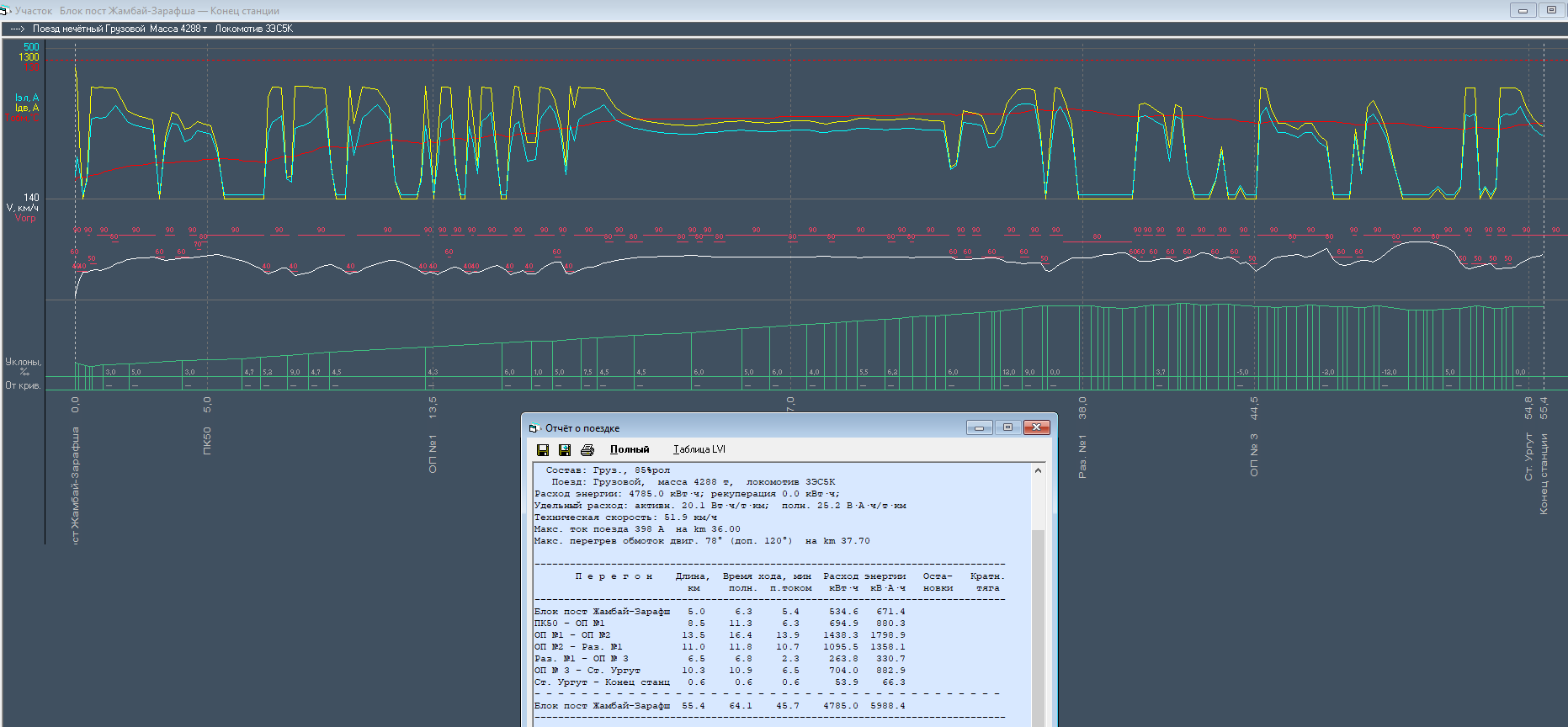
**FIGURE 1.** 27.5 kV Outdoor Feeder Bay of the Overhead Contact System at «Jambay» TSS

**SCENARIOS CONSIDERED IN THE CALCULATIONS**

**One Locomotive on the Section**

To assess power supply parameters, calculations of currents and voltages at the pantograph were performed for single train movements in both directions. Results are presented in Tables II and III. The maximum power consumption ranged from 4300 to 9071 kW, and pantograph voltages ranged from 19 to 25 kV depending on the locomotive type and location.

To perform accurate calculations, it is essential to take into account factors such as terrain profile, conductor heating temperature, and the level of voltage drop with increasing distance from the power source. The calculations were carried out using the KORTES software environment. The KORTES computer software enables calculation of energy consumption, losses, and traction power system parameters for various train operating modes and schedules [21, 22, 23]. All key data for the section were entered into the program, including the longitudinal track profile with gradients and inclines, curve characteristics, speed limits, stations, and stops. The traction characteristics of the locomotives, as well as the train mass and length, were also taken into account. A sample freight train calculation is shown in Fig. 2, and for a passenger train in Fig. 3.



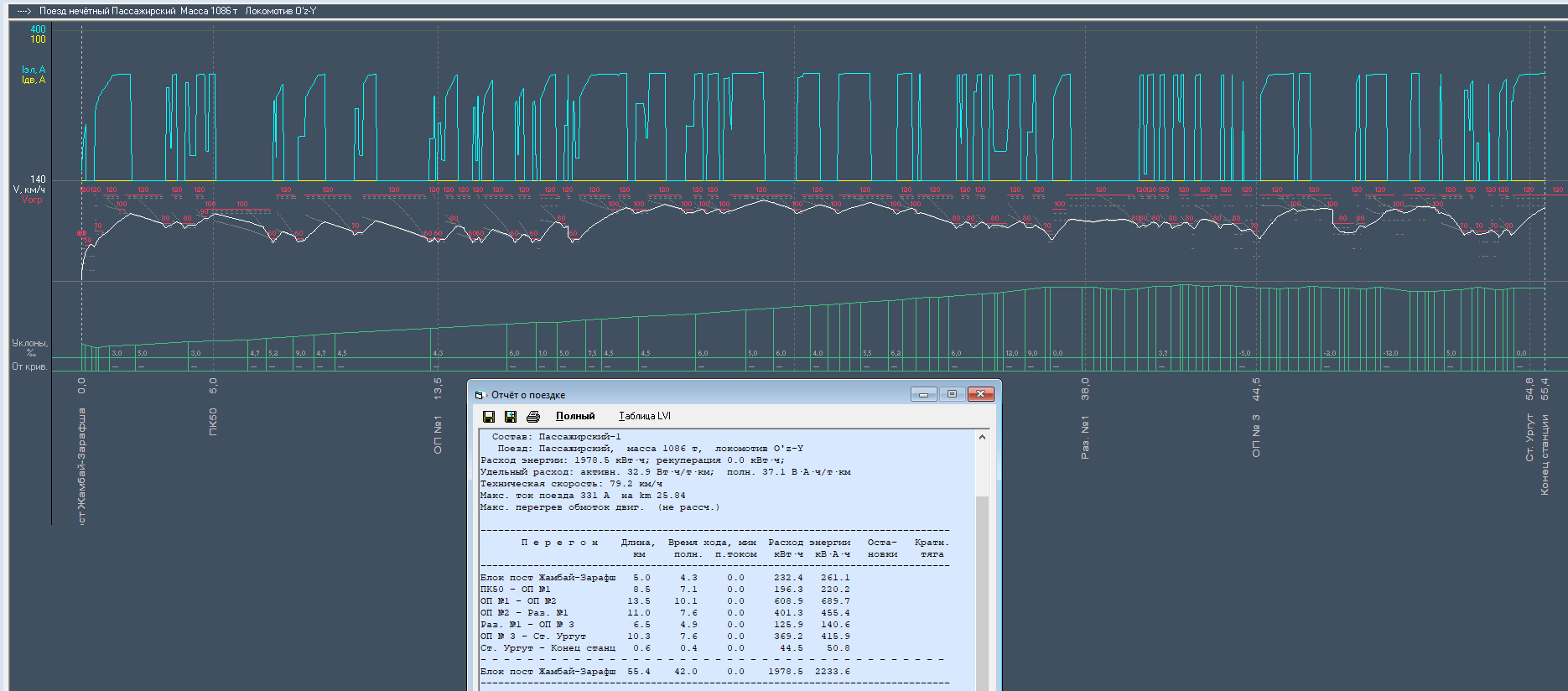
**FIGURE 2.** Sample freight train calculation

**TABLE 2.** Direct direction

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **Type of electric locomotive** | | | | |
| **OZ-Y** | **OZ-ELR** | **3ES5K** | **3VL80s** | **VL60K** |
| Current (A) per km:4  9  20  25  30  35  37  41  45  50  54 | 169  204  248  251  140  147  163  140  262  183  281 | 270  253  299  308  315  295  248  245  319  240  307 | 235  380  391  280  292  395  386  320  384  246  385 | 320  297  292  404  341  343  258  317  375  209  351 | 160  255  246  181  233  199  113  181  271  116  214 |
| Maximum power consumption (kW) | 5990 | 7150 | 9071 | 9069 | 5950 |
| Travel energy consumption (kWh) | 1978.5 | 4501,2 | 4785 | 5147.4 | 2158.8 |
| Current collector voltage (V) per km: 20  25  30  35  41  45  50  54 | 24190  23730  24460  24120  23920  21910  22760  21200 | 23890  23240  22660  22380  22470  21140  21850  20510 | 23200  23480  22890  21300  21510  20320  21760  19440 | 23880  22450  22410  21850  21540  20430  22340  19890 | 24200  24340  23480  23490  23340  21790  23890  21990 |

**TABLE 3.** Reverse direction

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **Type of electric locomotive** | | | | |
| **OZ-Y** | **OZ-ELR** | **3ES5K** | **3VL80s** | **VL60K** |
| Current (A) per km: 55  51  39  32  14  2 | 151  193  185  174  118  145 | 169  275  319  60  196  0 | 329  364  258  298  379  312 | 292  280  351  148  181  280 | 199  203  160  132  115  172 |
| Maximum power consumption (kW) | 4300 | 6940 | 7280 | 6030 | 4540 |
| Travel energy consumption (kWh) | 1007.5 | 1610.7 | 2288.4 | 2310.6 | 1220.6 |
| Current collector voltage (V) per km 55  51  39  32  14  2 | 23040  22530  23410  23980  25380  25890 | 22710  21240  21710  25290  24980  26000 | **20110**  **19999**  22460  22630  24070  25770 | **20650**  21160  21340  24270  25060  25790 | 22180  22370  23740  24450  25400  25870 |

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**FIGURE 3.** Sample passenger train calculation

**Two Locomotives on the Section**

Methods for calculating traction power supply system’s vary depending on how the traction load is represented—either deterministically or probabilistically. Deterministic methods are based on the use of an exact train timetable and allow for the analysis of time-dependent parameters of the traction power network, such as feeder currents *If(t)*, traction substation currents *ITSS(t)*, and voltage at the locomotive pantograph *Ulp(t)*.

The input data for such calculations include the results of traction force computations *I(L)*, the power supply scheme of the contact system, and the train schedule *L(t)*. Based on the timetable, it is possible to determine the trains present on a given section at any point in time, and using the functions *In(L)*, their corresponding current loads can be obtained.

One widely used approach within deterministic methods is the method of uniform time slicing of the train schedule. In this method, the timetable is divided into equal time intervals known as the discretization step. For each time slice, an instantaneous load diagram is constructed, showing the current positions of the trains and the respective traction currents. This enables the calculation of network parameters such as:

*If=f(t)* ­­– feeder current over time;

*ΔU=f(t)* ­­– voltage drop dynamics, etc.

The instantaneous diagram method provides a means to evaluate the temporal distribution of electrical loads and identify critical operating conditions of the traction power supply system.

The analysis was carried out for various combinations of trains moving in opposite directions, with indications of current and voltage at each pantograph. In some scenarios (especially involving 3ES5K locomotives), a voltage drops down to 17 kV was noted, which does not comply with standards. (See Table IV)

**TABLE 4.** Combined movement

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Instant value option | The first train | | | | The second train | | | |
| Train type (direction) | *l, км* | *I, А* | *Uт, кВ* | Train type (direction) | *l, км* | *I, А* | *Uт, кВ* |
| 1-combination | OZ-Y  (direct) | 25 | 251 | 21.7 | VL60K  (back) | 51 | 203 | 19.73 |
| 2- combination | VL60K  (direct) | 20 | 246 | 22.56 | OZ-Y  (back) | 51 | 193 | 20.66 |
| 3- combination | OZ-Y  (direct) | 25 | 251 | 20.18 | 3ES5K  (back) | 51 | 364 | 17.02 |
| 4- combination | VL60K  (direct) | 20 | 246 | 21.9 | 3VL80s  (back) | 55 | 292 | 19 |
| 5- combination | OZ-ELR  (direct) | 25 | 308 | 21.25 | VL60K  (back) | 51 | 203 | 19.33 |
| 6- combination | 3ES5K  (direct) | 20 | 391 | 21.41 | OZ-Y  (back) | 51 | 193 | 19.3 |

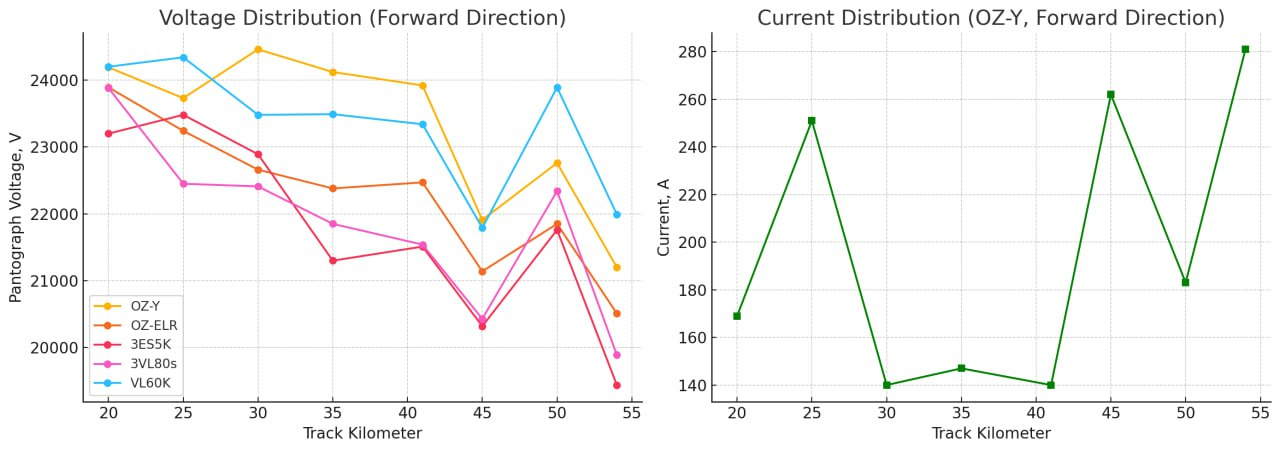
**ANALYSIS OF RESULTS**

Based on the analysis, the following was established:

* **O‘z-Y** and **VL60k** ensure stable voltage operation even during single-train movement on the section.
* When operating **O‘Z-ELR, 3ES5k** and **3VL80s** beyond 45 km, voltage drops to 19 kV are observed, allowing operation at 80% power or, with the permission of the Chairman of JSC “О‘zbekiston temir yо‘llari”, at full power [24, 25, 26].
* Combined train movements require limiting the second train’s locomotive power, especially if located beyond 40 km (voltage may drop below 19 kV).
* Simultaneous movement of three trains is allowed only if all trains move in the reverse direction.
* The maximum electric load from locomotives on the section will not exceed 20 MVA, requiring an appropriate reserve at the traction substation.

**CONCLUSION**

The conducted analysis showed that with proper train movement distribution and power limitation at certain points, the Samarkand – Urgut section can be efficiently electrified from the Jambay TSS without the need to construct additional traction substations. Based on the results, a voltage and current distribution diagram was constructed for the projected section (Fig. 4).



**FIGURE 4.** Diagram of voltage distribution at the pantographs of various electric locomotives during forward movement (left) and current distribution for OZ-Y locomotive at the same kilometers (right)

However, a number of works must be carried out at the existing traction substation "Jambay": in accordance with the technical specifications of the Power Supply Department of JSC "Uzbekiston Temir Yullari", it is necessary to determine the power reserve of the substation’s power transformers, install a new catenary feeder cell to supply the new electrified Samarkand–Urgut railway line, ensure proper connection of this feeder to the flexible busbars of the 27.5 kV switchgear, and also provide for the installation of a catenary sectioning post at the junction point of the new railway line. It is also necessary to develop electrical design documentation, including secondary circuits and relay protection and automation (RPA) systems, for the installation of the new catenary feeder cell at the existing "Jambay" traction substation and for the new sectioning post.

The study confirmed that traction load calculations using a deterministic model and the method of uniform time slicing of the train schedule allow for an accurate assessment of the dynamic parameters of the power supply system, including feeder currents and pantograph voltage. It was found that during the simultaneous operation of high-power locomotives on remote sections, voltage drops below acceptable levels may occur, requiring either power limitation or special permission for operation under such conditions.

The maximum load on the Samarkand–Urgut section does not exceed 20 MVA; at the same time, it should be noted that the Jambay traction substation also supplies a section of the high-speed Tashkent–Samarkand line, which has its own electrical load. However, even taking this additional load into account, the total installed capacity of the two 40 MVA transformers at the substation remains sufficient to ensure reliable power supply for both directions, provided that redundancy and selectivity standards are met.

The obtained calculation data can be used in the development of power supply projects and optimization of traffic schedules on the section, as well as in the design of the 27.5 kV outdoor switchgear bay, selection of secondary circuits, and configuration of relay protection settings.

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