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Energy efficiency analysis of two-sided feed scheme of DC traction network with high asymmetry of feeders parameters

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Abstract. In a given research using the example of traction network area with high asymmetry of power supply parameters, the sequence of comparative assessment of power losses in DC traction network with parallel and traditional separated operating modes of traction substation feeders was shown. Experimental measurements were carried out under these modes of operation. The calculation data results based on statistic processing showed the power losses decrease in contact network and the increase in feeders. The changes proved to be critical ones and this demonstrates the significance of potential effects when converting traction network areas into parallel feeder operation. An analytical method of calculation the average power losses for different feed schemes of the traction network was developed. On its basis, the dependences of the relative losses were obtained by varying the difference in feeder voltages. The calculation results showed unreasonableness transition to a two-sided feed scheme for the considered traction network area. A larger reduction in the total power loss can be obtained with a smaller difference of the feeders' resistance and / or a more symmetrical sectioning scheme of contact network.

1. Introduction

The paper is sequel to earlier papers on energy efficiency of DC traction power supply of urban electric transport [1-3].

The modern stage of power engineering development induces the dissemination of decentralized power supply sytsem based on the combination of various energy sources [4-10]. This direction in terms of traction networks (TN) supposes the use of parallel contact network (CN) feed which in comparison with traditional one-sided feed circuit provides the power reserve of CN sections; the increase of probability of power delivery recuperation through the CN; the powerdown of traction substations (TSS); more favourable modes of impressed voltage to the electric motive power (EMP); maintenance costs decrease etc.

For the existing TN, the usage of parallel feeder operation is related to the research needs of current distribution at specific areas given that at high parameter asymmetry, feeders connected in parallel, power losses caused by balancing current could substantially decrease the energy efficiency indices. At the same time, so far this area of research was not given pride of place.

In terms of current research, the task is to analyze the relative power loss in CN and feeders based on experimental measurements and to make analytical calculations with traditional single-way feed circuit and with converting it into parallel feeder operation in conditions of high parameter asymmetry of power supply.

2. Subject of research and experiment background

As a subject of research, the TN area of tram in Novosibirsk along Volochaevskaya street was chosen. It included the following circuit: SS310 – F75 – SS311 (F135) – SS312 – SS313. The TN area circuit is shown in Figure 1.

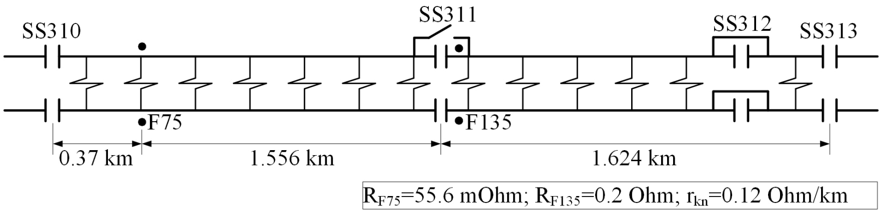

Figure 1. The supply and sectioning circuit of investigated TN area

The area is characterized by various lengths of feeders and favorable conditions for emergency of balancing current. Besides, when converting into parallel operation mode the circuit is not a conventional two-sided but a combined circuit as the sectioning is very close to F135 but not in the middle of the area between F75 and F135.

To solve a set challenge synchronous experimental measurements on feeders №75 and №135 of fourunits of TSS №7 and №13 were made using recording measuring instruments developed at the department «Electrotechnical Units». The measurements were carried out in two stages: 1 – under one-sided feed circuit used; 2 – under close section switch (SS) №13 used for converting it into parallel joint of F75 and F135. As a result, the data of current and voltage of feeders №135 and №75 for 14-day cycle with single-way feed and for 5-day cycle with parallel one were obtained.

3. Experimental outcomes

Probabilistically-statistic processing was fulfilled for supply feeder data, empirical distributions and more appropriate theoretic characteristic are presented in Figure 2.

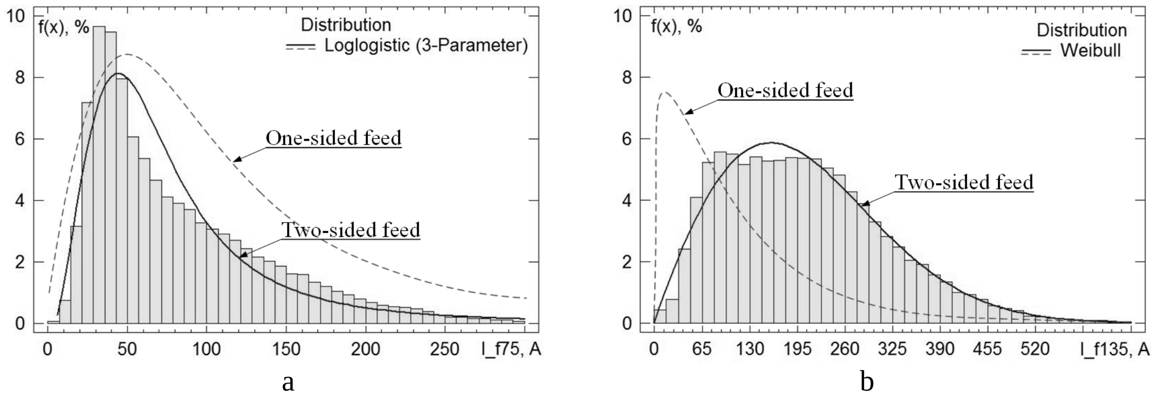

Figure 2. The statistical distribution functions of feeders currents

The changes in distribution functions are quite predictable as it is obvious that the current increase of F135 is caused by the increase of feed zone range and the current decrease of F75 is caused by simultaneous power supply load of the F75-F135 area from two feeders.

According to measured data the difference of voltage at TSS buses and at connection points to CN is defined and the results are shown in Figure 3. Voltage measurements at TSS buses show the average difference of 14.9 V. A great impact of feeders' resistance on voltage levels at connection points to CN is evident.

With parallel feeder operating conditions the whole area can be conditionally divided into zones of two-sided feed and one-sided feed: power supply from one feeder of F75-SS310 and F135-SS313; parallel power supply from two feeders of F75-F135. To confirm this hypothesis, the evenly-distributed load method was used. The calculation of dead section reference point coordinates relative to the length of area of interest was made. In addition, the specific currents at section of F135-SS313 were calculated based on instant current value of F135 one minute-averaged intervals for parallel and initial separated circuit excluding the section of F75-SS311.

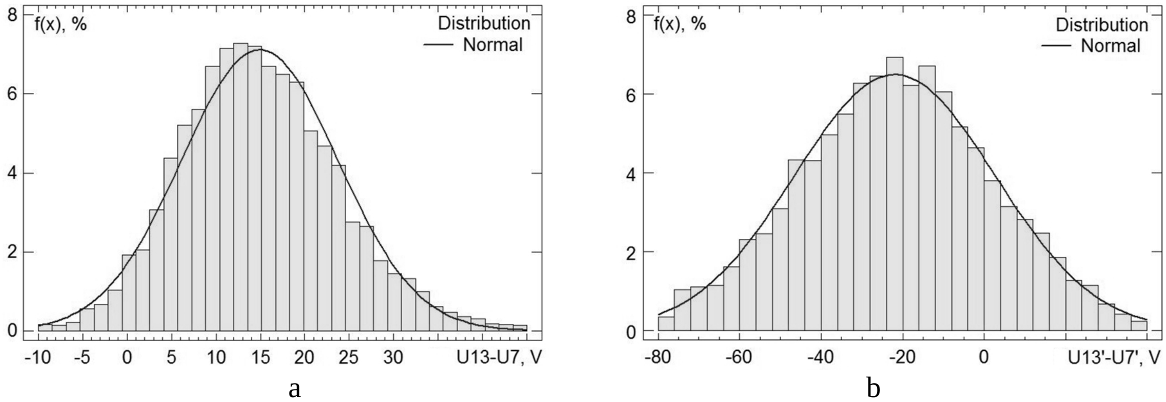

Figure 3. The statistical distribution functions: a – voltage difference at TSS buses; b – voltage difference at connection points to CN.

The best possible values of relative difference of real and calculated conventional boarder of dead section are fallen within the range of 7 %. Besides as a result of correlation analysis of daily-average current distributions of F135 brought to the section F135-SS313 with various circuits of power supply a positive interrelationship including correlation factors 0.958 is related, thus the level of significance is obtained lower than 0.05. It means that statistic significance of derived estimates of correlation factors with probability is not less 95%, in other words distributions of this specific current are related to correlation dependence.

Consequently, actual current distribution is close to assumed conditions of area division into one-sided and two-sided feed and the results of method of evenly-distributed load will adequately describe real area parameters. As stated before this suggests that power losses of sections SS310-F75 and F135-SS313 have not undergone important transformations so let us rule them out further analysis.

An unambiguous answer to the highlighted issue about the viability of modifying power supply circuit gives superposition of power losses values through feeders and area of CN in similar time axes for averaged 24-hour period – Figure 4. As expected, power losses in CN are lower for parallel feeder operation their total loss has reduced by 37 % for average 24-hour period. The situation is similar with F75 however, the load increase of F135 resulted in total difference of power losses by 60% in favour of initial one-sided feed circuit. This is due to the conductivity difference of current loop of paralleled feeders (F135 with high voltage has 3,5 times greater resistance than F75).

In respect to the considered area of TN the transition to feeders parallel operation without additional events is not efficient. That is why at conversion of TN areas into two-sided feed and at building a new urban traction supply system by one of the most important engineering projects is the use of voltage inequalities of contiguous TSS for forcing reallocation of load in feeder zone through voltage regulation [11].

4. Determination of the optimum voltage regime

To determine the best voltage mode, the considered TN area of interest has been calculated when changing the TSS voltage difference for a two-sided scheme and an original one-sided scheme.

For the calculation, the authors used the analytical method of Professor Rosenfeld, based on the sizes of the movement [12]. This method has been improved to take into account the difference in voltage and resistance of feeders. Jointly with the experimental voltage measurements on the feeders, this makes it possible to determine the limits of admissibility of the parallel feed operation mode and the requirements for the voltage regulation regimes. In power losses in the CN determining, only the load of the section F75-F135 was considered. Therefore, for the modes of parallel operation and one-sided feed, the power losses calculation was performed with respect to F75-SS311.

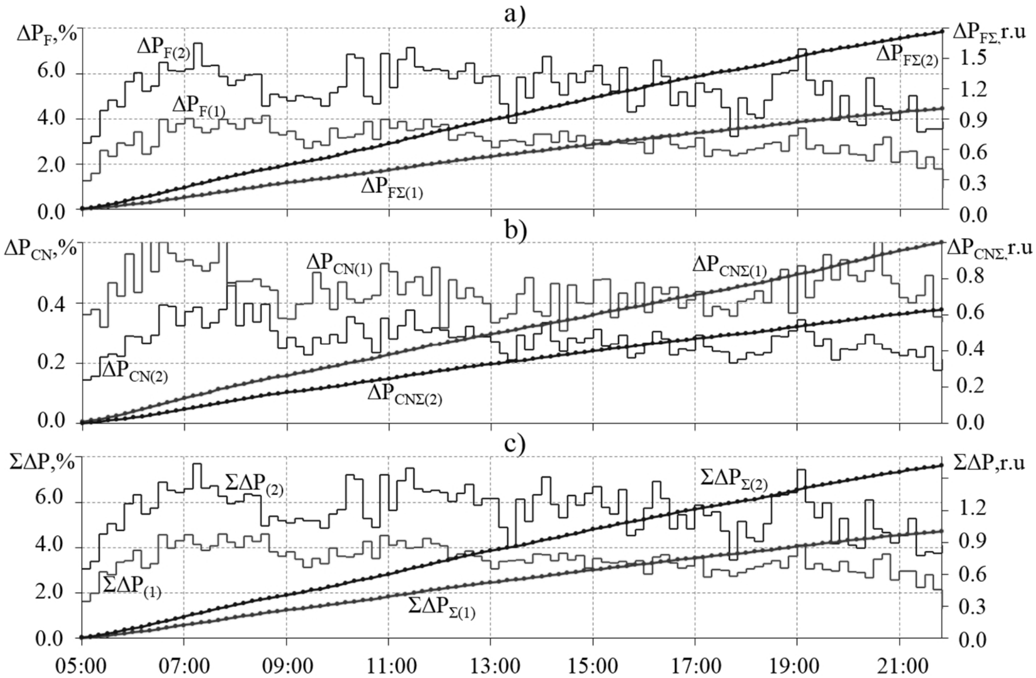

Figure 4. Daily average curves of relative power loss: a – in feeders; b – in CN; c – total.

The equations for calculating the investigating TN area in a general form, are presented in Table 1.

Table 1. Equations of the refined analytical method

Calculated values	Equations
Used scheme of one-sided feed	
Feeders	$\Delta P_{F(1)} = I_{F(1)rms}^2 \cdot R_F$; $I_{F(1)rms}^2 = I_n^2 \cdot \left[n_{rms}^2 + n \cdot \beta \right]$
Contact network	$\Delta P_{CN(1)} = \frac{I_n^2 \cdot L \cdot r}{3} \cdot \left[n_{rms}^2 + n \cdot \frac{3\beta+1}{2} \right]$
Scheme of parallel connection of feeders	
Feeders	$\Delta P_{F(2)} = I_{A(2)rms}^2 \cdot R_A + I_{B(2)rms}^2 \cdot R_B$; $I_{A(B)rms}^2 = \frac{I_n^2}{L_\Sigma^2} \cdot \left[\frac{L^2}{4} \left(n_{rms}^2 + n\frac{4\beta+1}{3} \right) + l_{B(A)} \left(L + l_{B(A)} \right) \cdot \left(n_{rms}^2 + n\beta \right) \right] + n_{rms}^2 \cdot \gamma_{4(5)}$; $\gamma_1 = \frac{L}{L_\Sigma} \cdot \left(1 + \frac{3 \cdot \left(l_A^2 + l_B^2 \right)}{L\left(L + 2 \cdot \left(l_A + l_B \right) \right)} \right)$; $\gamma_2 = 1 + \frac{l_A + l_B}{L_\Sigma}$; $\gamma_3 = \frac{L \cdot \Delta U}{L_\Sigma^2} \left(I_n \cdot \left(l_A - l_B \right) + \frac{\Delta U}{r} \right)$
Contact network	$\Delta P_{CN(2)} = \frac{I_n^2 \cdot L \cdot r}{12} \cdot \left[n_{rms}^2 + n \cdot \left(2(\beta+1) \cdot \gamma_1 - 1 \right) \right] \cdot \gamma_2 + n \cdot \gamma_3$; $\gamma_4 = \left(\frac{\Delta U}{R_\Sigma} \right)^2 \cdot \left(1 + \frac{I_n \cdot r \cdot \left(L + 2l_B \right)}{\Delta U} \right)$; $\gamma_5 = \left(\frac{\Delta U}{R_\Sigma} \right)^2 \cdot \left(1 - \frac{I_n \cdot r \cdot \left(L + 2l_A \right)}{\Delta U} \right)$

In accordance with the timetable of tram routes operating on the investigated TN area, traffic schedules in both directions were compiled. Based on these schedules, an average and effective amount of EMP was calculated for each feed zone. The mean current of the EMP and its variation coefficient were determined on the basis of the data obtained by generalizing the experimental tests results under real operating conditions. At the same time, corrections were made for slopes, operating speed, length of distances and traffic conditions for the selected TN area.

Based on the presented equations, the dependences of the relative power losses ($\Delta P_{(2)}/\Delta P_{(1)}$) as a function of the voltage difference were obtained, which are shown in Figure 5.

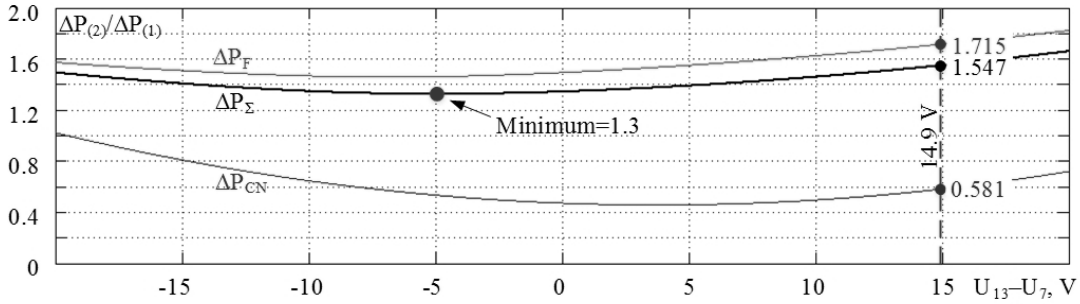

Figure 5. Determination of the optimum voltage regime.

Comparison of the analytical calculation results with the calculation results based on the evenly-distributed load method (under a mathematical expectation ΔU = 14.9 V) showed a difference of 6.27% for CN, 2.83% for feeders and 4.52% for total.

The obtained dependences show that losses in the CN area of interest can be reduced by 57% with voltage regulation. However, losses in feeders are in any case significantly lower with the original one-sided scheme. The minimum total power loss will be achieved at ΔU = -5 V, which is approximately equal to zero of voltage difference at the feeders connection points to the contact network (see Figure 3, b). Nevertheless, the total power losses in parallel operation will be higher than the total power losses in a one-sided scheme, at least 28%.

Thus, for the investigated TN area, the transition to a two-sided feed scheme is inexpedient, even with the use of TSS voltage regulation means.

5. Conclusion

In a given research using the example of TN area with high imbalance of power supply parameters, the sequence of quantitative assessment of power losses in TN with parallel feed operation was shown in order to determine the viability of such solution.

The foregoing example demonstrated the power losses decrease in CN and the increase in one of feeders; moreover, these changes are meaningful and this gives evidence of high potential positive effect, which could be obtained by voltage regulation at TSS buses:

- by changing the number of activated converter units on TSS (with the availability of power reserve) [2];
- by special technical devices of self-regulation with different construction design.

However, the results of the analytical calculation showed unreasonableness transition to a two-sided feed scheme for the considered TN area with a high asymmetry in the feeder parameters, even with the use of voltage regulation.

A larger reduction in the total power losses can be obtained with a smaller difference of the feeders' resistance and / or a more symmetrical sectioning scheme of CN. This indicates a benefit of decentralized traction power supply system whereby feeders have short length and this provides lower power losses in TN.

Future research will be devoted to determining the requirements for the regulation voltage mode for various TN area configurations with a two-sided feed scheme, as well as the development of appropriate technical means.

6. Acknowledgments

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