Evaluation of central tendency measures in relation to the parameters of contact network feeders controlled by relay protection

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Abstract. The paper considers the importance of possible input values of standby stages of remote protection of contact network feeders from the point of view of their influence on the reliability of protection. The measures of the central tendency of parameters controlled by relay protection of contact network feeders were evaluated based on the theory of statistics, using the example of the Trans-Baikal Railway for 2018-2019. In total, 14 parameters were measured according to GOST 32144-2013. Electric power. Electromagnetic compatibility of technical facilities. Standards for the quality of electric energy in general-purpose power supply systems, in 2020 on the feeder of the contact network of the Sokhondo traction substation of the Trans-Baikal Railway against 88965290 obtained values, which made it possible to select significant values from all possible parameters on the basis of mathematical analysis. Statistical data on the following parameters were considered and analyzed: effective voltage value, effective current, peak voltage amplitude factor, peak current amplitude factor, harmonic voltage distortion factor, harmonic current distortion factor, phase shift factor, load resistance, angle between the first voltage harmonic on substation buses and feeder current. The reasonable selection of significant parameters proposed by the authors allows improving the operation of standby stages of remote protections of contact system feeders in heavy traffic conditions and increasing their selectivity.

1. Introduction

Russian Railways is a dynamically developing company with a number of strategic objectives specified in [1].

The analysis of the current state of the infrastructure performed in block 5.3 [1] indicates the following key problems of the company at the time of strategy development:

- non-compliance of the level of carrying capacity in certain areas with the transport market demand, presence of about 10.2 thousand km of “bottlenecks”;
- high wear and tear of certain infrastructure elements;
- lack of opportunities for breakthrough growth of reliability, speed and accuracy.

In the same section [1], the key tasks of the company’s infrastructure development include the following:

- development of infrastructure in order to switch to heavy-weight traffic with weight standards of trains of 9 thousand tons or more;
- optimization of expenses due to increase of energy efficiency and labor productivity, rational organization of repair and maintenance works;
- improvement of transport safety and mitigation of risks associated with the influence of the “human factor” on the production process.

Since the launch of the development strategy many things have already been achieved by 2020. Thus, for more than five years double trains of increased weight reaching 12,600 tons have been running along the Trans-Baikal Railway using performance charts, which generally corresponds to the strategic objectives and goals outlined in [1].

However, in some cases the increase in the weight of trains has a very negative effect on the operation of directional remote protection of contact network feeders (DRP CNF), in particular the third backup stage. The increase in the weight of train sets while reducing the inter-train interval in order to optimize the economic performance has led to the fact that the maximum operating current tends to the maximum permissible value in the operating mode, which in turn leads to a decrease in the voltage of the contact network feeder, and in some cases to the minimum permissible value, especially in sections with a complex track profile, which also include the Trans-Baikal Railway, and the undervoltage may lead to the shutdown of trains. Current stepup – to contact wire burns and spurious tripping – again shutdown, wear and tear of switching equipment.

Mathematically, this can be generally represented as follows. The variety of factors affecting the operation of the standby stage of remote protection of the contact network feeders can be conditionally divided into two classes – external (endogenous) and internal (exogenous):

\[ O_1(t) = S \cup T, \]

where \( O_1(t) \) – m-dimensional vector-function characterizing a set of external primary influencing factors;
\( S \) – m-dimensional vector determining the state of external power supply system (EPSS);
\( T \) – m-dimensional vector describing the state of the traction power supply system (EPSS) associated with the parameters of the traction network of the protected feeder zone.

EPSS parameters are determined by the state of the vector \( S \) depending on the following values:

\[ S = [P, Q, \cos \varphi, U, X_s]^T, \]

where \( P \) – m-dimensional vector-function characterizing the active power transmitted through the EPSS;
\( Q \) – m-dimensional vector-function determining the reactive power transmitted through the EPSS;
\( \cos \varphi \) – active power factor of the EPSS;
\( U \) – m-dimensional vector-function representing the level of the EPSS voltage;
\( X_s \) – m-dimensional vector-function describing the EPSS resistance to the traction substation on which the protection is installed.

In turn, the EPSS parameters are determined by the state of the vector \( T \) depending on the following variables:

\[ T = [K, F, W, Q, M, P]^T, \]

where \( K \) – m-dimensional vector characterizing the type of the traction network of the protected feeder zone;
\( F \) – m-dimensional vector describing the EPSS state associated with motion parameters on the protected feeder zone;
\( W \) – m-dimensional vector defining parameters of traction substations;
\( Q \) – m-dimensional vector characterizing the parameters of electric motive power in the protected section;
\( M \) – m-dimensional vector representing weight parameters of trains running on the protected section;
\( P \) – m-dimensional vector characterizing the path profile of the protected section.
Many external (endogenous) secondary factors characterize the parameters of the mode, in which the protected system is located, and are divided into two subsets – \( O_{\text{nl}}(t) \) and \( O_{\text{le}}(t) \) characterizing the current mode of the system.

The set of the normal mode parameters are characterized by the state of vector \( O_{\text{nl}}(t) \):

\[
O_{\text{nl}}(t) = [I_x(t), U_x(t), \lambda, V_1, V_U, \phi_{\text{sl}}, \phi_{\text{a}}]^T,
\]

where \( O_{\text{nl}}(t) \) – m-dimensional vector-function characterizing a set of external secondary influencing factors in a normal mode;

\( I_x(t) \) – m-dimensional vector-function determining the current of the protected feeder in a normal mode;

\( U_x(t) \) – m-dimensional vector-function describing the voltage in the traction network of the protected feeder in a normal mode;

\( \lambda \) – system power factor;

\( V_1 \) – m-dimensional vector-function characterizing harmonic current of the traction network;

\( V_U \) – m-dimensional vector-function characterizing harmonic voltage of the traction network;

\( \phi_{\text{sl}} \) – m-dimensional vector representing the current angle of the \( k \) harmonic in a normal mode;

\( \phi_{\text{a}} \) – m-dimensional vector characterizing the voltage angle of the \( k \) harmonic in a normal mode.

The set of the emergency mode parameters are characterized by the state of vector \( O_{\text{le}}(t) \):

\[
O_{\text{le}}(t) = [I_x(t), U_x(t), \phi_{\text{sl}}, \phi_{\text{a}}, S, T, W]^T,
\]

where \( O_{\text{le}}(t) \) – m-dimensional vector-function characterizing a set of external secondary influencing factors in the emergency mode;

\( I_x(t) \) – m-dimensional vector-function determining the current of the protected feeder in the emergency mode;

\( U_x(t) \) – m-dimensional vector-function describing the voltage in the traction network of the protected feeder in the emergency mode;

\( \phi_{\text{sl}} \) – m-dimensional vector representing the current angle of the \( k \) harmonic in the emergency mode;

\( \phi_{\text{a}} \) – m-dimensional vector characterizing the voltage angle of the \( k \) harmonic in the emergency mode.

External factors are interconnected: \( O_{\text{nl}}(t) \subseteq O_1(t) \), \( O_{\text{le}}(t) \subseteq O_1(t) \). A different combination of primary factors leads to various changes within a limited region of secondary values for each mode:

\[
O_{\text{nlmin}}(t) \leq O_{\text{nl}}(t) \leq O_{\text{nlmax}}(t), \quad O_{\text{lemin}}(t) \leq O_{\text{le}}(t) \leq O_{\text{lemax}}(t).
\]

Change of parameters \( F \) and \( M \) is critical for the operation of the standby stage of remote protection of the contact network feeders. So, if \( F \to \min \) (packet traffic schedule), and \( M \to \max \) (handling of heavy trains), then the state of the vector \( O_{\text{le}}(t) \) changes so that it takes the value \( O_{\text{le}}(t) = \sup O_{\text{le}}(t) \) and tends to the region \( O_{\text{le}}(t) \).

If in this case the vector \( O_{\text{le}}(t) \) takes the value \( O_{\text{le}}(t) = \inf O_{\text{le}}(t) \), then \( O_{\text{le}}(t) \cap O_{\text{le}}(t) \), which dramatically increases the possibility of false response and hence non-selective operation of the standby stage of remote protection.

The negative impact on the operation of the third stage of DRP CNF is the decrease of protection reliability manifested as the increase in the number of non-selective actuations.

This statement can be illustrated by the analysis of the number of outages at the Trans-Baikal Railway for 2018 and 2019, presented in Figures 1 and 2.
Figures 1 and 2 show the total number of actuations of contact network feeder protections by types of outages for all power supply distances of the Trans-Baikal Railway. The analysis of diagrams shows that the largest number of protection actuations is observed for the following types of outages:

- unspecified outages;
- electric motive power failure;
- overload.

Table 1 shows the calculation of central tendency measures for frequent types of outages for 2018 and 2019 for the Trans-Baikal Railway as a whole.
Table 1. Central tendency measures for the most frequent types of outages for 2018/2019

| Central tendency measures | Overload 2018/2019 | Unspecified outages 2018/2019 | Electric motive power failure 2018/2019 |
|---------------------------|-------------------|-------------------------------|----------------------------------------|
| Mean                      | 94.00 / 47.50     | 95.80 / 79.80                 | 104.70 / 86.8                          |
| Standard deviation min    | 101.24 / 60.11    | 163.97 / 107.67               | 78.48 / 72.26                          |
| 25%                       | 4.00 / 4.50       | 6.50 / 14.25                  | 42.75 / 37.00                          |
| 50%                       | 77.50 / 19.00     | 27.50 / 37.50                 | 87.00 / 69.00                          |
| 75%                       | 139.25 / 68.50    | 113.50 / 101.00               | 166.75 / 144.50                        |
| max                       | 260.00 / 162.00   | 532.00 / 342.00               | 234.00 / 204.00                        |

The analysis of the table shows that according to the specified indicators, 2019 in general is characterized by the decrease in the total number of outages compared to 2018, but their number remains significant, since the fact of each outage bears a risk for the reliability and continuity of the transportation process. It is also necessary to clarify that for a number of traction substations the situation is more critical, which, in particular, is indicated by a significant margin of standard deviation and as a result of a strong variation of outage values relative to the mean value, as well as the presence of upward trends indicated as separate points in Figures 1 and 2.

This situation is largely caused by the fact that after the transition to the microprocessor base for DRP CNF terminals the algorithms forming the basis of protection remained unchanged.

The fundamental disadvantage of these algorithms is that they do not make it possible to unambiguously distinguish between normal and emergency operating modes of the system during the movement of heavy trains. When the algorithms were developed, they showed a significant increase in the EPSS reliability with weighting standards and intervals of ordinary freight traffic. However, in modern conditions, they do not provide a proper level of reliability, which is confirmed by outage statistics.

The modern microprocessor element base allows utilizing a variety of possibilities in applying new approaches to the development of remote protection algorithms. The first step in developing new algorithms and generally improving the technical perfection of relay protection system of contact network feeders is to understand the processes within the traction power supply system of heavy trains.

To this end, experimental measurements of electrical energy quality indicators of the contact network feeder No. 4 (CNF-4) were made at the Sokhondo traction substation of the Trans-Baikal Railway. The purpose of this paper is to analyze the results of measurements in order to understand the processes and nature of changes in values for heavy trains.

2. Description of conditions and measurement results

Experimental measurements were carried out at the CNF-4 of the Sokhondo traction substation of the Trans-Baikal Railway using an electrical energy quality analyzer PQM-700 by Sonel.

According to its type, the Sokhondo traction substation is a transit substation. The choice of the feeder for the installation of the quality analyzer is caused by the fact that in case of heavy trains, regular false actuations of the third stage of the DRP CNF are observed. According to the substation report, in 2019 the largest number of outages on the fourth feeder was 89, which is 33% more than in 2018.

This feeder has a microprocessor protection terminal CZA-27.5 kV equipped with all required types of protection according to the current norms and rules [2].

The measurements were carried out from 2020-09-08 04:22:49.242 to 2020-09-19 18:03:11.715, which amounted to a total duration of 1 week, 4 days, 13 hours, 40 minutes and 22 seconds.
The parameters were measured according to [3] in the amount of 14 items. The sampling rate was 1 second.

For further study, the interesting parameters from the point of view of the DRP CNF operation were selected both for the analysis of current algorithms and for the development of new approaches:
- \( U \) – effective voltage, kV;
- \( I \) – effective current, A;
- \( CF_U \) and \( CF_I \) – peak amplitude factors of voltage and current;
- \( THD_U \) and \( THD_I \) – harmonic distortion factors of voltage and current;
- \( U_{hi} \) and \( I_{hi} \) – voltage and current harmonics, kV and A;
- \( \cos(\phi) \) – phase shift factor.

The final dataset form for the study made 89 variables and 999610 observations totaling to 88965290 values. There are no missing and duplicate values.

3. Analysis of central tendency measures
Before further data analysis, it is necessary to indicate the secondary controlled parameters of the DRP CNF, which are not measured directly by the quality analyzer, but were calculated additionally.

The protection calculates secondary controlled setpoints as follows:

\[
Z(nT) = [U(nT), I(nT), \varphi_Z]^T = \frac{U(nT)}{I(nT)}
\]

(6)

\[
\varphi_Z = \arg[Z(nT)] = \arg \left[ \frac{U(nT)}{I(nT)} \right]
\]

(7)

\[
THD_I = \frac{\sum_{n=1}^{9} I_n^2(nT)}{I(nT)} \times 100%,
\]

(8)

where \( Z(nT) \) – m-dimensional vector function characterizing the resistance of the protected feeder;
\( \varphi_Z \) – m-dimensional vector defining the resistance angle;
\( U(nT) \) and \( I(nT) \) – discrete values of the vector function of voltage and current after filtration;
\( THD_I \) – harmonic factor of the feeder current;
\( n \) – number of samples;
\( T \) – sampling period.

Table 2 shows the calculation results of central tendency measures for measured parameters.

| Central tendency measures | Mean \( U \), кB | Mean \( I \), A | \( CF_U \) | \( CF_I \) | \( THD_U \) | \( THD_I \) | \( \cos(\phi) \) | \( Z \), Ohm | \( \varphi \), ° |
|--------------------------|----------------|--------------|-----|-----|---------|---------|---------|--------|------|
| Mean                     | 25.15          | 355.06       | 1.59 | 1.59 | 13.51   | 24.11   | 0.47    | 135.28 | 25.15 |
| Standard deviation       | 0.57           | 186.71       | 0.06 | 0.26 | 3.36    | 10.18   | 0.27    | 259.60 | 0.57  |
| min                      | 21.93          | 5.59         | 1.42 | 1.25 | 2.80    | 8.08    | -1.00   | 22.41  | 21.93 |
| 25%                      | 24.79          | 209.57       | 1.55 | 1.43 | 11.15   | 19.91   | 0.42    | 50.90  | 24.79 |
| 50%                      | 25.18          | 339.52       | 1.59 | 1.52 | 13.50   | 22.37   | 0.55    | 74.06  | 25.18 |
| 75%                      | 25.57          | 488.85       | 1.63 | 1.66 | 15.95   | 25.73   | 0.62    | 121.31 | 25.57 |
| max                      | 26.74          | 1033.10      | 1.97 | 5.95 | 26.22   | 327.67  | 1.00    | 4557.87| 26.74 |
| Shift                    | -0.42          | 0.33         | 0.63 | 2.89 | -0.03   | 10.94   | -2.23   | 7.03   | -0.42 |
| Excess                   | 0.39           | -0.52        | 0.90 | 12.23| -0.39   | 208.23  | 5.91    | 58.52  | 0.39  |
The analysis of descriptive statistics of the effective voltage value of the CNF-4 of the Sokhondo traction substation shows that the mean value equal to 25.15 kV is almost equal to the nominal effective value specified by [3] and equals 25 kV.

The standard deviation of 0.57 indicates that the values have a slight variation relative to the mean value, and this also confirms the value of the median or 50% percentile, which equals 25.18 kV. The excess has a value of 0.39, which indicates an “acute” distribution of voltage values, while observing a slight negative shift of -0.42 indicating that in general the values are shifted upwards. From the point of view of the DRP CNF operation, the minimum voltage is 21.93 kV, which is close to the minimum permissible value specified by [3]. Figure 3 shows the distribution presented as a violin diagram (left) and the distribution function (right) of voltage values illustrating the above conclusions.

![Figure 3. Violin diagram and voltage distribution function diagram](image)

The analysis of the descriptive statistics of the current distribution diagrams presented in Figure 4 shows that the mean current equal to 355.06 A is generally characteristic of the normal mode in the conditions of freight traffic. However, the standard deviation of 186.71 A indicates that the current values have a significant variation relative to the mean. The median value of 339.52 A is slightly different from the average, which indicates a shift to the left relative to the average, and this is also confirmed by the asymmetry value equal to 0.33.

![Figure 4. Current distribution](image)
Figure 5 shows the distribution of the peak voltage factor. The analysis of the central tendency measures shows that the mean value equals 1.59, which is quite close to the normal value of the sinusoidal signal equal to 1.414, however, there are significant voltage distortions from the variable load and a number of other factors characteristic of the traction power supply system, which is clearly seen by the shape of the distribution function diagram. The standard deviation equals 0.06, which generally indicates a slight variation in values relative to the average, and this is also confirmed by the fact that the median value coincides with the mean value. The data have a normal distribution with a slight shift towards smaller values since the shift value is positive and equals 0.63. The excess value of the peak voltage amplitude factor is 0.90, which indicates the presence of an “acute” distribution vertex, which is also confirmed by the violin diagram in Figure 5.

![Figure 5. Distribution of peak voltage amplitude factor](image)

The distribution of the peak current amplitude factor is shown in Figure 6. The joint analysis of Table 2 shows that, like the voltage, the current on average has a shape close to the ideal sinusoid, since the mean value is similar to the value of the peak voltage amplitude factor and equals 1.59. However, there is a significantly higher standard deviation of 0.26, which indicates a shift in values relative to the average, and this is also confirmed by the fact that the median is different from the average and equals 1.52. A significant positive asymmetry of 2.89 indicates the distribution shift towards smaller values, while the shift value itself is much greater than 1, which indicates a distribution of data different from normal. The maximum value of the peak current amplitude factor is 5.95, and the excess equals 12.23, which indicates significant peak current values of about 5-8% of the total number of observations according to the distribution function diagram.

![Figure 6. Distribution of peak current amplitude factor](image)
Figure 7 shows the distribution of the harmonic voltage distortion factor for the main harmonic of 50 Hz. The average value equals 13.51, which indicates the significant presence of higher harmonic components in the voltage signal, which is generally a significant factor in terms of the DRP CNF operation, since signal distortions significantly affect both the measurement results and the protection. The standard deviation equals 3.36, which indicates a slight shift in observations relative to the average, which is further confirmed by the fact that the median value is almost equal to the average and makes 13.50. The maximum value of the harmonic voltage distortion factor equals 26.22, which indicates a significant distortion of the waveform, while the number of such observations according to the distribution function diagram ranges from 3 to 5% of the total number of observations. The shift value is -0.03, and the excess value is -0.39, which indicates data distribution close to normal.

![Figure 7. Distribution of voltage harmonic distortion factor](image)

The distribution of the harmonic current distortion factor is shown in Figure 8. The analysis shows that the average value of the factor is 24.11, which indicates even more “dirt” current signal with higher harmonic components compared to the voltage. This circumstance also has an extremely negative impact on the DRP CNF operation. A median of 22.37 indicates a shift of values to the left relative to the average, with an asymmetry value of 10.94, which indicates a strong shift towards smaller values and that the structure of data distribution is not normal. A significant excess of 208.23 indicates that the distribution structure has a significant sharp vertex and long tails. The analysis of the violin diagram shows that the right tail of the distribution is significant caused by the relatively rare heavy trains in relation to the number of other types of trains. The maximum value of the harmonic current distortion factor is 327.67 and the number of such observations varies from 3 to 5% of the total number of observations, which is generally typical for heavy trains. Such high maximum value indicates that in case of heavy trains the current shape is significantly distorted.

![Figure 8. Distribution of harmonic current distortion factor](image)
Figure 9 shows the distribution of the phase shift factor. The average value of the factor is 0.47, which in general indicates the unsatisfactory quality of electric energy. The median value equals 0.55, which indicates a shift in observations relative to the average value towards large values. The minimum and maximum values vary from -1 to 1, which indicates a change in the nature of the load from capacitive to inductive. Besides, according to the diagram of the distribution function, most of the load is inductive and a long tail indicates a shift towards the capacitive load. From the point of view of the DRP CNF operation, this circumstance is a complicating factor because it may lead to distortion of remote measurements and, as a result, to failures or false protection operations. A negative displacement of -2.23 indicates a shift towards larger values, and a high excess value of 5.91 indicates that there are more values at the distribution edges than around the average.

Figure 9. Distribution of phase shift factor

Figure 10 shows the distribution of load resistance. The average value is 135.28 Ohm, which is generally normal for freight traffic, since according to [4, 6] the values $Z > 30$ Ohm belong to the normal mode according to the resistance criterion. The standard deviation of 259.60 Ohm indicates that the values are strongly displaced from the average, which is also confirmed by the shape of the violin diagram and the significant difference between the median and the average equal 74.06 Ohm. The minimum resistance was 22.41 Ohm, which, according to the criteria of the boundary conditions presented in [4], indicates the load value of heavy trains below the limit of the accepted normal mode. The maximum value of load resistance equal to 4557.87 Ohm is derived from the minimum current of 5.59 A, which indicates the possible presence of equalizing currents in the studied inter-substation zone, which is also a complicating factor for the DRP CNF operation. A significant positive asymmetry value of 7.03 Ohm indicates a shift in the distribution towards smaller values. The value of the excess resistance of 58.52 Ohm indicates the presence of long tails, i.e. there are higher values at the distribution edges than around the average.

Figure 10. Load resistance distribution
Figure 11 shows the angle distribution between the first harmonics of the voltage on substation buses and feeder current. The average angle is 25.15°, which from the point of view of the DRP CNF operation is a positive factor, since according to [4] the boundary condition for the angle is $\phi < 40^\circ$. A relatively small standard deviation of 0.57, as well as the median value almost coinciding with the average of 25.18 and the negative asymmetry value of -0.42 indicate a slight spread of values relative to the average and their shift towards large values. A positive angle excess of 0.39 indicates a sharp shape of the distribution, as confirmed by the shape of the violin diagram.

![Figure 11. Distribution of phase angle between first harmonics of voltage on substation buses and feeder current](image)

4. Conclusion
In this work, the main central tendency measures of parameters controlled by relay protection of contact network feeders during the operation of heavy trains were studied using the example of the fourth feeder of the contact network of the Sokhondo traction substation of the Trans-Baikal Railway.

The results of the study confirm the authors’ hypothesis that the operation of heavy trains on a regular basis leads to a decrease in voltage in the contact network feeder to the boundary values of the minimum permissible value specified in [3], which is presented in Figure 3 in the form of a tail with a range of values from 23 to 22 kV and below.

Besides, the values of the feeder current also tend to the maximum permissible values and go beyond the limits of the normal mode equal to 850 A specified in [4]. This fact is presented in Figure 4 as a current distribution tail.

The operation of heavy trains does not best affect the quality of electrical energy and leads to significant distortions in current and voltage waveform, which is confirmed by high values of peak amplitude factors of voltage and current, reaching 1.97 and 5.95 at their maximum, respectively. The operation of heavy trains causes a strong “contamination” of the traction network with the highest harmonic components, which is confirmed by high harmonic distortion factors of voltage and current reaching 26.22 and 327.67 at their maximum, respectively. It is worth noting an extremely low average value, which generally indicates an unsatisfactory quality of electric energy. The above facts have a very negative effect on the quality and accuracy of the DRP CNF operation and, as a result, on the reliability of the transportation process as a whole.

The analysis and evaluation of load resistance distribution and angle between the first harmonics of voltage on the substation buses and feeder current confirms the authors’ hypothesis that the operation of heavy trains may lead to overlapping of normal and emergency modes, thus causing ambiguity in the assessment of the DRP CNF mode and, as a result, an increase in the number of protection actuations due to overload and unspecified causes.

The general results of the analysis as a whole confirm the key thesis of the authors, that on the one hand the existing element base allows implementing fundamentally new protection algorithms, but the
classical approaches used today to a great extent: first, do not unlock the full potential of the modern element base, and second, do not allow unambiguously distinguishing between normal and emergency operation modes and, as a result, failure to fulfill key requirements for relay protection such as selectivity, reliability and stability.

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