Hardware and algorithm of digital protection of electrified railway transport

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Abstract. The paper analyzes current analog protection devices, presents an experiment on the introduction of digital terminals, considers the possibility of improving the efficiency of digital protection system of direct current within traction railroad net-work.

1. Introduction

Today there is a variety of protection methods of separate elements within the traction substation system – traction network – electrorolling stock, each of which found their practical application in some field of industry, logistics, etc., and are used partially, typically at the stage of pilot studies, but not implemented in practice due to various reasons.

According to the study [2], the complex protection system (classical MPP – maximum pulse protection) that includes the protection set – the digital terminal InTer is considered the basic system. The main disadvantage of a complete protection set is that it makes signaling – reacts (controls) only to one indicator of a short circuit and its parameter in the sensitivity zone (area of intersubstation zone) set by the unit. All indicators, such as current, stress, temperature, resistance are subject to the influence of each element of a system “traction substation – traction network – electrorolling stock” and the entire element base in general. The protection scheme does not control of joint change of parameters, which, according to theoretical studies and the carried-out approbation within [1], are often similar at normal and emergency modes. This leads to malfunction of protection selectivity.

Considering the lack of a system approach to the solution of the problem related to the protection of traction network, today it cannot be considered solved, even via the latest prototypes of both two zonal [2-5, 8] and two parametrical [4, 6, 7] or digital terminals [1, 2, 12].

2. Statement of problem

The problem statement defines the need for protection of traction network feeder according to some features of a short circuit. The suggested protection will be able to effectively and selectively disconnect short circuit currents both near traction substations and in remote locations. Such type of protection is called multi-parameter protection [7] unlike digital terminals, within the block diagram of which there may be up to four protection systems, but the action of each of them independently in the relevant zone
(therefore it is called multichannel, but not multi-parameter protection) may be different [6].

The main difference of multi-parameter protection compared to the existing protection systems is the ability to consider several parameters of transition processes within the traction network at once and synchronously, to compare them in real time and to operate following a certain algorithm set by the operator corresponding to the existing operating modes of the traction network. This mechanism of protection systems will allow reducing the length of dead zones and in certain cases avoid- ing them completely.

As an example let us consider the standard double-track line of direct current traction network, which block scheme included two feeders of adjacent traction substations. All feeders of traction substations have high-speed automatic switches ensuring the maximum pulse protection of the traction network and the digital terminal.

Maximum Pulse Protection (MPP) is implemented on a separate electromagnetic element built in the mechanism of a high-speed switch or external electromechanical relay of RDSh or RPT-46 NIIEFA-Electra, which actually reacts to increment of current $\Delta I$ within a certain unstable time [8].

Due to the lag effect of electromagnetic mechanism the relay has sufficient sensitivity only in a near field. At more remote distance at big initial loading of a feeder and small increments of current $\Delta I$ in case of a short circuit there may be the loss of sensitivity and failure to trip depending on settings. Thus, the maximum pulse protection cannot ensure selective protection along the entire intersubstation zone, therefore it is recommended in [1, 2, 6, 10] to create additional more innovative types of protection.

The digital terminal uses indicators of a transition process within the traction network: initial speed of current change ($\frac{di}{dt}$), increment of current $\Delta I$ during settings (in fact this is the average current speed change per setting interval), residual resistance of the traction network ($R=U/I$). Heat protection is used as a back-up and controls temperature of a contact wire line ($T_{кп}$), zone of its action equals $l_{ЗП}$.

The protection for each indicator in a protection set operates in a set zone since the parameters of transition process indicators at short circuit (numerical value) are decreased while removing from a substation or a post of sectioning and can be equal to their values at stationary operating mode of the traction network (TN).

Multi-parameter protection ensures the protection against short circuit in points remote from the traction substation and continuously analyzes changes of transition parameters in the traction network following the chosen indicators. Technical parameters of chosen indicators are compared to setting and the possibility of their coincidence can distinguish the transition process from the stationary one at emergency operation. Hence, it is possible to conclude that functionally the multi-parameter protection shall only be designed following a digital principle.

3. Theory

The carried-out analysis of electromagnetic processes in a system allows concluding that the most effective solution of a problem of fast and selective shutdown of short circuit currents can be found through the creation of protective devices reacting to several indicators of the transition process related to a short circuit and their coincidence by amplitude and time. The equivalent circuit of the traction network with lumped parameters is provided for the analysis of electromagnetic processes in the traction network at transient operating modes, which will not introduce intolerable errors in the analysis.
The solution of the system of differential equations (1) for feeder current

\[ i_1 = \frac{U_{do}}{L} \left( \alpha \cdot e^{-\alpha T} + e^{-\beta T} (\beta \cdot \cos ct + \theta \cdot \sin ct) + K \right) \]  

(2)

Speed of current buildup on a feeder:

\[ \frac{di_1}{dt} = \frac{U_{do}}{L} \cdot \left( \alpha' \cdot e^{-\alpha T} + e^{-\beta T} (\beta' \cdot \cos ct + \theta' \cdot \sin ct) \right) \]  

(3)

In formulas (2 and 3) \( \alpha, K, \beta, \theta, \alpha', \beta', \theta', \epsilon, \lambda \) – coefficients characterizing parameters of current chains at short circuit, they can be calculated according to formulas in [1].

The variable component of a current can be defined similarly (2)

\[ i_{nep} = \frac{U_{do}}{L} \cdot \left( \alpha \cdot e^{-at} + e^{-bt} (\beta \cdot \cos ct + \theta \cdot \sin ct) \right) \]  

(4)

The transient value of current increment can be defined as follows

\[ i_1 - i_2 = \Delta i. \]  

(5)

Increment of current \( \Delta I \) for a certain interval of \( ty \) (setting), i.e. average value of current speed change equals

\[ I_{i1} - I_{i2} = \Delta I_{ij}. \]  

(6)

In (5) and (6) there will be different values of current increments, which can be used in the structure of multi-parameter protection scheme.

In the period of time of any transition process within the traction network the current built-up curves are different from the exhibitor. At the same time, the higher the current step and the speed of its change and the lower the distance to the place of loading or short circuit, the higher the amplitude of a variable component of electric current. The transition process becomes oscillatory fading.

For practical calculations the amplitude of a variable component of the rail-ground voltage can be presented as the voltage drop at input impedance of the rail-ground contour in the zone of traction substation \( Z_{res.in} \) from a variable component of the passing current \( i_{tr} \), i.e.

\[ U_{restr} = i_{tr} z_{resin}. \]  

(7)

It shall also be noted that the amplitude of voltage variable component depends on rail-ground conductivity (\( R_n \)) therefore it can be a reliable characteristic of the transition process only in conditions
of stable rail-ground conductivity, which in general is only possible in the conditions of a dry subway or in regions with low level of rainfall.

It is possible to estimate the transition process based on the analysis of traction substation operability in the suction-ground chain according to the level of a variable component. Depending on contour parameters the frequency of the suction-ground variable component will slightly change within 120-270 Hz. More accurately this variable can be defined considering that the rails have induced electromotive force from the current on a contact wire. In this case the system of equations connecting contours “rails-ground” and “contact wire-ground” will be as follows:

\[
\begin{align*}
-\frac{dU_{res}}{dx} &= \varepsilon_p I_p + z_{cr} I_k \\
-\frac{dI_{res}}{dx} &= U_{res} g
\end{align*}
\]

where \( U_{res} \) – potential of rails in relation to ground, V; \( I_p \) – current in rails in the considered point, A; \( z_p \) – longitudinal resistance of rails, Ohm/km; \( g \) – rails-ground conductivity, sim/km; \( z_{cr} \) – mutual resistance between contact network and rails, Ohm/km.

Knowing expressions for currents (2…4) it is possible to find the induced voltage in rails at the ends of the line between the suction of the traction substation and the ground, in a contact wire and any wire, for example in a wave guide hung on supports of a contact network [1] and to use it as a indicator of the transition process in the traction network. The variable component of the voltage (amplitude and frequency) will be different, which will allow distinguishing the operating modes of the traction network. The numerical value \( U_{P3} \) is defined by the solution of a system (6) on model [1].

The variable component of the voltage \( U_{kp,z} \) can be considered as total induced by currents in a contact wire and a rail (Fig. 3). Then, having expressed \( i_{22} \) through \( i_{11} \), after the corresponding transformations it is possible to receive the resulting value \( U_{kp,z} \) taking into account interinduction resistance \( z_{res} \) [1]:

\[
z_{res} = \left( z_k - z_{cr} \frac{z_{cr}}{z_p} \right) l_c - z_{cr} \left( 1 - \frac{z_{cr}}{z_p} \right) \frac{1 - e^{-\gamma_2 l} + e^{-\gamma_2 (l_c-l)}}{2\gamma_2},
\]

then

\[
U_{kp,z} = i_{11} \left( z_k - z_{cr} \frac{z_{cr}}{z_p} \right) l_c - i_{11} z_{cr} \left( 1 - \frac{z_{cr}}{z_p} \right) \frac{1 - e^{-\gamma_2 l} + e^{-\gamma_2 (l_c-l)}}{2\gamma_2},
\]

where \( z_k \) and \( z_p \) – respectively the longitudinal resistance of contact network and rails, Ohm/km; \( z_{cr} \) – mutual resistance between contact network and rails, Ohm/km; \( l \) and \( l_c \) – respectively distance between the traction substation or from the substation to the place of loading or short circuit; \( \gamma_2 \) – constant of current wave distribution in rails-ground contour, which equals \( \gamma_2 = \sqrt{g z_p} \) km -1; resulting interinduction resistance.
4. Experiment
The studies [1, 3, 7, 11] showed that the variable component of the voltage Uкп.з in the traction mode has the amplitude of 20-90 V, key harmonica changes with a frequency of 100-400 Hz; at short circuit the amplitude makes 145-995 V depending on the distance to the place of short circuit and the type of short circuit, and the carrier frequency changes within 170-250 Hz.

The analysis of experimental data allowed establishing that in the majority, namely in 85% of cases the amplitude Uкп.з in short circuit mode considerably exceeds the level of quasi-stationary modes, and the pulse duration makes 1.8-2 frequency periods. For example, at a short circuit on a rail at the distance of 15 km from the substation the amplitude Uкп.з reached 350 V, and at short circuit on the ground – 570 V. Arching also causes the increase of the amplitude of a voltage variable component. It is found that even with a double length of a feeder zone the Uкп.з voltage level in the short circuit mode is more than twice higher than the levels corresponding to starting of the train.

Hence, it is advisable to consider the influence of electrorolling stock only in short circuit on the support disconnected from a rail and having dissipation resistance of more than 10 Ohms. This operating mode occurs only in 8% of cases, and on sites with reinforced insulation of the traction network has probability below 3%.

It is established through the experiment that in general on the substation there is no coordination and reservation of the traction network protection with protection systems of a converting unit from a cathode and a traction transformer. This type of reservation matters at nearby faults and in systems with one-modular traction substations.

5. Structure of protection device
The study and analysis of electromagnetic processes in a system [1, 8, 9] allows confirming that the most rational solution of the problem of fast and selective short-circuit clearing shall be the creation of protective devices reacting not to one, but to several indicators of the transition process connected with short circuit. Such indicators include the following:

1) change of a variable component of the traction network voltage;
2) current increment over a certain period of time (average speed of increase during time setting);
3) change of current and speed of its increase;
4) change of high-frequency fluctuations spectrum in electromagnetically connected contours located parallel to the traction network;
5) increase of temperature of a contact wire above the established one;
6) change of the traction network impedance;

There is a need to control the chosen number of parameters and to ensure continuous analysis of their change in comparison with design values. For each site of the traction network it is advisable to select values following the results of modeling (to consider parameters of the elements of the traction network of a site) and monitoring (to consider movement parameters, i.e. route profile, type of locomotive and weight of trains). Besides all above the use of indirect protection methods is possible:

7) voltage of the traction network (potential protection);
8) control of contact wire integrity by currents from a foreign source with individual correction of controlling current (CC) frequency for each site of the traction network (to consider CC attenuation);
9) telesignals of the condition of any element of the power supply system – traction substation – electrorolling stock transferred along the channels of telecontrol – remote signaling – telemetry to the central processing unit for continuous analysis and solutions (teleblocking).

For the chosen site of the traction network there is a need to concretize the necessary set of direct and indirect indicators of short circuit.

6. Conclusion
The analysis of the transition processes in the traction network via mathematical modeling allows setting key indicators and parameters characterizing the modes of emergency and quasi-stationary transition processes, but the coincidence of several indicators allows distinguishing short circuits (by rail, by
rolling stock, by ground) from the normal modes (staring of a train, transition through section insulator, current collector lift and other procedures) and selectively disconnecting the place of damage. In certain cases, when the section pillar is shutdown the length of a feeding zone increases, at the same time the reliability of functioning may be maintained by indirect actions: teleblocking or thermal protection.

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