CONSTRUCTION OF A METHOD TO PROTECT A TRACTION ELECTRIC NETWORK AGAINST SHORT-CIRCUIT CURRENTS, BASED ON THE NEW ATTRIBUTE

P. Mikhalichenko
Doctor of Technical Sciences, Associate Professor, Head of Department*

I. Biliuk
PhD, Associate Professor, Head of Department**

O. Krychenko
PhD, Associate Professor**

V. Nadtochii
PhD*

A. Nadtoshyi
PhD*

E-mail: tasman.leh.85@gmail.com

*Department of Automation and Electrical Equipment
Kherson Branch of the National University of Shipbuilding named after Admiral Makarov
Ushakova ave., 44, Kherson, Ukraine, 73022

**Department of Automation
Admiral Makarov National University of Shipbuilding
Heroiv Ukrainy ave., 9, Mykolayiv, Ukraine, 54025

DOI: 10.15587/1729-4061.2019.186485

UDC 681.5

1. Introduction

It is known that all kinds of protection of electrical systems from emergency modes of operation are based on certain attributes. Comparing values of these attributes under the normal and emergency states of an electrical system underlies the principle of operation of protective devices.
In relay-protection systems of traction power supply such attributes include: the maximum current in a feeder, current surges, the steepness of the feeder current growth front, a time constant, etc. This predetermined the existence of current types of protection (maximum current, current cut-off, maximum pulse current), protection that reacts to transient processes based on the rate of growth of feeder’s current or its surge (gain). However, protection from such a mode as a short circuit in the traction network could be built based on other features. The need to find such attributes is associated with the ambiguity in determining the moment of a short circuit occurrence in traction electric networks, which results in failures in the operation of protective switching equipment.

The use of protection from short circuit in the traction network, based on the new attribute, would make it possible, first, to improve reliability of traction networks and reduce the accident rate related to them. Consequently, that could reduce the cost of eliminating accidents and loss of time to restore transportation networks. The new-attribute protection could function either as a separate system or can be integrated into the conventional relay protective equipment of a traction network feeder.

2. Literature review and problem statement

Paper [1] reports results from studying the dynamic processes in a subway power station. It is shown that improving energy efficiency of electric traction requires the optimization of dynamic modes. Short circuit (SC) in traction electric networks is the most intensive dynamic mode. A protection system is designed to prevent and manage SC. When determining a short circuit, the main role belongs to such parameters as a line’s resistance and current [2]. Despite significant progress in the construction of various mathematical models, there is no any general method for determining the parameters of a traction network under dynamic modes [1–3]. That relates to significant discrepancies in the structural features, characteristics, and topologies of traction networks, as well as their loads. This circumstance necessitates searching for more universal technologies for protection against short circuits.

Three areas in the search for such technologies are distinguished. A first direction is the improvement of existing or conventional systems. Thus, work [4] proposes a protection scheme that combines two criteria in order to protect shunt reactors with magnetic control in power lines. These criteria are based on the overall controlling current and identification of the equivalent inductance of scattering. An emergency mode can be determined based on the estimation of a heat output in the network [5], etc.

A second direction is a combination of conventional systems of protection with digital computing platforms and specialized software. This strategy can be termed the intellectualization of relay protection [6–8]. In fact, these are additional protection algorithms in conventional systems of protection, which remain principal in high-voltage power systems. In addition, a given strategy includes protection methods based on multicriterial systems with neural networks [9]. Among others, these include the protection systems whose elements are integrated into the structural nodes of networks, such as converting devices, mounting fittings, isolators, etc. [10].

A third direction is the search for new protection systems based on the new attributes of an emergency mode. Thus, work [11] proposes a scheme of line protection based on a running wave. The possibility of protection of traction networks based on unproductive losses in the network was substantiated in paper [12].

The effectiveness of each technology for improving protection systems is determined by specific application conditions and depends on the structural characteristics of a network, its electrical characteristics and load.

For the direct current traction networks that are operated in Ukraine, effective protection can be based on measuring the interval of change in the feeder voltage as an attribute of SC.

3. The aim and objectives of the study

The aim of this study is to construct a method for estimating a SC mode in a DC traction network based on a new attribute.

To accomplish the aim, the following tasks have been set:
- to establish a dependence of the feeder voltage drop’s duration on a short circuit mode in a traction network;
- to justify the principles of operation of protection against short circuit based on the attribute of a time interval of the feeder voltage drop;
- to prove the efficiency of the new technique for protecting a direct current traction network from short circuits.

4. Establishing a dependence of the feeder voltage drop’s duration on a short circuit mode in a traction network

By comparing the basic attributes underlying the aforementioned types of protection, one can draw the following conclusions. At significant distances between the substations, currents of remote short circuit (small currents) are close in value to the maximum load currents of a standard mode, and sometimes they are lower. It is not possible to reliably determine, based on the steepness of the current growth front and a circle’s time constant, the mode of a traction network, because under normal conditions and in case of short circuit, in many cases these indicators are almost the same. Current surges in case of short circuit are typically higher than those under a standard mode. The exception is the power disabling mode (if $t_{pw}>0.5$ s) with a repeated recovery of voltage; however, this mode is frequent in practical operation. A potential protection also has disadvantages – the need to build a special wire line for each pair of blocking minimum voltage relay switches, installed at various points of a traction network. These disadvantages of attributes, and, therefore, of the protection systems themselves, make specialists in electrical engineering work on finding other attributes (principles) of building a relay protection.

It is known that in case of short circuit in a traction network its voltage is reduced. Its sharpest, almost linear, decrease is observed, first, at the first moment of an emergency transition process, and, second, at a site of short circuit (to zero at a metallic short-circuit) and at points near it (Fig. 1–3). Therefore, the attribute on which the protection can be built is the steepness of the front of such a reduction in
feeder voltage \( \frac{du_F}{dt} \). Speed \( \frac{du_F}{dt} \) is different depending on the distance of a short circuit site to the feeder with the considered \( u_F \).

In order to theoretically substantiate a possibility of using the front steepness \( \frac{du_F}{dt} \) to build protection, let us enable a branch \( R_dC \) between a feeder and a rail (which we call a “protection link”) (Fig. 2).

\[ G(t) = \frac{i_{ch}(t)}{U_{ch}} = \frac{1}{R} \frac{1}{C} e^{-\frac{t}{\tau}}. \tag{2} \]

where \( T_{ch} = R_dC \) is the time constant of circuit with a “protection link”.

Next, substitute (2) in (1); for the moments of a transition process \( 0 \leq t \leq T_F \) (Fig. 3), the magnitude of current \( i_F(t) \) can be recorded

\[ i_F(t) = \frac{1}{R_d} \int_0^t \frac{du_F}{dt} e^{-\frac{t}{\tau}} \ dt. \tag{3} \]

According to experimental data (the oscillogram of short-circuit, Fig. 1), at the moment of short circuit, the voltage drop on the feeder in a traction substation \( u_F(t) \) linearly decreases; it can be described by equation

\[ u_F(t) = \frac{U_{F,\text{nom}} - U_{F,\text{end}}}{t_F} t \tag{4} \]

and then its derivative is a certain constant magnitude

\[ \frac{du_F}{dt} = \frac{U_{F,\text{nom}} - U_{F,\text{end}}}{t_F} \tag{5} \]

accordingly, this derivative can be taken out of the integral sign in expression (3), whose integration results in deriving the following, taking into consideration the formula for \( T_F \).

\[ i_F(t) = \frac{1}{R_d} \int_0^t \frac{du_F}{dt} e^{-\frac{t}{\tau}} \ dt = \frac{1}{R_d} \int_0^t e^{-\frac{t}{\tau}} \left( T_F e^{-\frac{t}{\tau}} \right) \ dt = \frac{1}{R_d} \left| \int_0^t \frac{du_F}{dt} e^{-\frac{t}{\tau}} - \frac{T_F}{R_d} e^{-\frac{t}{\tau}} \right| = \frac{1}{R_d} \left[ \int_0^t \frac{du_F}{dt} e^{-\frac{t}{\tau}} - \frac{T_F}{R_d} e^{-\frac{t}{\tau}} \right] \]

\[ = \frac{1}{R_d} \left[ \frac{R_d C}{e^{\frac{t}{\tau}} - 1} - \frac{T_F}{R_d} e^{-\frac{t}{\tau}} \right] \tag{6} \]

If the time constant \( T_{ch} \) is large enough, while \( t_F \) is very small \( \left( e^{-\frac{t}{\tau}} \right) \), then

\[ i_F(t) = \frac{C}{R_d} \left\{ \int_0^t \frac{du_F}{dt} \ dt \right\}. \tag{7} \]

That is, according to (6) and (7) the current \( i_{ch}(t) \) in the “protection link”, which is under the influence of a feeder voltage drop, is directly proportional to the rate of the decrease in this voltage at the beginning of its change. In other words, to the feeder voltage drop’s steepness.

5. Substantiating the operational principles of protection from short circuit based on the attribute of a feeder voltage drop rate

We shall give a theoretical justification to the operation of a series (including some known) of principal circuits of
Energy-saving technologies and equipment

The simplest scheme is based on a shunt with \( r_{sh} \) shown in Fig. 4, where \( r_o, L_p \) are the active resistance and inductance of the relay.

\[
\begin{align*}
\text{Fig. 4. Enabling a current relay into a } R_C \text{ protection link} \\
\text{through the shunt}
\end{align*}
\]

For it, according to the law by Kirchhoff, we obtain:

\[
i_{sh} - i_{sh} - i_p = 0,
\]

\[
r_{sh} i_{sh}(t) = r_p i_p(t) + L_p \frac{di_p}{dt}.
\]

By solving the system of equations (6), (8), (9) we obtain:

\[
i_p(t) = \frac{r_o C}{r_o + r_p} \frac{du_p}{dt} \left( 1 - e^{-r_p / (r_o + r_p) dt} \right).
\]

If one selects a relay so that its time constant \( T_p = L_p / r_p \) is so small that it is possible to neglect the second component in expression (10), then, for the time interval \( 0 \leq t < t_f \) (Fig. 3), we obtain:

\[
i_p(t) = \frac{r_o C}{r_o + r_p} \frac{du_p}{dt} \left( 1 - e^{-r_p / (r_o + r_p) \cdot t} \right).
\]

that is, in fact

\[
i_p(t) \left. \frac{du_p}{dt} \right|_{t < t_f}.
\]

Consider a circuit in which the source of a signal for the considered protection is a special current transformer with an air gap (Fig. 5).

\[
\text{Fig. 5. Enabling a current relay into a } R_C \text{ protection link} \\
\text{through the current transformer}
\]

Under a short circuit mode and, thus, when changing feeder voltage \( u_f(t) \), there is an alternating current \( i_{sh}(t) \) in the “protection link”. The result, due to the phenomenon of inter-induction, is the induced inter-induction EMF at the secondary winding of current transformer \( TA \), which creates voltage due to inter-induction at the secondary winding:

\[
u_i(t) = M \frac{di_{sh}}{dt}
\]

where \( M \) is the coefficient of inter-induction between the windings of a current transformer.

On the other hand, for a circuit with the current relay, in line with the 2nd law by Kirchhoff:

\[
u_i(t) = r_p i_p(t) + L_p \frac{di_p}{dt}.
\]

Equating (12) to (13) and replace \( i_q(t) \) with expression (6), we obtain:

\[
M \frac{du_f}{dt} \left( 1 - e^{-r_p / r_o} \cdot t \right) = r_p i_p(t) + L_p \frac{di_p}{dt}.
\]

Since function \( u_f(t) \) at the initial stage of short circuit is linear, the steepness of its front, that is \( du_f / dt \), is a constant magnitude; then, following the differentiation of the left-hand side of equality (14), it takes the form:

\[
M \frac{du_f}{dt} e^{-r_p / r_o} = r_p i_p(t) + L_p \frac{di_p}{dt}.
\]

By dividing both sides of equality (15) by \( r_p \) and assuming the time constant \( T_p \) accepts a small value and that the second component of the right-hand side of expression (15) can be ignored, we obtain

\[
i_p(t) = \frac{M}{r_p} \frac{du_f}{dt} e^{-r_p / r_o}.
\]

Thus, the current in a current relay (that is its reaction) is directly proportional to the steepness of the front of a feeder voltage drop’s pulse.

Consider operation of the protection based on a bridge circuit, whose diagonal includes a relay (Fig. 6). Due to equal active resistances \( R \) of the shoulders, a bridge under normal operation modes (even if \( U_f \) is not perfectly smoothed) would be in equilibrium, then \( u_{24}(t) = 0 \) and the relay current \( i_p(t) \) would also be equal to 0 \( (i_p(t) = 0) \).
At a sharp change in \( u(t) \) current \( i_d(t) \neq 0 \). And if the bridge's time constant \( T_M \) accepts a very small value in comparison with the time constant time of “protection link” \( T_p \), then at a small current through the relay \( i_d(t) \) the current through the shoulder of the bridge would equal:

\[
i_k = i_l = \frac{r_p}{2R}i_{\text{d}0}.
\]

For circuit 1-2-3-4, Fig. 6, we obtain:

\[
-R_i(t) - L \frac{di_p}{dt} = t_p(t) + t_L \frac{di}{dt} + R_i(t) = 0
\]

or, considering \( i_k = i_l \):

\[
\frac{L}{2R} \frac{di_p}{dt} = t_p(t) + t_L \frac{di}{dt}.
\]

For a node with the shunt, Fig. 6:

\[
i_{d0}(t) - i_{m0}(t) + i_{d0}(t).
\]

Accordingly, for node 1:

\[
i_{m0}(t) - i_{l0}(t) + i_{d0}(t) = 2i_{l0}(t).
\]

Then \( i_{d0}(t) - i_{d0}(t) = 2i_{l0}(t) \).

hence

\[
i_{d0}(t) - i_{d0}(t) = 2i_{l0}(t).
\]

Substitute expression (6) in (19) for \( i_{d0}(t) \) and the current \( i_{d0}(t) \) from expression (17), we obtain:

\[
\frac{2R}{r_p} i_l = c \frac{du}{dt} \left(1 - e^{-\frac{a}{c}}\right) - 2i_k.
\]

From this expression the current \( i_k \) equals:

\[
i_k = \frac{Gr_s}{2(R + r_p)} \frac{du}{dt} \left(1 - e^{-\frac{a}{c}}\right).
\]

Substitute (21) in (18) and, following the differentiation, we obtain:

\[
\frac{L}{2(R + r_p)} \frac{du_{\text{p}}}{dt} - \frac{\gamma}{a} = \rho_{i_p}(t) + L \frac{di}{dt}.
\]

By dividing both sides of equality (22) by \( r_p \) and considering that the time constant \( T_p \) is so small that the component \( L_p (di/dt) \) can be neglected, we obtain:

\[
i_p(t) = \frac{L}{2(R + r_p)R_m r_p} \frac{du_{\text{p}}}{dt} e^{-\frac{a}{c}},
\]

that is, the reaction from a time relay is proportional to the rate of a feeder voltage decrease.

It should be noted that formulae (11), (16) and (23) for the relay's current hold under condition that the time constant \( T_p \) is very small, which is easily achieved by applying electronic relays (it becomes very difficult when electromagnetic ones are applied).

### 6. Testing effectiveness of the new technique to protect a traction network against short circuits

As specified above, all types of relay protection are based on comparing the values for certain attributes under the standard and emergency modes of system operation. For the proposed type of protection, such attributes are \( du/dt \), whose values under a short circuit mode are given in Table 1 for one of the sections of traction power supply at the "Prydniprovskaya Railroad" branch of AT "Ukrzaliznytsya". Experiments were conducted using the digital oscilloscope ACS-3106. The oscilloscope is equipped with a feature of recording digital data to a hard-disk media in the .csv format.

Conditions for experiments, as well as results from them, are given in work [13].

| High-speed breaker type | Value \( du/dt \), kV/s |
|-------------------------|------------------------|
| Close SC                | 3.2140                 |
| Middle SC               | 1.2544                 |
| Far SC                  | 586.4                  |
| VAB-43                  | 2.7225                 |
| VAB-49                  | 712.5                  |
| VAB-206                 | 476.5                  |
| VAB-206                 | 621.5                  |

When disabling during the time of current overload \( du/dt \approx 330 \) kV/s. When starting EMF, the feeder's voltage is not changed.

To determine \( du/dt \) under a standard mode of operation we shall turn to such a concept for the DC electrical networks (according to GOST 13109-97) as a voltage fluctuation, which implies a rapid change that occurs at a speed of 1...2 % per second. Here, 1...2 % is the relative deviation (amplitude) of a voltage fluctuation \( \delta U \), which is determined based on the relative difference between successive voltage extrema

\[
\delta U = \frac{U_{\text{max}} - U_{\text{min}}}{U_{\text{min}}} \times 100\%.
\]

Hence, it follows that the maximum change in feeder voltage (according to this expression) is 0.02×3.3×0.066 kV per second, which is considerably lower than \( du/dt \), given in the Table 1.

Next, we consider the extreme value for a change in the feeder voltage according to RTO (Rules of technical operation). It is known that according to RTO, \( U_{\text{max}} \approx 4 \) kV, \( U_{\text{min}} \approx 2.7 \) kV. Then the most adverse voltage deviation would equal: 4−2.7=1.3 kV, which is considerably lower than the tabular values.

It follows from this brief analysis that the protection based on the proposed principle:

1) “distinguishes” between normal and emergency modes;
2) “distinguishes” a short circuit type (“close”, “medium”, “far”).

This requires installing at a traction substation of three sets of the protection, in each of which the current relay should be set to the appropriate value of \( du/dt \). In this case, the corresponding relay would be triggered in case of an appropriate SC. Or, apply this principle in multi-parametric protection systems built on microprocessor element base.
It is known that in case of short circuit, the value of current strength in a network significantly increases, which could lead to the destruction of elements, flashes, and other serious consequences. In addition, an increase in current strength leads to an increase in the electrodynamic forces influencing the chain elements, which could also lead to their destruction. Modern systems of protection against short circuits such as current cutoff, maximum-current protection, are mainly built on a direct measurement of the current force in the controlled network with the help of shunts, transformers of current, electromagnetic (relay) systems. This predetermines the main drawback of these devices – their sensing elements must be switched on sequentially to the power line. Therefore, they are calculated for appropriate rated currents and short circuit currents in a network as well as significant electrodynamic loads. In addition, the sensing elements of current protection must be appropriately insulated to tolerate the voltage in a network. Thus, in power electrical networks, these devices have rather significant mass-dimension indicators. As shown in [1], the working currents in a traction network could be 4 to 6 times higher than their rated values. The same currents could operate under certain conditions in case of short circuits. Thus, there is an uncertainty in the operating mode of a traction power grid. This uncertainty could be overcome in existing systems of protection, such as current cutoff, maximum current protection, and time-based current protection. However, that requires complex procedures for configuring such systems. The system of protection of a traction network against short-circuit currents, considered in the framework of this article, is based on employing another attribute of emergency mode. This makes it possible to use sensing elements with a parallel connection to the controlled section of the network. It would suffice for such a system of protection, in order to detect a short circuit, to control the speed of change in the feeder voltage $du/dt$. This magnitude varies depending on the distance between a short circuit site and the feeder. The current $i(t)$ in a “protection link”, which is under the influence of a feeder voltage drop in case of short circuit, is directly proportional to the speed of this voltage decrease at the start of its change, that is, the steepness of a feeder voltage drop.

1. In case of short circuit in a traction network, its voltage is reduced. Its sharpest, almost linear, decrease is observed, first, at the first moment of an emergency transition process, and, second, at a short circuit site. The speed $du/dt$ varies depending on the distance between a short circuit site and the feeder. The current $i(t)$ in a “protection link”, which is under the influence of a feeder voltage drop in case of short circuit, is directly proportional to the speed of this voltage decrease at the start of its change, that is, the steepness of a feeder voltage drop.

2. The simplest protection scheme is a shunt-based circuit. Circuits with a peak-transformer and a bridge scheme could also be used.

3. The protection based on measuring the speed of a feeder voltage drop could detect not only the SC itself. In addition, this technique “distinguishes” standard and emergency modes and “distinguishes” the type of SC based on the distance from a power supply (“close”, “medium”, “far”).

References

1. Yatsko, S., Sytnik, B., Vashchenko, Y., Sidorenko, A., Liubarskyi, B., Veretenikov, I., Glebova, M. (2019). Comprehensive approach to modeling dynamic processes in the system of underground rail electric traction. Eastern-European Journal of Enterprise Technologies, 1 (9 (97)), 48–57. doi: https://doi.org/10.15587/1729-4061.2019.154520

2. Wiszniewski, A., Solak, K., Rebizant, W., Schiel, L. (2018). Calculation of the lowest currents caused by turn-to-turn short-circuits in power transformers. International Journal of Electrical Power & Energy Systems, 95, 301–306. doi: https://doi.org/10.1016/j.ijepes.2017.08.028

3. Alluhaidan, M., Almutairy, I. (2017). Modeling and Protection for Low-Voltage DC Microgrids Riding Through Short Circuiting. Procedia Computer Science, 114, 457–464. doi: https://doi.org/10.1016/j.procs.2017.09.024

4. Zheng, T., Liu, X., Huang, T. (2019). Novel protection scheme against turn-to-turn fault of magnetically controlled shunt reactor based on equivalent leakage inductance. International Journal of Electrical Power & Energy Systems, 112, 442–451. doi: https://doi.org/10.1016/j.ijepes.2019.05.002
5. Tartaglia, M., Mitolo, M. (2010). An Analytical Evaluation of the Prospective I(2)t to Assess Short-Circuit Capabilities of Cables and Busways. IEEE Transactions on Power Delivery, 25 (3), 1334–1339. doi: https://doi.org/10.1109/tpwrd.2009.2037505

6. Sanchez-Sutil, F., Hernández, J. C., Tobajas, C. (2015). Overview of electrical protection requirements for integration of a smart DC node with bidirectional electric vehicle charging stations into existing AC and DC railway grids. Electric Power Systems Research, 122, 104–118. doi: https://doi.org/10.1016/j.epsr.2015.01.003

7. Mahmoudian Esfahani, M., Mohammed, O. (2020). An intelligent protection scheme to deal with extreme fault currents in smart power systems. International Journal of Electrical Power & Energy Systems, 115, 105434. doi: https://doi.org/10.1016/j.ijepes.2019.105434

8. Peres, L. M., Silva, K. M. (2019). Power transformer protection using an instantaneous-current-value negative sequence differential element. International Journal of Electrical Power & Energy Systems, 108, 96–106. doi: https://doi.org/10.1016/j.ijepes.2018.12.033

9. Abdali, A., Mazlumi, K., Noroozian, R. (2019). High-speed fault detection and location in DC microgrids systems using Multi-Criterion System and neural network. Applied Soft Computing, 79, 341–353. doi: https://doi.org/10.1016/j.asoc.2019.03.051

10. Caramel, C., Austin, P., Sanchez, J. L., Imbernon, E., Breil, M. (2006). Integrated IGBT short-circuit protection structure: Design and optimization. Microelectronics Journal, 37 (3), 249–256. doi: https://doi.org/10.1016/j.mejo.2005.09.028

11. Jia, Q., Dong, X., Mirsaeidi, S. (2019). A traveling-wave-based line protection strategy against single-line-to-ground faults in active distribution networks. International Journal of Electrical Power & Energy Systems, 107, 403–411. doi: https://doi.org/10.1016/j.ijepes.2018.11.032

12. Mykhalichenko, P., Nadtochii, V., Nadtochiy, A. (2019). Defining energy indicators for detecting short circuits in a dc electric traction system. Eastern-European Journal of Enterprise Technologies, 5 (8 (101)), 6–14. doi: https://doi.org/10.15587/1729-4061.2019.180796

13. Mykhalichenko, P. Ye. (2012). Results of Experimental Research of the Modes of Short Circuit in a Traction Network. Visnyk DNUZT, 41, 81–85.