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*Всі види релейного захисту основані на порівнянні значень певних ознак при нормальних та аварійних режимах роботи системи. Запропоновано нову ознаку визначення аварійного режиму системи тягового електропостачання постійного струму, а саме, швидкість спадання напруги фідера тягової підстанції. Як відомо, при короткому замиканні в тяговій мережі її напруга знижується. Найбільш різке, практично лінійне, її зменшення спостерігається, по-перше, в перший момент часу аварійного перехідного процесу, і, по-друге, в місці короткого замикання і в точках поблизу нього. Тому крутизна фронту такого зменшення фідерної напруги може бути ознакою короткого замикання. Дана ознака дозволяє визначати вид короткого замикання за дальністю від джерела живлення. Крім того, запропоновані схемні рішення реалізації системи захисту, основані на цій ознаці. Розглядається три варіанти побудови таких систем захисту. Перший варіант з використанням RC фільтра. Другий варіант з використанням імпульсного трансформатора. Третій варіант полягає у використанні мостової схеми. Кожна схема має свої переваги та недоліки, але сучасна електроніка та цифрова техніка дозволяють реалізувати будь яку з них. Це у перспективі сприятиме побудові селективного за дальністю захисту від КЗ. Для цього необхідно використовувати стільки комплектів захисту, скільки точок вздовж тягової лінії необхідно контролювати. Така система також легко реалізується програмними засобами з використанням мікропроцесорної техніки.*

*Практичні результати, отримані при дослідженні в ділянці тягового електропостачання Придніпровської залізниці, дозволяють стверджувати, що запропонований спосіб визначення коротких замикань є досить ефективним. Його можливо використовувати як додаткову (дублюючу систему) в загальній релейній-захисній апаратурі. Це підвищить надійність систем електропостачання тягових мереж. Загалом розглянутий спосіб визначення коротких замикань може бути використаний у будь-якій електроенергетичній системі постійного струму*

*Ключові слова: коротке замикання, напруга фідера, швидкість зміни напруги, релейний захист, тривалість спаду напруги, селективний захист*

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

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## 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.

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## 2. Literature review and problem statement

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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.

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## 3. The aim and objectives of the study

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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.

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

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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  $t_{per} > 0.5$  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  $\left. \frac{du_F}{dt} \right|_{t=0}$ . Speed  $du_F/dt$  is different depending on the distance of a short circuit site to the feeder with the considered  $u_F$ .

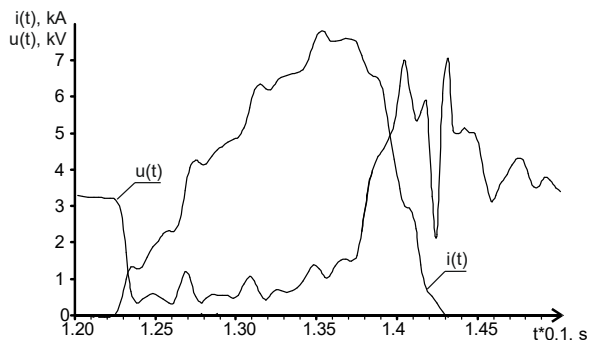


Fig. 1. Experimental study of a close SC at TP Verkhivtseve, 2×VAB-43

In order to theoretically substantiate a possibility of using the front steepness  $\left. \frac{du_F}{dt} \right|_{t=0}$  to build protection, let us enable a branch  $R_dC$  between a feeder and a rail (which we call a “protection link”) (Fig. 2).

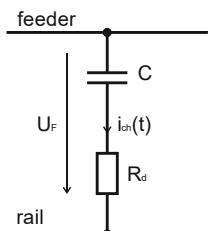


Fig. 2. Protective link for a protection system against a voltage surge

Until the moment of short circuit, current  $i_q(t)$  did not pass along this branch, due to the feeder voltage  $u_F$  being constant (we consider an ideal case), equal to some initial value  $U_{Fstart}$ .

At the moment of short circuit voltage  $u_F$  starts decreasing linearly from point “start”, (Fig. 3); until, we assume, to some value  $U_{Fends}$ , to point “end”. We shall shift a short circuit occurrence moment (point “start”) at time count “0”, that is, at the moment of its occurrence and the subsequent progress of the transition process of a feeder voltage decrease  $u_F(t)$ .

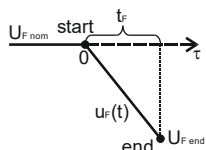


Fig. 3. Timeline feeder voltage chart at the moment of short circuit

Under the action of a changing (decreasing) voltage  $u_F(t)$ , applied to a “protection link”, current  $i_{ch}(t)$  is generated in the latter. We determine it using the Duhamel integral, according to which one can write:

$$i_{ch}(t) = \int_0^t \frac{du_F}{dt} G(t - \tau) d\tau, \tag{1}$$

$G(t)$  is the transitional conductivity of simple  $R_dC$ -circuit in a “protection link” (Fig. 2). This conductivity is equal to the desired transitional current  $i_{ch}^1(t)$  of the circle (Fig. 2) when it is enabled for a single voltage. For  $R_dC$ -circuit, transitional conductivity is determined from

$$G(t) = i_{ch}^1(t) = \frac{1}{R_d} e^{-\frac{t}{T_{ch}}}, \tag{2}$$

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  $i_q(t)$  can be recorded

$$i_{ch}(t) = \frac{1}{R_d} \int_0^t \frac{du_F}{dt} e^{-\frac{(t-\tau)}{T_{ch}}} d\tau. \tag{3}$$

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  $u_F(\tau)$  linearly decreases; it can be described by equation

$$u_F(\tau) = \frac{U_{Fend} - U_{F0}}{t_F} \tau \tag{4}$$

and then its derivative is a certain constant magnitude

$$\frac{du_F}{dt} = \frac{U_{Fend} - U_{F0}}{t_F}, \tag{5}$$

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  $T_q$ ,

$$i_{ch}(t) = \frac{du_F}{dt} \frac{1}{R_d} \int_0^t e^{-\frac{t-\tau}{T_{ch}}} e^{-\frac{\tau}{T_{ch}}} d\tau = \frac{du_F}{dt} \frac{1}{R_d} e^{-\frac{t}{T_{ch}}} \left( T_{ch} e^{\frac{\tau}{T_{ch}}} \right) \Big|_0^t = \frac{du_F}{dt} \frac{R_d C}{R_d} \left( e^{-\frac{t}{T_{ch}}} - 1 \right) = C \frac{du_F}{dt} \left( 1 - e^{-\frac{t}{T_{ch}}} \right). \tag{6}$$

If the time constant  $T_{ch}$  (6) is large enough, while  $t_F$  is very small  $\left( e^{-\frac{t}{T_{ch}}} \approx 1 \right)$ , then

$$i_{ch}(t) = C \left. \frac{du_F}{dt} \right|_{t=0}. \tag{7}$$

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

relay protection devices based on the obtained, according to the new attribute, expressions (6) and (7).

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

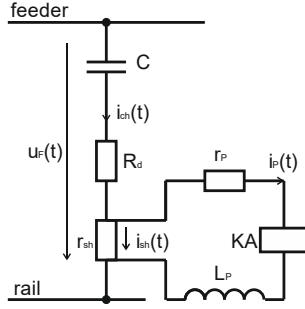


Fig. 4. Enabling a current relay into a  $R_dC$  protection link through the shunt

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

$$i_{ch} - i_{sh} - i_p = 0, \quad (8)$$

$$r_{sh}i_{sh}(t) = r_p i_p(t) + L_p \frac{di_p}{dt}. \quad (9)$$

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

$$i_p(t) = \frac{r_{sh}C}{r_{sh} + r_p} \frac{du_F}{dt} \left( 1 - e^{-t/\tau_{ch}} \right) - \frac{L_p/r_p}{r_{sh} + 1} \frac{di_p}{dt}. \quad (10)$$

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:

$$i_p(t) = \frac{r_{sh}C}{r_{sh} + r_p} \frac{du_F}{dt} \Big|_{t < t_F} \left( 1 - e^{-t/\tau_{ch}} \right), \quad (11)$$

that is, in fact

$$i_p(t) \sim \frac{du_F}{dt} \Big|_{t < t_F}.$$

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).

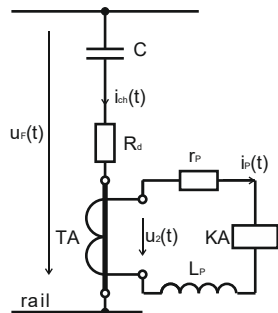


Fig. 5. Enabling a current relay into a  $R_dC$  protection link through the current transformer

Under a short circuit mode and, thus, when changing feeder voltage  $u_F(t)$ , there is an alternating current  $i_{ch}(t)$  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:

$$u_2(t) = M \frac{di_{ch}}{dt}, \quad (12)$$

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:

$$u_2(t) = r_p i_p(t) + L_p \frac{di_p}{dt}. \quad (13)$$

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

$$MC \frac{d}{dt} \left[ \frac{du_F}{dt} \left( 1 - e^{-t/\tau_{ch}} \right) \right] = r_p i_p(t) + L_p \frac{di_p}{dt}. \quad (14)$$

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:

$$\frac{M}{R_{arc}} \frac{du_F}{dt} e^{-t/\tau_{ch}} = r_p i_p(t) + L_p \frac{di_p}{dt}. \quad (15)$$

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

$$i_p(t) = \frac{M}{R_{arc} r_p} \frac{du_F}{dt} \Big|_{t < t_F} e^{-t/\tau_{ch}}. \quad (16)$$

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 ( $i_p(t) = 0$ ).

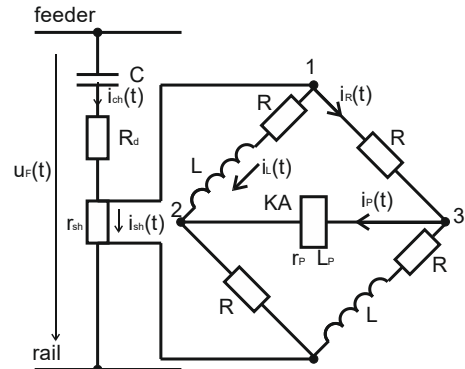


Fig. 6. Enabling a current relay through the bridge circuit

At a sharp change in  $u_F(t)$  current  $i_{ch}(t) \neq 0$ . And if the bridge's time constant  $T_M$  accepts a very small value in comparison with the time constant time of "protection link"  $T_{ch}$ , then at a small current through the relay  $i_p(t)$  the current through the shoulder of the bridge would equal:

$$i_R = i_L = \frac{r_{sh}}{2R} i_{sh}. \tag{17}$$

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

$$-Ri_L(t) - L \frac{di_L}{dt} + r_p i_p(t) + L_p \frac{di_p}{dt} + Ri_R(t) = 0$$

or, considering  $i_R = i_L$ :

$$L \frac{di_L}{dt} = r_p i_p(t) + L_p \frac{di_p}{dt}. \tag{18}$$

For a node with the shunt, Fig. 6:

$$i_{ch}(t) = i_M(t) + i_{sh}(t).$$

Accordingly, for node 1:

$$i_M(t) = i_R(t) + i_L(t) = 2i_L(t).$$

$$\text{Then } i_{ch}(t) = i_{sh}(t) + 2i_L(t),$$

hence

$$i_{sh}(t) = i_{ch}(t) - 2i_L(t). \tag{19}$$

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

$$\frac{2R}{r_{sh}} i_L = C \frac{du_F}{dt} \left( 1 - e^{-t/T_{ch}} \right) - 2i_L. \tag{20}$$

From this expression the current  $i_L$  equals:

$$i_L = \frac{Cr_{sh}}{2(R+r_{sh})} \frac{du_F}{dt} \left( 1 - e^{-t/T_{ch}} \right). \tag{21}$$

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

$$\frac{Lr_{sh}}{2(R+r_{sh})R_{arc}} \frac{du_F}{dt} e^{-t/T_{ch}} = r_p i_p(t) + L_p \frac{di_p}{dt}. \tag{22}$$

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

$$i_p(t) = \frac{Lr_{sh}}{2(R+r_{sh})R_{arc}r_p} \frac{du_F}{dt} \Big|_{t < T_F} e^{-t/T_{ch}}, \tag{23}$$

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  $du_F/dt$ , whose values under a short circuit mode are given in Table 1 for one of the sections of traction power supply at the "Prydniprovska 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].

Table 1

The speed of a feeder voltage drop under a short-circuit mode

High-speed breaker type	Value $du_F/dt$ , kV/s		
	Close SC	Medium SC	Far SC
2×VAB-43	3,214.0	1,254.4	586.4
2×VAB-49	2,722.5	712.5	476.5
VAB-206	2,182.8	–	621.5

When disabling during the time of current overload  $du_F/dt = 330$  kV/s. When starting EMF, the feeder's voltage is not changed.

To determine  $du_F/dt$  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  $\delta U_t$ , which is determined based on the relative difference between successive voltage extrema

$$\delta U_t = \frac{U_{\max} - U_{\min}}{U_{\text{nom}}} 100\%.$$

Hence, it follows that the maximum change in feeder voltage (according to this expression) is  $0.02 \times 3.3 = 0.066$  kV per second, which is considerably lower than  $du_F/dt$ , 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,  $U_{\max} = 4$  kV,  $U_{\min} = 2.7$  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  $du_F/dt$ . 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.

## 7. Discussion of results from studying the system of a traction power supply protection against short-circuit currents based on the new attribute

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  $du_F/dt$ . This magnitude varies depending on the distance between a short circuit site and the feeder with the considered  $u_F$  (Table 1); however, it is within the limits that characterize the short circuit, rather than some other process. The results of measurements (Table 1) indicate that a given method provides for a possibility to construct the systems of protection against short circuits, selective in terms of a distance to the circuit site. It is possible to configure such a system of

protection based on simple instrumental measurements of a power network and by selecting the parameters for protection schemes built on using a RC link as a sensing element. For the direct, transformer, and bridge circuits of relay protection such parameters are determined from (11), (16), or (23). These dependences show an almost unambiguous sensitivity of the examined protection schemes to such a characteristic short-circuit parameter as  $du_F/dt$ .

Structurally, the protection systems against short circuit that are built on the new attribute could use, as a sensor, low-power voltage sensors, whose size is defined only by the class of a network's voltage and, accordingly, by the strength of own insulation.

It should be noted that the emergency modes of short circuit were considered in the absence of electric rolling stock at the section of a traction power supply. The presence of electric locomotives and electric trains would affect the magnitude of a voltage drop and, as we predict, the speed of its change. Therefore, our next task is to undertake a research in the presence of electric rolling stock at sections. However, conducting field experiments involving short circuit at an actual section of the electrified railroad with electric locomotives is almost impossible. Mathematical modeling may come in handy. Input data for a mathematical model will be the parameters for an actual contact network with real electric locomotives.

## 8. Conclusions

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  $du_F/dt$  varies depending on the distance between a short circuit site and the feeder. The current  $i_{ch}(t)$  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”).

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