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Reliability Assessment of the Digital Relay Protection System

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Abstract

The quantitative assessment attempt of reliability indicators for the specific digital structure of the relay protection system by analogy with an assessment of similar digital systems in other industries is given in this work. The reliability models of system components are provided. The calculation sequence is shown. Calculation results give an optimistic evaluation of such protection creation and indicate the influence of the number of autonomous protection blocks reserved by the central protection and recovery time on the system availability.

Keywords: relay protection, digital system, reliability, availability.

1. Accepted Abbreviations

The list of the accepted abbreviations in article is included below,

- IED Intellectual Electronic Device executes control functions and protection of substation equipment according to the specified algorithms.
- SW Switch works with an Ethernet network, creating transmission channels of digital information.
- MU Merging Unit accepts input analog signals from CT/PT, creates digital synchronized time sampling of the measured values and transfers them to numerous IEDs on a substation local network.
- PT Potential Transformer measures analog voltage values in substation buses.
- CT Current Transformer measures analog current values in substation branches.
- PB Process Bus provides information exchange between connected IEDs.
- BC Breaker Controller controls the power circuit-breaker.
- PS Power Supply provides electronics with the electric power.
- CB Circuit Breaker is intended for power network switching.

2. Introduction

One of the most important characteristics of the relay protection is its reliability. Many researches have been done in this area. However, at the present a complete digital relay protection is developed and implemented, which is completely different from the traditional protection. Nevertheless, requirements for reliability remain the same.

Mainly, typical complete digital protection system integrates the merging units, timing sources, digital protective relays and communication devices. Both relay devices and signal outputs of measuring transformers are digital in such system. These digital signals are transmitted by the digital relay via the process bus that integrates interaction of digital blocks. Complete digital protection has more components, than a traditional one that should have a certain influence on its reliability.

Example of the similar protection is the protection system for a distribution network of 110/35/10 kV with digital converting of power system [1]. In this work, the structure and functioning of protection system on substation are considered in detail. Feature of structure offered by the authors is redundancy of the autonomous digital protection for a substation segment (the transformer, bus system section) by the centralized digital protection and control device. Thus, an important function of the substituting protection reservation for joining that should increase protection reliability in general. Other feature is redundancy failure circuit current measurement by its value determination on a segment under the first Kirchhoff's law.

It is necessary to estimate reliability of such a protection structure. As its hardware basis is made by the electronic digital elements, unlike traditional protection with estimates of unnecessary, false operations and failure in operation here it is possible to estimate the protection system availability to operation, as well as at similar electronic digital systems in other industries.

3. Protection Models of Functioning Reliability

Let's consider the reliability indicators on the example of the structural diagram for the protection and control module of bus section 35 kV (fig. 1, a) and of the transformer section (fig. 1, b). As it was noted above, autonomous protection (IEDA) failure has two consequences for the centralized protection (IEDC): 1) results of failure protection measurements can be used; 2) results of failure protection measurements cannot be used. In the second case, the first Kirchhoff's law determines the current of the protected element. Reliability of such definition is connected with all *m*

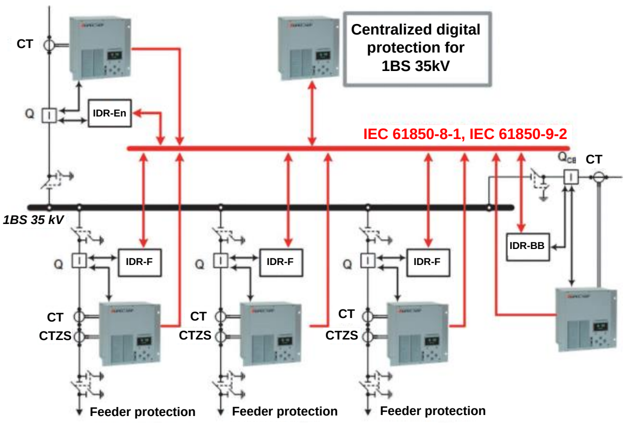

Fig. 1a. Block diagram of the protection module and control section for the bus 35 kV. IDR-interposing digital relay, F-feeder, En-entrance, BB-bus-tie breaker, CTZS-zero phase sequence current transformer.

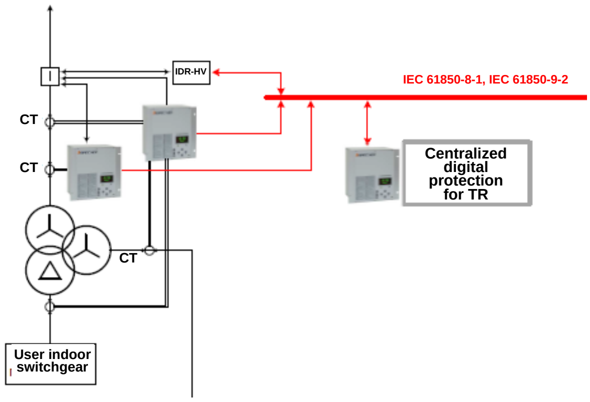

Fig. 1b. Block diagram of the protection and control module for the transformer section. IDR-interposing digital relay, HV-high voltage,

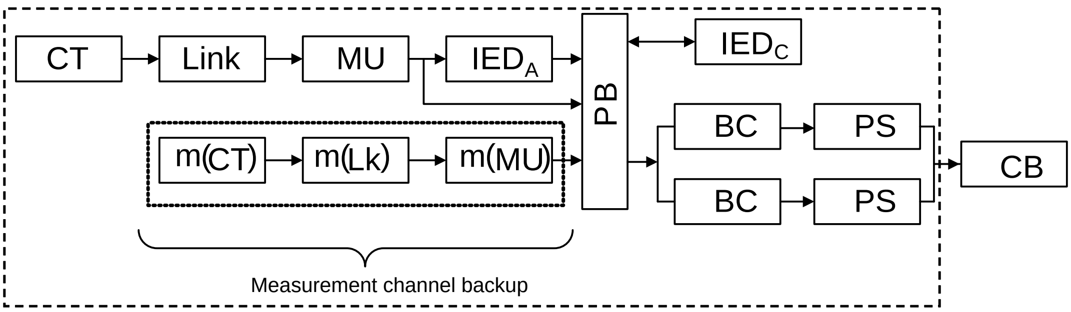

Fig. 2. Reliability block diagram of protection.

intact measuring channels. The general diagram of component communications for separate IEDA with the centralized IEDC, and measuring and executive channels is given in fig. 2 in terms of reliability. The breaker controller (BC) is entered behind the process bus (PB) and in the same place the power supply (PS) block as it is included consistently with all scheme is entered in terms of reliability.

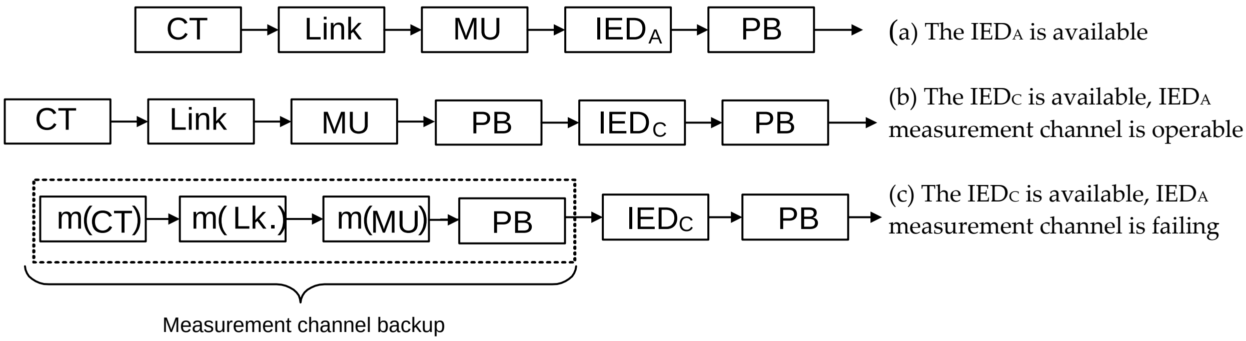

Fig. 3. Reliability block diagram for various component states.

Let's select structures of communications between components when protection functions in different situations. At operable autonomous protection, the model of its reliability is given in fig. 3a. It consists from series-connected components of the autonomous protection, and PB switch λ-s integrate with its λ-s on number of connections. Since equivalent failure rate is equal to the sum of element failure rate in series connection

$$\lambda_e = \sum_{i=1}^{n} \lambda_i, \quad (1)$$

and equivalent renewal rate is equal to mean value of separate indicators [2]

$$\mu_e = \lambda_e / \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}, \quad (2)$$

where n is component quantity in model chains, protection reliability indicators are defined for this case (fig. 3a) as:

model (a) $\lambda_{mdl\,A} = \lambda_{CT} + \lambda_{Lk} + \lambda_{MU} + \lambda_{IED} + \lambda_{PB}$,

$$\mu_{mdl\,A} = \lambda_{mdl\,A} / (\lambda_{CT}/\mu_{CT} + \lambda_{Lk}/\mu_{Lk} + \lambda_{MU}/\mu_{MU} + \lambda_{IED}/\mu_{IED} + \lambda_{PB}/\mu_{PB}). \quad (3)$$

At IEDA failure, but at its operational measurement channel (a case 1) the IEDC work model is reflected in fig. 3b. Its reliability indicators is

model (b) $\lambda_{mdl\,B} = \lambda_{CT} + \lambda_{Lk} + \lambda_{MU} + \lambda_{PB} + \lambda_{IED} + \lambda_{PB}$,

$$\mu_{mdl\,B} = \lambda_{mdl\,B} / \left(\frac{\lambda_{CT}}{\mu_{CT}} + \frac{\lambda_{Lk}}{\mu_{Lk}} + \frac{\lambda_{MU}}{\mu_{MU}} + \frac{\lambda_{PB}}{\mu_{PB}} + \frac{\lambda_{IED}}{\mu_{IED}} + \frac{\lambda_{PB}}{\mu_{PB}} \right). \quad (4)$$

In the second case, when the y measurement channel of the autonomous protection is fault, the IEDC work model corresponds fig. 3c and its reliability indicators is

model (c) $\lambda_{mdl\,C} = (\lambda_{CT} + \lambda_{Lk} + \lambda_{MU} + \lambda_{PB}) \cdot (m-1) + \lambda_{IED} + \lambda_{PB}$,

$$\mu_{mdl\,B} = \lambda_{mdl\,C} / \left[\left(\frac{\lambda_{CT}}{\mu_{CT}} + \frac{\lambda_{Lk}}{\mu_{Lk}} + \frac{\lambda_{MU}}{\mu_{MU}} + \frac{\lambda_{PB}}{\mu_{PB}} \right) \cdot (m-1) + \frac{\lambda_{IED}}{\mu_{IED}} + \frac{\lambda_{PB}}{\mu_{PB}} \right], \quad (5)$$

where m is a block number of the substation autonomous protection for section. m = 5 for bus section (fig. 1a) and m = 2 for transformer section (fig. 1b).

Let's consider a mutual work of **a** and **c** models for an availability quotient determining according to fig. 2 as the worst in reliability sense option.

The model of breaker circuit and PS block represents a redundant serial circuit, and its reliability indicators is

$$\lambda_{br.circ.} = \lambda_{BC} + \lambda_{PS}, \ \ \mu_{br.circ.} = \lambda_{br.circ.} / (\lambda_{BC}/\mu_{BC} + \lambda_{PS}/\mu_{PS}). \quad (6)$$

Then we define the Markov equations for reliability models of a protection complex **a** and **c** in state space **S1-S4** (fig. 4) [3]. Here possible statuses are defined by digit at **S**, i.e. 4 states are possible. **Up** at a letter points to up state of the corresponding model, and **Down** - disabled.

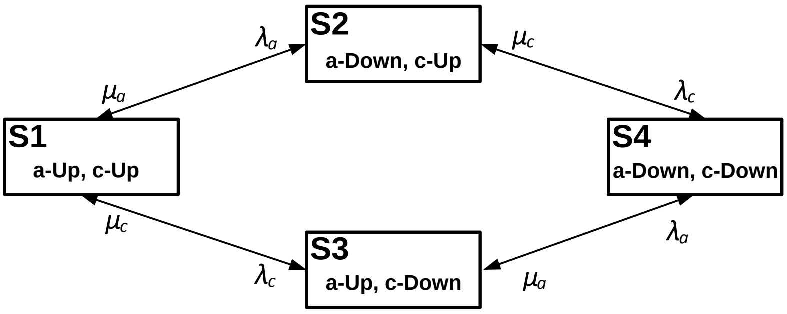

Fig. 4. State space diagram of models a and c

The corresponding state transition array given in (7).

$$\boldsymbol{T} = \begin{bmatrix} 1-(\lambda_a+\lambda_c) & \lambda_a & \lambda_c & 0 \\ \mu_a & 1-(\mu_a+\lambda_c) & 0 & \lambda_c \\ \mu_c & 0 & 1-(\mu_c+\lambda_a) & \lambda_a \\ 0 & \mu_c & \mu_a & 1-(\mu_a+\mu_c) \end{bmatrix}. \quad (7)$$

From Markov's principle that probabilities of boundary statuses do not change in further process of transition, i.e. ***TP* = *P***, where P_i is probability of *i*-th state, ***T*** is state transition array, the equation (7) is written as

$$\begin{bmatrix} -(\lambda_a+\lambda_c) & \mu_a & \mu_c & 0 \\ \lambda_a & -(\mu_a+\lambda_c) & 0 & \mu_c \\ \lambda_c & 0 & -(\mu_c+\lambda_a) & \mu_a \\ 0 & \lambda_c & \lambda_a & -(\mu_a+\mu_c) \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (8)$$

We replace the first equation on $\sum_{i=1}^{4} P_i = 1$, i.e. the sum of all states is equal to 1, and Markov's equation system takes the form (9) where the penultimate column reflects probabilities of the corresponding states,

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \lambda_a & -(\mu_a+\lambda_c) & 0 & \mu_c \\ \lambda_c & 0 & -(\mu_c+\lambda_a) & \mu_a \\ 0 & \lambda_c & \lambda_a & -(\mu_a+\mu_c) \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad (9)$$

hence the probabilities corresponding to the states are equal

$$P_1 = \frac{\mu_a\mu_c}{(\mu_a+\lambda_a)(\mu_c+\lambda_c)}, \quad (10)$$

$$P_2 = \frac{\lambda_a\mu_c}{(\mu_a+\lambda_a)(\mu_c+\lambda_c)}, \quad (11)$$

$$P_3 = \frac{\mu_a\lambda_c}{(\mu_a+\lambda_a)(\mu_c+\lambda_c)}, \quad (12)$$

$$P_4 = \frac{\lambda_a\lambda_c}{(\mu_a+\lambda_a)(\mu_b+c)}. \quad (13)$$

For the model of breaker controller and PS block, Markov's equation system is constructed similarly.

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \lambda_{BC} & -(\mu_{BC}+\lambda_{PS}) & 0 & \mu_{PS} \\ \lambda_{PS} & 0 & -(\mu_{PS}+\lambda_{BC}) & \mu_{BC} \\ 0 & \lambda_{PS} & \lambda_{BC} & -(\mu_{BC}+\mu_{PS}) \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad (14)$$

whence

$$P_1 = \frac{\mu_{BC}\mu_{PS}}{(\mu_{BC}+\lambda_{BC})(\mu_{PS}+\lambda_{PS})}, \quad (15)$$

$$P_2 = \frac{\lambda_{BC}\mu_{PS}}{(\mu_{BC}+\lambda_{BC})(\mu_{PS}+\lambda_{PS})}, \quad (16)$$

$$P_3 = \frac{\mu_{BC}\lambda_{PS}}{(\mu_{BC}+\lambda_{BC})(\mu_{PS}+\lambda_{PS})}, \quad (17)$$

$$P_4 = \frac{\lambda_{BC}\lambda_{PS}}{(\mu_{BC}+\lambda_{BC})(\mu_{PS}+\lambda_{PS})}\,. \quad (18)$$

Here, as well as in the previous case, the probability P_i is probability for the corresponding i-th state. The probability of the fourth state ($P_4^{(1)}$ in the first (13) and $P_4^{(2)}$ in the second (18) case) is necessary for determination of protection set availability at failure of all model components. Then protection set availability from the measuring transformers to trip signal output is defined as

$$A_{set} = \left(1 - P_4^{(1)}\right)\left(1 - P_4^{(2)}\right). \quad (19)$$

Since the centralized protection reserves m sets, the availability quotient A_{Mdl} of the entire protection module is equal

$$A_{Mdl} = (A_{set})^m\,. \quad (20)$$

4. Calculation of the Hardware Digital Protection Availability

The failure rate values of the components are taken as the average from several sources, since the statistics of the actual digital protection is still insufficient to determine such values, and they are taken according to the statistics of electronic equipment involved in industrial control processes [4–9]. The reliability indicators of individual model components on this basis are summarized in Table 1, where in the last column are these average values. For the process bus, λ is given in parentheses with regard to the switches.

Table 1

Component failure rates

Component	λ_i, year^{-1}	λ_i, year^{-1}	λ_i, year^{-1}	λ_i, year^{-1}	λ_i, year^{-1}	λ_i, year^{-1}	λ_e, year^{-1}
IED	0.00833	0.00100	0.00966	0.00667	0.00150	0.00330	0.005077
Software	0.00444						0.00444
Networks	0.00333	0.00300					0.003165
PT, CT	0.00200						0.002
Opt. PT, CT	0.00333			0.003			0.003165
Wire	0.00020					0.01000	0.0051
BC		0.01000	0.00333	0.00667	0.00077	0.02280	0.008714
PB		0.01000		0.01000			0.01(0.07)
PS			0.00912		0.03924		0.02418
Opt. fiber			0.00333			0.01000	0.006665
SW		0.01000	0.00869	0.02000		0.01000	0.01217
Server			0.06993				0.06993
Splitter			0.00947				0.00947
CB	0.01000			0.01000			0.01
MU	0.00200	0.01000			0.02545	0.00330	0.010188
Source	[4]	[5]	[6]	[7]	[8]	[9]	

The equivalent failure rates of the models (a and c) are summarized in Table 2, with μ_{2h} = 8760/2 = 4380 year^{-1}; μ_{48h} = 8760/48 = 182.5 year^{-1}. The failure rate of the breaker controller λ_{BC} = 0.008714 year^{-1}.

Regarding the intensity of restoration (repair or replacement of the failed component), in the known literature one of the following approaches is used, or the repair time is taken at 2 hours [11], or the replacement time is 48 hours [4-9]. In the latter case implies delivery if necessary to replace the failed module. One from cases, when all values of the components λ_i are taken equal to 0.0701 year^{-1}, is based on the time between failures of 125 thousand hours [11]. It can be seen from the first half of the Table 2, the transition from traditional devices and measurement circuits to optoelectronic slightly increases the failure rate. It is clear that an increase in the failure rates of the components to 0.0701 year^{-1} increases the equivalent intensities of the models by 3-4 times.

Table 3 shows the failure probability of the protection set $P_4^{(1)}$, the probability of failure of the switch controller set $P_4^{(2)}$ and the protection module availability A_{Mdl} for the 35 kV busbar section and for the transformer.

Table 2

Model reliability indicators

Model	$\lambda_{35кВ}$, year^{-1}	$\lambda_{тр.}$, year^{-1}	Model	$\lambda_{35кВ}$, year^{-1}	$\lambda_{тр.}$, year^{-1}
According to table 1, measurements by traditional transformers, wire communication			According to table 1, measurements by optotransformers, optical fiber communication		
a	0.092364	0.092364	**a**	0.095094	0.095094
c	0.511514	0.0249651	**c**	0.525164	0.255112
According to [11], measurements by traditional transformers, wire communication			According to [11], measurements by optotransformers, optical fiber communication		
a	0,3504	0,3504	**a**	0,3504	0,3504
c	1.5416	0.7007	**c**	1.5416	0.7007

From Table 3, it can be seen that, in general, the approach proposed in [1] ensures sufficient reliability of the digital protection operation.

Table 3

Module availability in various conditions

Measurements by traditional transformers, wire communication								
Para-metr	According to table 1				According to [11]			
	Bus 35 kV		Transformer		Bus 35 kV		Transformer	
	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h
$P_4^{(1)}$	2.46237E-09	1.41384E-06	1.20187E-09	6.91033E-07	2.81449E-08	1.60518E-05	1.27951E-08	7.32948E-06
$P_4^{(2)}$	1.09830E-11	6.32514E-09	1.09830E-11	6.32514E-09	2.56138E-10	1.47427E-07	2.56138E-10	1.47427E-07
A_{Mdl}	0.9(7)876	0.9(5)2899	0.9(8)757	0.9(5)860	0.9(6)858	0.9(4)190	0.9(7)739	0.9(4)850
Measurements by optotransformers, optical fiber communication								
Para-metr	According to table 1				According to [11]			
	Bus 35 kV		Transformer		Bus 35 kV		Transformer	
	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h	with μ^{-1}= 2 h	with μ^{-1}= 48 h
$P_4^{(1)}$	2.60279E-09	1.49434E-06	1.26445E-09	7.26985E-07	2.81449E-08	1.60518E-05	1.27951E-08	7.32948E-06
$P_4^{(2)}$	1.09830E-11	6.32514E-09	1.09830E-11	6.32514E-09	2.56138E-10	1.47427E-07	2.56138E-10	1.47427E-07
A_{Mdl}	0.9(7)869	0.9(5)249	0.9(8)745	0.9(5)853	0.9(6)858	0.9(4)190	0.9(7)739	0.9(4)850

A record of the form 0.9 (8) 437 indicates that after zero there are 8 nines followed by other digits, it's 437 in the example, i.e. the record would look like 0.99999999437 with a wide table column.

A certain decrease in the availability of its work causes an increase in the number of redundant devices (6 protection devices per 35 kV bus section) and recovery time (2 hours or 48 hours). However, even in the worst conditions, protection availability with redundancy is within acceptable limits. With the known repair rates and the famous formula, $1 - A_{Mdl} = \lambda/(\lambda + \mu)$ the failure rate of the protection module λ_M is defined as

$$\lambda_M = \frac{\mu_{rr}(1-A_{Mdl})}{A_{Mdl}}, \quad (21)$$

where μ_{rr} is specified repair rate. Then in the worst case, with λ_i = 0.0701 and μ_{48h} = 182.5 λ_M = 0.014784 for 35 kV buses and λ_M = 0.0027375 for a transformer. Here the number of autonomous protection blocks of a substation segment m is reflected more clearly.

5. Conclusions

In modern electric power industry, digital protection systems are widely used. One of important indicators is the reliability of its functioning. Its reliability assessment, in contrast to traditional relay protection, is performed by analogy with digital devices in other industries. In the given work, the reliability indicators of the original backup structure for a specific digital protection system were assessed, at that its hardware was assessed without taking into account the software reliability. The software reliability, unlike the technical part, does not wear out over time, but only improves. The study takes into account traditional measuring transformers with the transmission of information in analog form by wire and optoelectronic measuring transformers with information converting in digital form via optical fiber to the relay hall. The assessment did not include the circuit breaker reliability, as external to the protection component. Reliability is also not taken into account associated with communication traffic. Reliability indicators of individual protection components are mainly taken from similar electronic digital devices with built-in diagnostics, which is used in other industries, as there are not enough statistics on digital protection components.

Calculations of the availability for the considered protection system show that the proposed scheme with the stipulated conditions provides an acceptable level of the availability for its operation. It should be noted that the availability to some extent depends on the number of reserved sets m by the central protection and the recovery time t_{rr}. The measuring circuit redundancy has a small effect, worsening this indicator with an increasing m. It can be assumed that the accuracy of the current measurement, determined by the errors of all replacement sets, more affects on this parameter. The transition to fiber optic technology does not have any noticeable effect in terms of reliability. In general, the calculations show values of the availability for protection complex in the worst case at four nines after the point, which meets the requirements for relay protection.

6. Referances

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