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Functional reliability of protective devices

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Abstract
The paper presents the reliability parameters of the devices, used in relay protection systems and switching equipment. A methodology has been developed for evaluating the reliability of these devices in case of supplying a consumer according to a scheme with automatic engagement of the backup power supply. A mathematical model for evaluating the parameter of the flow of failures with respect to the load has been obtained, taking into account the reliability of the aforementioned devices in the described case. The mathematical model is compiled by applying the theory of planning experimental research.

Keywords: relay protection devices, switching equipment, reliability.

Introduction
Faults detection and supply of power from a backup source to the electrical load is performed by means of the relay protection (RP) and switching equipment (SE) devices [1,2].
An element of the electric circuit is the switching equipment, for which two groups of failures are possible. The first group comprises the static failures in a normal mode, which are not related to the devices for relay protection. These include failures due to overheating of the contacts, breaks in the insulation etc. The second group consists in failures to execute switching off/on in response to a supplied by the RP device pulse signal.

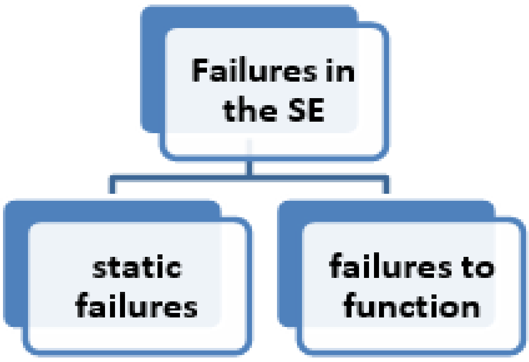

Fig.1. Failures in the switching equipment

The following types of failures are observed during the operation of the RP devices: failures to function, redundant and false activation [3,4,5,6].
The non-execution of pre-set functions during the operation of the RP devices is sometimes due to failures of their elements. These are the failures of the protection [7,8,9,10,11]. The failures to function refer to the cases when a pulse signal for switching off is supplied, but not executed. The redundant activation is defined as a failure or abnormal mode when the protection is not required to start functioning. False operation is observed when the protection starts functioning in the absence of a failure in the protected circuit.
Sometimes the redundant and false starts are summarized by the term incorrect operation [3].

This type of summarization is desirable when it is not needed to differentiate between the various types of protection failures.
Of essential importance in evaluating the reliability of the relay protection circuits is the quantitative assessment of both the failures to operate of the RP devices and the static failures of the switching equipment.
The aim of the paper is to develop a methodology for determining the reliability parameters of an electric circuit, taking into account the operation of both the relay protection and the switching equipment devices.

Reliability Parameters of The Rpa And Se Devices

In the analysis of the reliability of electrical circuits, the flow of failures to function of the RP and SE devices is used and considered as a common flow. The probability of non-performance (q_B) is defined as the ratio of the number of failures to function of both the relay protection devices (n_{P3A}) and the SE devices (n_{KA}) to the total number of commands, requiring operation (N):

$$q_B = \frac{nP3A + nKA}{N} \quad (1)$$

$$\omega_B = \alpha \, q_B , \quad (2)$$

The parameter of the flow of failures (wB) relative to the load node B depends on the probability of failure to start q_B of the RP and SE devices where a is the frequency of the commands for activation of the RP and SE devices, which, for an overhead power line (OPL) is determined by the equation

$$\alpha = k_H \, \omega_{W0} . l_W , \quad (3)$$

where k_H is the coefficient of increase of the number of commands for activation of the RP and SE devices due to the occurrence of unstable failures (assumed that k_H = 1.5 for medium voltage and k_H = 1.6 for high voltage); w_W - the parameter of the flow of failures for 1 km of the power line; l_W
- the length of the power line.
The parameter of the flow of failures (w_{W12}) and the average recovery time (t_{W12}) for the power lines W1 and W2, connected in parallel, are calculated by the expression

$$\omega_{W12} = \frac{1}{8760}\left[\omega_{W1}\,\omega_{W2}\,(\tau_{W1} + \tau_{W2}) + \omega_{W1}\nu_{W2}\eta_{W2} + \omega_{W2}\nu_{W1}\eta_{W1}\right] \quad (4)$$

$$\tau_{W12} = \frac{\omega_{W0}\tau_0 + \tau_{W2}) + \omega'\tau' + \omega''\tau''}{\omega_{W12}} \quad (5)$$

where ωW1 and ωW2 are the parameters of the failure flows of the power lines W1 and W2; τW1 and τW2 - the average time for recovery of the power lines W1 and W2; νW1 and νW2 - the frequency of the intentional shutdowns of the lines W1 and W2; γW1 and γW2 - the average time for servicing the power lines W1 and W2;

$$\tau_0 = \frac{\tau_{W1} \cdot \tau_{W2}}{\tau_{W1} + \tau_{W2}}, \quad \tau' = \frac{\tau_{W1} \cdot \eta_{W2}}{\tau_{W1} + \eta_{W2}}, \quad \tau'' = \frac{\tau_{W2} \cdot \eta_{W1}}{\tau_{W2} + \eta_{W1}}.$$

Methodology For Evaluating the Reliability of The Rp and Se Devices in Case of Power Supplying a Consumer According to A Scheme with Automatic Engaging of The Backup Power Source

When disconnecting a damaged power line and connecting a backup power supply to the calculation node of the load *B*, the elements, presented in Fig.2, are considered.

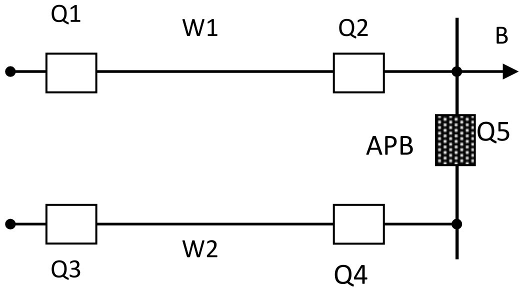

Fig.2: Power supplying of the consumer B according to the scheme with automatic switching of the backup source on

The busbar system is partitioned and a switch Q5 is installed between the two sections, equipped with an automatic transfer switch for activating the backup power supply. In normal mode each section is powered by its own line - W1 or W2 - and the transfer switch Q5 is switched off. In the event of afault on line W1, the following operations are performed:

- the relay protection of the circuit breaker Q1 gives a command for switching it off;
- the circuit breaker Q1 activates and disconnects W1 from the power supply;
- the relay protection of the circuit breaker Q2 gives a command to switch it off.
- the switch Q2 activates, disconnecting W1 from the load node B;
- In case of voltage loss of on the bus section, the automatic switch-on/off device activates and gives a command to turn the switch Q5 on; after that the power supply to the load B from the busbar section, connected to the power line W2, is restored.

Thus, several operations need to be performed to provide power to the load node. In each of them there may occur a reason for their non-execution.
The methodology for evaluating the reliability of the RP and SE devices in case of power supplying a consumer according to a scheme with automatic switching of the backup source on is implemented in the following sequence:

- The lengths l_{W1} and l_{W2}, the parameter of the flow of failures ω_{W10} and ω_{W20} for 1 km, the average recovery time τ_{W1} и andτ_{W2}, the intensity of the intentional shutdowns ν_{W10} and ν_{W20},, the average time of servicing γ_{W1} и γ_{W2} for the power lines W_1 и W_2, respectively, are set.
- The parameter of the flow of failures □$_W$ is calculated for each of the power lines by the equation

$\omega W1=\omega W10.lW1$; $\omega W2=\omega W20.lW2$;

- The intensity of the intentional shutdowns is determined $\nu W1=\nu W10.lW1$; $\nu W2=\nu W20.lW2$;

The intensity of failures to operate for the RP and SE devices is calculated by the equation (3).

- The probability of a failure to operate q_B for the RP and SE devices is found by means of the equation (1).
- The parameter of the flow of failures $\omega W12$ and the average recovery time for the connected in parallel power lines are calculated by the equations (4) and (5).
- The parameter of the flow of failures ω_B is determined in relation to the load node B, taking into account the reliability parameters of the RP and SE devices $\omega_B=\omega_{W12} + \omega_3 + \omega_4 + \omega_5$.

The application of the developed methodology and algorithm are presented in Fig.3.

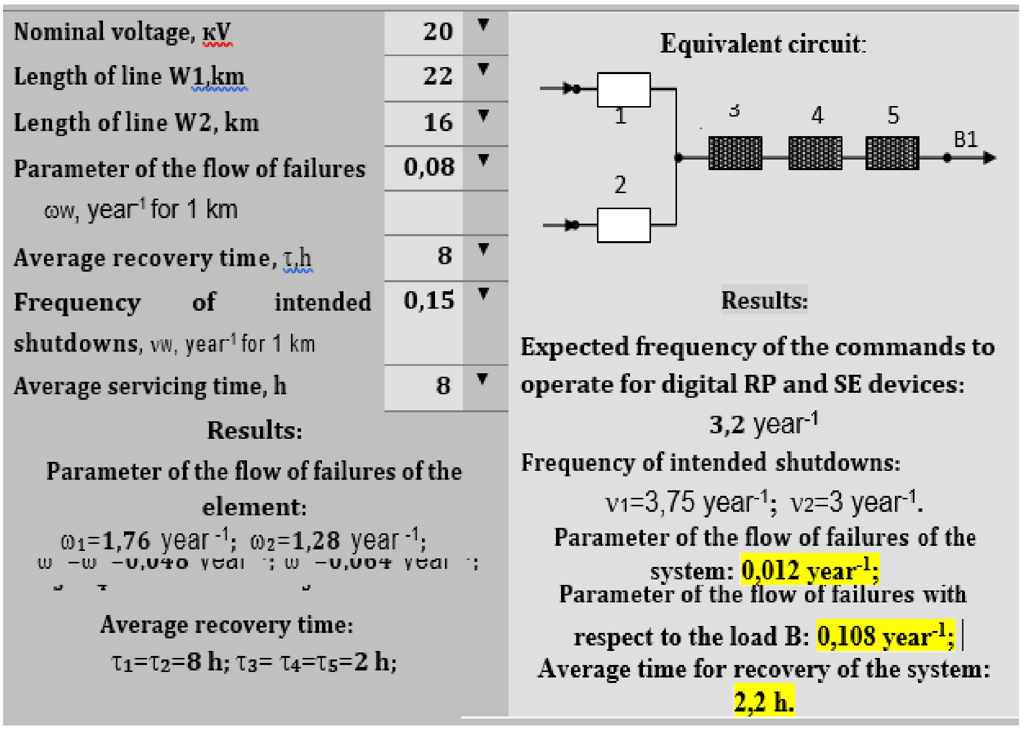

Fig. 3: Evaluation of the reliability of RP and SE devices in case of power supplying a consumer according to a scheme with automatic switching of the backup power source on

When calculating the reliability of RP and SE devices in case of power supplying a consumer according to a scheme with automatic switching of the backup source on, it turns out that 89% of the parameter of the flow of failures is due to these devices.

Obtaining a mathematical model for evaluating the parameter of the flow of failures with respect to the load, taking into account the reliability of the RP and SE devices in case of power supplying a consumer according to a scheme with automatic switching of the backup source on

The determination of the flow of failures with respect to the load is simplified if a mathematical model is built up, applying the theory of experimental design [12,13,14].

The evaluated parameter is the flow of failures relative to the load. This parameter depends on three independent influencing variables. A linear model of the first order is chosen for the three of them:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_{12} x_1 x_2 + a_{13} x_1 x_3 + a_{23} x_2 x_3 + a_{123} x_1 x_2 x_3, \quad (6)$$

where y is the evaluated parameter; x_1, x_2, x_3 - the influencing variables in a coded form; a_0, a_1, a_2, a_3, a_{12}, a_{13}, a_{23}, a_{123} - the coefficients of the regression equation.

The levels of the variables are denoted by 0, - 1, +1, respectively, whereas +1 is the upper level, 0 is the basic level, -1 - the lower level. The coding is done by:

$$x_j = \frac{\overline{x}_j - \overline{x}_{j0}}{y_j} \quad (7)$$

where x_j is a coded value of the variable; x_j - real value of the variable; x_{j0} real value of the basic level; y_j - interval of variance; j – number of the variable.

The following variables have their impact on the parameter of the flow of failures in relation to the load:

- x_1 – the length of the power line W1;
- x_2 – the length of the power line W2;
- x_3 - the reliability parameters of the electrical circuit, which are interdependent for the power lines with different rated voltages (20 kV and 110 kV).

The independent influencing variables and the levels of their variance for power lines with nominal voltage of 110 kV are given in Table 1, and the experiment design plan is shown in Table 2.

Table 1: Levels of Change of The Influencing Variables.

№	Characte-ristics	Length of the power line W1, km	Length of the power line W2, km	Parame-ter of the flow of failures ωw, $year^{-1}$ per 1 km
1.	Basic level($x_j = 0$)	60	60	0,08
2.	Interval of variance y_j	40	40	0,04
3.	Upper level ($x_j = +1$)	100	100	0,12
4.	Lower level ($x_j = -1$)	20	20	0,04
5.	Variable code	x_1	x_2	x_3

Table 2: Experiment Design Plan.

№	x_1	x_2	x_3	y
1	-1	-1	-1	0,165
2	+1	-1	-1	0,188
3	-1	+1	-1	0,188
4	+1	+1	-1	0,299
5	-1	-1	+1	0,173
6	+1	-1	+1	0,192
7	-1	+1	+1	0,192
8	+1	+1	+1	0,752

The average values of the studied parameter from the individual experiments are shown in Table

2. The check of the uniformity of dispersion of the performed measurements is carried out according to the Cochran's criterion:

$$g = \frac{S^2_{im}}{\sum_{i=1}^{m} S_i^2} \quad (8)$$

Where S^2_{in} is the maximum value of dispersion. The sum of the dispersions is 1,678 and the maximum dispersion - 0,496. Thence, g = 0.4962/1.678 = 0.146. The check of the uniformity of dispersion is performed by means of the Cochran's criterion. According to equation (8), the calculated value of g equals to 0.146. The critical value is $gkp =$ 0,6798 . Since $g < gkp$ the hypothesis of uniformity of the dispersions is accepted.
The coefficients of the regression are determined by:

$$a_i = \frac{1}{N}\sum_{i=1}^{N} Y_i X_{ij}, \quad (9)$$

where j is the current number of the variables; i - the current number of the experiment.
The coefficients of the regression equation are the following:

$$a_0=0.269;\quad a_1=0.089;\quad a_2=0.089;$$
$$a_3=0,059;\quad a_{12}=0,078;\quad a_{13}=0,055;\quad (10)$$
$$a_{23}=0,055;\quad a_{123}=0,056.$$

The following mathematical model is obtained:

$$y= 0,269 + 0,089.x_1 + 0,089.x_2 + + 0,059.x_3 + 0,078.x_1.x_2 + 0,055.x_1.x_3 - + 0,055.x_2.x_3 + 0,056.\ x_1.x_2.x_3. \quad (11)$$

The significance of the regression coefficient is assessed after building up the confidence interval, first determining the variance of the regression coefficients by the formula:

$$S_b^2 = \frac{S_y^2}{N} \quad (12)$$

The check of the significance of the regression coefficients is performed on the basis of the confidence interval. The confidence interval of the significant coefficients is determined by the expression:

$$\Delta a_j = \pm t_j S^2_{bi} \quad (13)$$

Where Δa_j is the confidence interval of the regression coefficient; t_j - Student's quantile at a 5% level of significance; S^2_b - dispersion of the regression coefficient.
If the absolute values of the regression

coefficient are greater than the absolute meanings of the confidence interval according to (13), then all regression coefficients are significant.
The check of the coefficient significance in the model is performed for a confidence interval
aj = ± 0.026. According to the applied Student's criterion, all coefficients in equation (11) are significant.

The adequacy of the mathematical model
(11) is checked by the Fisher's test,
$F=1,68 < F_{kp}=4,07$,
showing that the model is adequate. If the coded value of the influencing variables is put in the model (11), the same result for the parameter of the flow of failures in relation to the load is obtained, taking into account the reliability of the RP and SE devices in case of a power supply according to an automatic switching of a backup source on, as it is obtained when calculating it by means of the methodology, presented in Fig. 3.

Conclusions

- The developed methodology for determining the reliability parameters of an electrical circuit with automatic switching-on of the backup power supply takes into account the operation of both the devices for relay protection and the devices in the switching equipment.
- The parameter of the flow of failures of the RP and SE devices when power supplying a customer by a scheme with automatic switching-on of the backup source makes about 90% of the total parameter of the flow of failures in relation to the load node.
- The obtaining of an adequate mathematical model for determining the parameter of the flow of failures relative to the load, taking into account the reliability of the RP and SE devices in case of power supplying by a scheme with automatic switching-on of the backup power source, significantly simplifies the calculations.

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