Development of the logical part of the intellectual multi-parameter relay protection

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Abstract. The issues of increasing the sensitivity and reliability of multi-parameter relay protection by sharing more than one information feature (current module, voltage module and phase, active and reactive power) are considered. In this case, the response parameters of individual one-dimensional measuring fault detectors based on the accumulation of statistical data during simulation in the Matlab / Similink software package are determined. A method for combining the signals of one-dimensional measuring fault detectors to increase the sensitivity of protection is proposed. The reliability of the organization of the logical part of multi-parameter relay protection was estimated using the theory of Markov processes, the principles of "2 out of 3" and "1 out of 2".

1 Introduction

The introduction of modern electrical equipment, the development of renewable energy sources and the integration of active elements for regulating the parameters of the electric network affect the complexity of its configuration and operating modes, which leads to increased requirements for the sensitivity and reliability of relay protection devices (RP) [1]. Currently, there is a massive transition of RP devices to a microprocessor elemental base, which allows a radical change in the methods and approaches of organizing the logical part of RP, improving technical excellence.

Until now, the logic of modern relay protection has remained unchanged. It practically corresponds to traditional electromechanical RP devices. This leads to the underutilization of the potential and computational power of digital RP devices.

In contrast to electromechanical RP, in microprocessor RP, in addition to the hardware, there is a software part that implements the logic of the protection device. The hardware and software of a modern RP device have different failure and recovery processes, which affects the adequacy of the overall operational reliability assessment. There are many methods that estimate the hardware reliability of devices [2,3]. However, today there are no stable methods for calculating reliability that estimate the operation of the logical part of a RP device.

In western countries, there are now modern and trendy approaches for organizing the logical part of "Special Protection Schemes (SPS)" [4,19] and "Protection Redundancy" [5], which use redundancy to ensure high indicators of technical excellence of RP devices.

2 The relevance and purpose of the research

The generally accepted method of increasing the sensitivity of RP and the recognition of emergency conditions is to expand the number of observed parameters and is associated with the construction of multi-parameter RP [6-9,13,18]. However, it is difficult to organize decision-making procedures with a large number of observed parameters and there are no unambiguous implementation methods for that.

The closest approaches to the practical implementation of decision-making procedures for multi-parameter RP are the information approach [6–9] and statistical methods for recognizing modes [10–14]. The disadvantages of these approaches is the complicated principle of constructing multi-parameter RP through multi-dimensional set-point spaces of measuring fault detectors. By the increase of the dimension of more than two observed parameters, we can see a sharp and unjustified increase in the computational cost of implementing such protections, their significant increase in cost, the decrease in reliability and a possible limitation of practical use.

The aim of this work is to build multi-parameter RP with the union of individual measuring fault detectors (FD) through the logical part of RP to increase sensitivity and ensure the maximum possible reliability of RP devices. This implies the development of special algorithms that are different from those that are currently intuitively used and that provide the processing of information to a fuller extent.

To achieve this aim it is necessary to know the probabilistic characteristics of each FD that affect the system of random disturbances (signals). The

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organization of the logical part is based on the voting scheme, including the principles of "1 out of 2" and "2 out of 3", and the reliability of the proposed structure is calculated using the theory of Markov processes.

3 Statement of the task

To train relay protection and obtain statistics on normal and emergency modes, a simulation of a 220 kV network with adjacent overhead lines was carried out (Figure 1). Network simulation is implemented in the Matlab/Simulink software package [15].

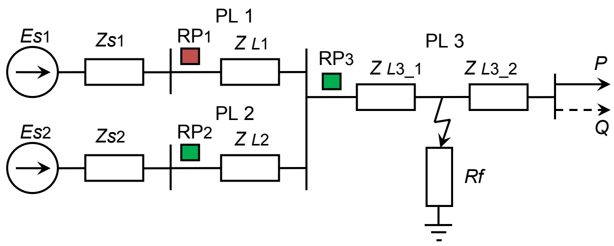

Fig. 1. The equivalent circuit of the observed section of the electric network 220 kV

The statistics on the modes were accumulated at the site of the observed RP_1, where 10,000 iterations of single-phase faults along overhead line 3 (VL3) were examined. One of the factors affecting the reduction in the probability of recognition of emergency conditions and the sensitivity of RP is the contact resistance at the site of fault (R_f). Therefore, the simulation of short circuits (SC) was carried out taking into account R_f. Thus, in the set-point space of RP, there is a region of intersection of normal and emergency modes, which leads to unrecognizability and complication of making the right decision on shutdown. Figure 2 shows an example implementation of a measurement FD based on measurements of current and voltage modules.

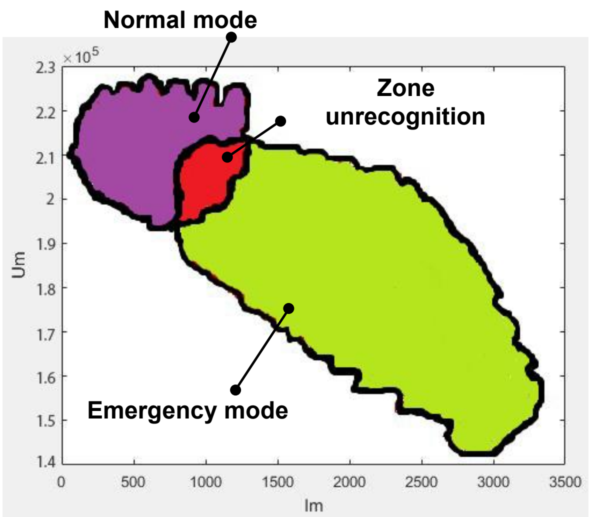

Fig. 2. Areas of normal and emergency modes of the current module and voltage module for simulated network

Presentation of the obtained statistics on the modes is possible in the form of graphs of the density of conditional probability, where the horizontal axis is the measured current in the normal and emergency modes in the place of the observed RP_1 (Figure 3). To simplify the calculation, the approximation of the probability by the normal distribution was carried out. The Bayesian criterion [14, 16] was used to make decisions.

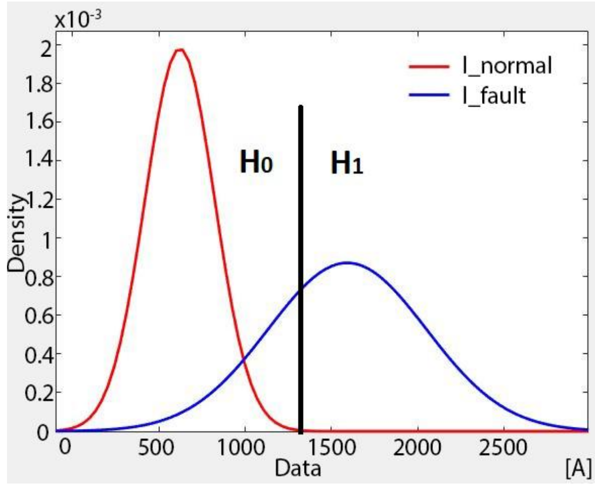

Fig. 3. Conditional Density Chart probabilities of normal permissible and current module emergency modes

To determine the response parameters, a solution of the two-hypothesis problem is proposed. It is accepted that the recognition problem has only two possible solutions and involves testing hypotheses H0 and H1: H0 - means that a measured signal of normal mode (zero) is formed at the output of the solving device (FD), H1 - at the output of the solving device (FD) a measured alarm signal is generated (unit) [11].

To increase the sensitivity of RP there was used the multidimensional approach. There were considered for example five separate one-dimensional FD: module current (Im); module voltage (Um); phase voltage (φ); active power (P); reactive power (Q). The Bayes criterion was used to calculate the settings and form two hypotheses task for each FD.

The total signal received from all FD and fed to the input of the logical part of the protection is a fixed sample of elementary discrete binary signals (0 or 1) observed at the same time: vector A ($A = A_{1i}, A_{2i}, \dots A_{pi}$, where i=1...n, n - the number of observed modes (iterations), p - the number of FD). To develop a decision rule for the logical part of RP, it is necessary to process the incoming logical signals in accordance with the results of preliminary simulation [11,16].

The formation of an algorithm for the recognition of RP of increased sensitivity is possible when the logical operation "OR" combines discrete signals - elements of vector A. The essence of the combination in this way is triggering the protection if it is recognized by at least one FD. Simulation showed that when using five FDs, the probability of recognition of emergency conditions increases by 67.5% in relation to the FD with the lowest probability of triggering. It also affects the overall increase in the sensitivity of the RP.

To estimate the sensitivity, an object characteristic was used - the dependence of the contact resistance on the distance of damage on the line at which RP provides short-circuit recognition (Figure 4) [17]. In accordance with the object characteristics, it is possible to establish at what contact resistances and remoteness from the substation there is a short circuit unrecognition by individual FD and the protection as a whole.

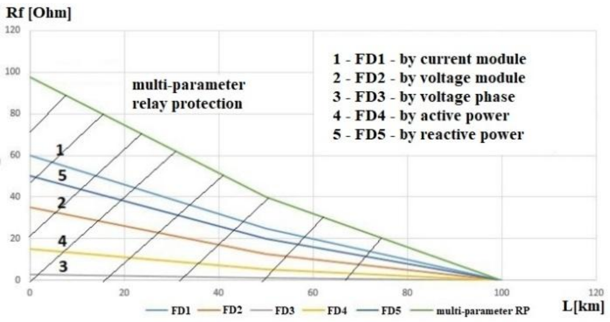

Fig. 4. Object characteristic of recognition of multi-parameter relay protection

For the circuit (Figure 1), simulation experiments were carried out at the beginning of the VL3 line (0 km), in the middle (50 km) and at the end (100 km). Figure 4 shows that multi-parameter RP provides an increase in sensitivity compared to the most sensitive FD, i.e. it recognizes emergency conditions for a given contact resistance.

4 The proposed method of organizing the logical part of multi-parameter relay protection

The proposed approach that increases the sensitivity of relay protection is focused on the functioning of RP in the conditions of absolute reliability of individual FDs. In practice there can occur failures, leading to failure of the relay protection in emergency mode or excessive operation in normal conditions. In practice, failures are possible that lead to failure of the RP in emergency mode or excessive triggering in normal conditions.

4.1 Principle "2 out of 3"

To organize the logical part (LP) of RP, it is proposed to use voting schemes with combining the logical signals of vector A on the principle of “2 out of 3” [18,19]. For this, three identical “OR” blocks are used, providing redundancy in information processing. The unstable operation of one of the logical elements does not affect the functioning of the RP, which ensures an increase in the necessary reliability. The structural diagram of the organization of the LP of the proposed algorithm is shown in Figure 5.

To estimate the reliability of the proposed structure, there was used Markov model of transitions from one state to another. It should be emphasized that the reliability estimation was carried out indirectly due to the fact that the source of the failure and recovery rate was the data from the published literature on the reliability of special protection schemes [19].

Table 1 shows the values of the failure rate and recovery, where: λ_{fd} - the failure rate for detecting the failure of a logical element; λ_{fnd} - failure rate for not detecting a logic element failure; μ_{rd} - recovery rate for detecting the failure of a logical element per year; μ_{rnd} - recovery rate for not detecting a logic element failure per year.

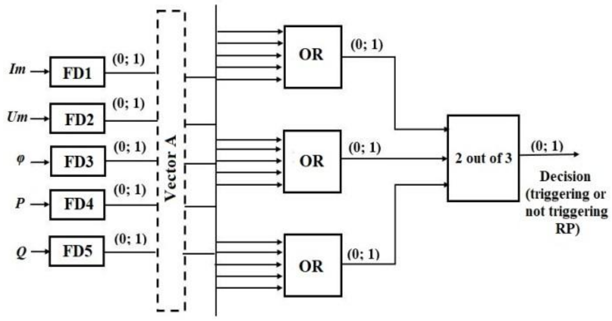

Fig. 5. The structural diagram of the organization of the LP when combining the totality of the signals of individual FD with the principle of "2 out of 3"

Table 1. Failure and recovery rates

Parameter	Values
λ_{fd}	0.018 (once every 25 years)
λ_{fnd}	0.026 (once every 35 years)
μ_{rd}	1095 (8 hours a year)
μ_{rnd}	4 (test 6 months)

4.2 Reliability estimation of the proposed structure using the theory of Markov processes

The Markov model of states of the proposed organization scheme of the logical part is shown in Figure 6. For this model, five states are identified: 1 - all three logical elements work without fail; 2 - one of the logical elements has failed and a failure has been detected; 3 - one of the logical elements has failed and no failure has been detected; 4 - two of the logic elements failed and a failure was detected; 5 - two of the logic elements failed and no failure was detected.

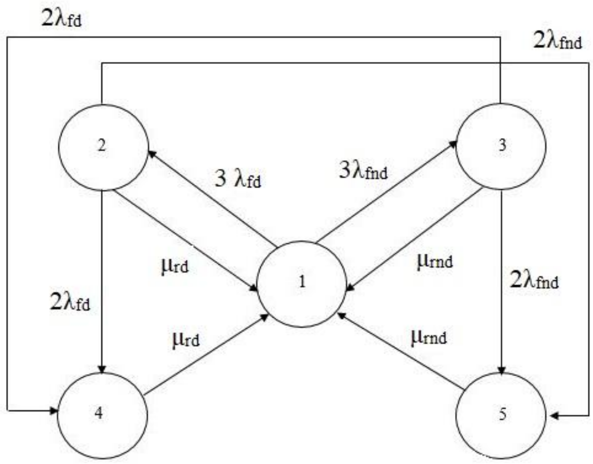

Fig. 6. Markov model of the state of the proposed organization of the logical part

For the Markov model, the determination of the probabilities $P_i(t)$ (i = 1,2, ... n) is performed by solving the Kolmogorov-Champen system of differential equations. Due to the fact that in the theory of random processes it was proved that homogeneous Markov processes without absorbing states (states from which there is no way out) have a stationary mode that occurs at sufficiently large times (t → ∞), we obtain a system of algebraic equations for determining the reliability exponents [20]. Thus, the following system of equations is formed:

$$
\begin{aligned}
&-\ 3\lambda_{fd} + 3\lambda_{fnd}\ P_1 + \mu_{rd}P_2 + \mu_{rnd}P_3 + \\
&\quad \mu_{rd}P_4 + +\mu_{rnd}P_5 = 0; \\
&-(2\lambda_{fd} + 2\lambda_{fnd} + \mu_{rd})P_2 + 3\lambda_{fd}P_1 = 0; \\
&-(2\lambda_{fd} + 2\lambda_{fnd} + \mu_{rnd})P_3 + 3\lambda_{fnd}P_1 = 0; \\
&-\mu_{rd}P_4 + 2\lambda_{fd}P_2 + 2\lambda_{fd}P_3 = 0; \\
&-\mu_{rnd}P_5 + 2\lambda_{fnd}P_2 + 2\lambda_{fnd}P_3 = 0; \\
&P_1 + P_2 + P_3 + P_4 + P_5 = 1.
\end{aligned} \tag{1}
$$

So that the resulting system is not degenerate, a rationing condition is added $\sum_{i=1}^{n} P_i$.

Further, after summing the first and last equations, we obtain the following system:

$$
\begin{aligned}
&1 -\ 3\lambda_{fd} + 3\lambda_{fnd}\ \ P_1 +\ 1 + \mu_{rd}\ P_2 + \\
&+\ 1 + \mu_{rnd}\ P_3 +\ 1 + \mu_{rd}\ P_4 + (1 + \mu_{rnd})P_5 = \\
&1; \\
&-(2\lambda_{fd} + 2\lambda_{fnd} + \mu_{rd})P_2 + 3\lambda_{fd}P_1 = 0; \\
&-(2\lambda_{fd} + 2\lambda_{fnd} + \mu_{rnd})P_3 + 3\lambda_{fnd}P_1 = 0; \\
&-\mu_{rd}P_4 + 2\lambda_{fd}P_2 + 2\lambda_{fd}P_3 = 0; \\
&-\mu_{rnd}P_5 + 2\lambda_{fnd}P_2 + 2\lambda_{fnd}P_3 = 0.
\end{aligned} \tag{2}
$$

By the substitution of numerical values of the probability of each state, we can calculate the following:

$$
\begin{pmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{pmatrix} =
\begin{pmatrix}
0.868 & 1096 & 5 & 1096 & 5 \\
0.054 & -1095.088 & 0 & 0 & 0 \\
0.078 & 0 & -4.06 & 0 & 0 \\
0 & 0.036 & 0,02 & -1095 & 0 \\
0 & 0.052 & 0.04 & 0 & -4
\end{pmatrix}^{-1}
\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} =
\begin{pmatrix} 0,981 \\ 4,8374 \cdot 10^{-5} \\ 0,0187 \\ 6,1696 \cdot 10^{-6} \\ 2,4396 \cdot 10^{-4} \end{pmatrix}. \tag{3}
$$

Calculations show that when using the "2 out of 3" principle, a sufficiently high reliability is obtained and the protection will work in 98.1% of cases without fail.

4.3 An additional increase in the reliability of the logic part of the relay protection

In order to further increase reliability, the “1 out of 2” principle was used. It does not affect the achieved maximum sensitivity and does not violate the essence of combining information from FDs [5,18]. This approach implies the redundancy of the system of logical elements, united by the principle of “2 out of 3” and supplemented by the logic “1 out of 2” (Figure 7).

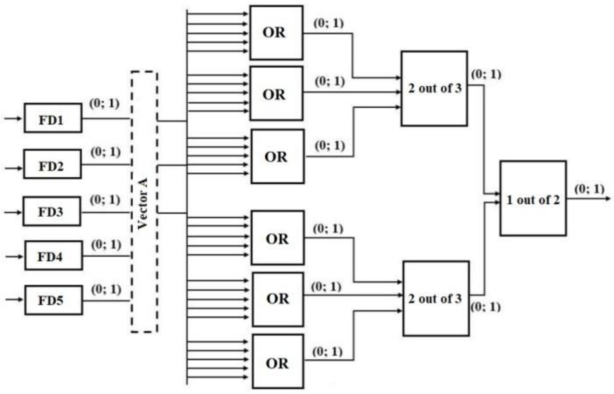

Fig. 7. The structural diagram of the organization of the logical part of the principle of "1 of 2"

To evaluate such a system, the failure model of non-renewable systems, parallel connection of elements was used. Suppose that both systems have the same characteristics and that their probability of failure-free operation *p(t)* is equal to the probability obtained by the calculation of the Markov model - $p_1(t) = p_2(t)$ = 98.1% = 0.981 p.u. According to this, the failure probability is equal to *q(t)* = 1-*p(t),* where $q_1(t) = q_2(t)$ = 1-0.981 = 0.019p.u. With a parallel connection of elements, the probability of failure of the system is:

$$q(t) = \prod_{i=1}^{n} q_i\ t\ . \tag{4}$$

Based on the expression (4), we find that the probability of failure of the system of the logical part based on the principle of “1 out of 2” is *q(t)* = 0.000361. According to this, the probability of uptime is *p(t)* = 1-*q(t)* = 1-0.000361 = 0.999639. The organization of a logical organ supplemented by the principle of “1 out of 2” leads to a probability of correct operation of up to 99.96%. Thus, an additional increase in reliability is provided, without violating the achieved level of sensitivity and recognition of emergency conditions.

Conclusion

1. An approach to organizing the logical part of multi-parameter relay protection in order to improve sensitivity and reliability has been proposed.
2. To determine the response parameters of various FD, a statistical approach was used with the formation of distribution laws, based on the application of the Bayes criterion and detuning from all admissible modes.
3. The method of organizing the logical part of the relay protection is based on the operation "OR" in order to increase the sensitivity and recognition of emergency modes by relay protection.
4. The organization of the relay protection logic by the principles of “2 out of 3” and “1 out of 2” ensured

high reliability of the device, which was evaluated using the theory of Markov processes.

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