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Method of automated synthesis of the logic part of relay protection device which increases its sensitivity

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Abstract. Often there are such modes of operation in the electric power systems where standard methods of relay protection and automation become insufficiently effective. For example, such modes are typical for electric networks with distributed generation and renewable energy sources. Today, the task of developing new digital relay protection methods, that have high technical excellence and fully comply with the requirements of IEC 61850, is relevant. A method of organizing the logical part of multiparameter relay protection is proposed, which improves its sensitivity. The method is based on the criterion of minimizing the average risk of decision making and solving the task of abstract synthesis of automata theory. The application of the proposed method is considered on the example of multidimensional relay protection with five measuring fault detectors and the implementation of simulation models in the Matlab/Simulink software package.

1. Introduction

The massive transition from electromechanical elemental base to microprocessor base creates the prerequisites for the development of new methods of organization of relay protection (RP) and improving the indicators of technical excellence. Despite the fact that digital technologies are becoming more common, as well as at substations [1,2], the principles of RP, methods of its organization remain largely borrowed from electromechanical relays.

Modern electrical networks are complex, multi-loop systems that include a large number of different power sources and new active elements. The continuous development of new technologies (renewable energy sources, FACTS, etc.), the introduction of digital technology, lead to the complication of the modes of energy systems and increase the requirements for sensitivity of RP.

2. The relevance of the logic synthesis of relay protection devices

The problem of recognizability of emergency modes, in most cases, exists in long-distance protection. The reasons for this is the similarity of short-circuit currents (SC) for the reserved transformers with load currents, surge magnetizing currents, starting and self-starting currents of powerful electric motors and switching currents of capacitor batteries. Also, the sensitivity is affected by the presence of transient resistances at the place of fault and low voltage levels of symmetrical components on the tires at the place of installation of RP for remote fault [3].

There are known methods for improving the recognizability of emergency modes based on the use of multidimensional (multiparameter) RP [4–10]. However, the achievement of high sensitivity by
these methods is associated with the implementation of complex procedures for comparing the areas of normal and emergency modes of the multidimensional space of signs of relay protection.

It should be noted, that the approaches for organizing the logical part of the “Special Protection Schemes” (SPS) [11-13] and “Protection Redundancy” [14,15] use redundancy to ensure high technical excellence and can be used to increase the sensitivity of multidimensional (multiparameter) RP.

3. Purpose of the research
Increasing the sensitivity of relay protection is possible by sharing more than one parameter (current value, voltage amplitude, ..., etc.) as a source of information [4-9]. For this purpose, several one-dimensional measuring fault detectors (FD) are implemented in the RP terminal. However, the method of combining the signals of individual FDs is important, as it increases the recognizability of emergency modes. Moreover, due to the combination of signals at the outputs of individual FDs and the effect of multidimensionality, an increase in the sensitivity of RP can be achieved.

Thus, the purpose of the research is to develop an automated method of organizing a logical part (LP) of relay protection for combining the results of the functioning of individual FDs in the interest of increasing the sensitivity of multidimensional RP.

To implement the proposed technical solution, a statistical approach is used, including the formation of the distribution laws of the triggering characteristics of relay protection, the criterion for minimizing the average risk of decision making, as well as methods of discrete mathematics and automata theory.

4. Statement of the task
The means of accumulating statistical data for the “training” of relay protection are simulation models of power facilities [4]. To implement a new digital RP method based on a statistical approach, it is necessary to know the probabilistic characteristics of each FD separately [7]. For this purpose, a simulation model of an adjacent overhead transmission power line (PL 2) of 220 kV is considered, taking into account the placement of the relay protection at the beginning of PL1 (Figure 1). The model is implemented in Matlab/Simulink software package (Figure 2).

Figure 1. The equivalent circuit of the simulated network segment.
Table 1. Parameters of model elements.

| Parameter | Fixed | Interval |
|-----------|-------|----------|
| $U_{nom}$ (kV) | 220 | $R_1^{1/2}$ (Ohm/km) | 0.13 ($\pm$ 0.1) |
| $L_1$ (km) | 100 | $R_0^{1/2}$ (Ohm/km) | 0.28 ($\pm$ 0.1) |
| $L_2$ (km) | 80 | $X_1^{1/2}$ (Ohm/km) | 0.43 ($\pm$ 0.2) |
| $b_{1/2}^{1/2}$ (S/ km) | $2.58 \times 10^{-6}$ | $X_0^{1/2}$ (Ohm/km) | 0.1328 ($\pm$ 0.2) |
| $b_{0/2}^{1/2}$ (S/ km) | $1.78 \times 10^{-6}$ | $R_{r1}^{1/2}$ (Ohm) | 9.3 ($\pm$ 1) |
| $U_{nom}$ (kV) | 220 | $R_{d1}^{1/2}$ (Ohm) | 5.7 ($\pm$ 1) |

In the simulation, there were conducted 10 000 iterations of single-phase short circuits along the adjacent power line (PL2).

Protection RP must be sensitive when single-phase faults appear in the reserve zone (zone PL2). The simulation was carried out taking into account five one-dimensional measuring fault detectors of the investigated RP: FD1 - by the absolute value of the current; FD2 - by the absolute value of the voltage; FD3 - in phase between current and voltage; FD4 - by reactive power; FD5 - by active power. To display the measurements of RP for each FD, we plotted the probability density graphs of the distribution of the parameters of the modes (Figure 3). In these graphs, the horizontal axes are measurements of the observed parameters of the FDs in normal and emergency modes in the reserve zone (adjacent line PL2). Depending on the sensitivity of the FDs, the degree of intersection of the probability densities of normal and emergency modes is more or less. This determines the ability to recognize the current mode of RP.

5. Proposed method
To combine signals from various FDs, it is proposed to reduce the task of recognizing the emergency modes of each FD to a binary (two-hypothetical) statistical task [7–10]. At the same time, two hypotheses are tested: H0 - means that the measured signal typical for the normal mode has arrived at the FD input (logical “0” at the output); H1 - means that the measured signal typical for the emergency mode has arrived at the FD input (logical “1” at the output).
5.1. Determination of the parameters of the relay protection for the areas of normal and emergency modes

In order to ensure the correct solution of the binary task, it is necessary to set the appropriate values, separating the areas of normal and emergency modes. The main requirement in determining the settings values of PR is to prevent protection operation in all possible normal modes (Figure 3) [7-10]. Bayesian decision criterion allows us to separate from all acceptable modes [16]. For each FD, hypotheses were defined and tested. If the measurement falls within the range of acceptable modes, then the hypothesis $H_0$ is accepted. If the measurement falls within the range of emergency modes (short circuit fact), then hypothesis $H_1$ is accepted.

The choice of triggering parameters allows us to estimate the sensitivity level of each FD. In this case, $p_1$ is the probability of RP triggering at fault. The probability of not triggering at fault is $q_1=1-p_1$. According to the main requirement, when choosing settings values (not allowing RP triggering in normal modes), the probability of operation of RP: under the hypothesis $H_0$ is equal to $p_0=0$ and the probability of not triggering under the hypothesis of $H_0$ is equal to $q_0=1$. The probabilities of recognition of each FD with the given set values are summarized in Table 2.

![Figure 3. Determination of the setting values for the Bayesian decision criterion: (a) FD1 - by absolute value of current, (b) FD2 - by absolute value of voltage, (c) FD3 - by phase with current and voltage, (d) FD4 - by reactive power, (e) FD5 - by active power](image)

| Measuring fault detectors       | Parameter       | $p_1$ (p.u.) | $p_1$ (%) | $q_1$ (p.u.) | $q_1$ (%) |
|---------------------------------|-----------------|--------------|-----------|--------------|-----------|
| FD1 - by absolute value of current | $I_m$           | 0.8801       | 88.01     | 0.1199       | 11.99     |
| FD2 - by absolute value of voltage | $U_m$           | 0.9893       | 98.93     | 0.0107       | 1.07      |
| FD3 - by phase with current and voltage | $\phi$         | 0.02         | 2         | 0.98         | 98        |
| FD4 - by reactive power         | $Q$             | 0.0799       | 7.99      | 0.9201       | 92.01     |
| FD5 - by active power           | $P$             | 0.7358       | 73.58     | 0.2642       | 26.42     |

5.2. The method of combining the signals of the FD to increase the sensitivity of relay protection

The proposed method of organizing LP is based on the application of automata theory and includes solving the abstract synthesis task of a finite discrete automaton [17]. It is advisable to organize the LP of two segments. The first includes $2^p-1$ logical elements ($p$-number of FD). The second segment is represented by one logical element "OR". The operations of the elements of the first segment include...
logical negation ("NOT") and logical conjunction ("AND"). Each logical element of the first segment includes a set of direct and inverse inputs. For five FDs, their number is $2^5-1=31$, instead of $2^5=32$, because there is no "AND" logical element with all inverse inputs. The input combination of only zeros from FD1-FD5 exists only in normal modes, so the corresponding logic element in Figure 4 is absent.

The number of possible combinations of binary FD signals is $2^5$. For the case of using five FDs, the number of combinations is 32. Combinations can have an arbitrary number of "0" and "1". For example, the first combination is a combination of all "0", the last one is all "1", and the remaining all possible combinations are "0" and "1" (Table 3).

Suppose that $X_i=(X_{1i}, X_{2i},..., X_{ki},..., X_{pi})$ is a vector representing a set of binary random variables ("0" or "1") from the output of each FD. Depending on the logical element in the first segment, the corresponding signals from the sample of the $X_i$ vector will first be transformed (inverted), and then combined ("AND" logical conjunction). The output signals of the logical elements of the first segment are combined within the second segment according to the "OR" rule. The vector of the output signals of the first segment is displayed as $Y_i=(y_1, y_2,.., y_k,.., y_m)$, where $i=1,..,n$, $k=1..m$, $n$ is the number of observed modes (iterations), $m=2^5-1$ - the number of logical elements of the first segment. The output of the second segment gives the expected signal, which is necessary for making a decision - "1" or "0" (triggering or not triggering of RP). The block diagram of the logical part of the combination of signals that implements the algorithm is shown in Figure 4.

**Table 3.** Possible combinations of binary signals from FD.

| Combination number | FD1 - by absolute value of current | FD2 - by absolute value of voltage | FD3 - by phase with current and voltage | FD4 - by reactive power | FD5 - by active power |
|--------------------|-----------------------------------|-----------------------------------|----------------------------------------|-------------------------|-----------------------|
| 1                  | 0                                 | 0                                 | 0                                      | 0                       | 0                     |
| 2                  | 0                                 | 0                                 | 0                                      | 0                       | 1                     |
| 3                  | 0                                 | 0                                 | 0                                      | 1                       | 0                     |
| 4                  | 0                                 | 0                                 | 0                                      | 1                       | 1                     |
| ...                | ...                               | ...                               | ...                                    | ...                     | ...                   |
| 31                 | 1                                 | 1                                 | 1                                      | 1                       | 0                     |
| 32                 | 1                                 | 1                                 | 1                                      | 1                       | 1                     |
Figure 4. Block diagram of the logical part of the combination of signals from FD.

An analysis of the operation of the logical part (Figure. 4) showed that with such an organization of the RP logic, the response of at least one measuring FD, which is rebuilt from the normal mode, is triggered by RP devices. In this case, the sensitivity of RP device will be determined by the highest sensitivity from the set of FD1 - FD5. Additionally, it is possible to increase reliability. By varying between the operating conditions of FD, it is possible to achieve the required performance indicators and adapt the operation of RP devices to the schematic-mode situation.

Conclusion
1. The new method of organizing the logical part of multiparameter relay protection with the aim of improving sensitivity is proposed. The method is based on the results of simulation, Bayes criteria and automata theory.
2. The considered example of multidimensional relay protection with five measuring fault detectors showed that when applying the developed method of combining binary signals, the probability of detecting a short circuit with a transition resistance in the reserve zone of RP increased from 98.93% to 99.99% compared to the most sensitive measuring fault detector.
3. The proposed method provided an increase in the recognizability of short-circuit in the reserve protection zone from 2% to 99.99% compared with the traditional combination of binary signals by the logical conjunction “AND”.
4. Model experiments substantiated the use of multidimensionality in order to improve the sensitivity of RP and confirmed the positive effect of the new approach in organizing the logical part of multidimensional RP.

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