

## Computer-based strategy for fault location and service restoration in electric power distribution systems

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### ABSTRACT

This paper presents a method for solution the problem of optimization of the process of faulted section localization, with the simultaneous re-routing of supply to customers. The criterion function in the model is the expected cost to the customer as a result of the break in supply together with the costs of the fault localization process. To solve the problem the original algorithm based on the branch and bound method was worked out. The original methods for the division of the solution set and the evaluation of the lower limits of the criterion function for the subset of solutions were developed. A computer program was designed to support utility control engineers, offering advice on fault location and restoration switching strategies.

### KEY WORDS

Power distribution systems, Fault location, Service restoration, Energy Services

### 1. INTRODUCTION

Electrical power distribution systems of medium voltage in Poland are badly equipped in terms of switching devices and anti-disturbance automation. There are no fault-localizers which allow quick and precise fault localization. In those systems with branched structures the localization of the faulted section of the line is rather time consuming. For this reason the economic losses caused during searching for the faulted section of a line form a significant part of the total costs of economic losses incurred by customers due to breaks in supply caused by permanent faults on the system [5, 6].

The paper presents a solution of the problem of optimization of the strategy of section localization of a single permanent fault in branched power distribution systems of medium voltage with the simultaneous re-routing of supply to customers. It is estimated [5, 6] that the optimization of the localization process results in a decrease in the economic losses incurred by customers because of a break in supply in excess of 20 percent compared with the losses incurred while using the present methods of operational practice.

The mathematical model of the process of faulted section localization is the basis on which the optimum strategy of localization is defined [6]. The chosen criterion of the decision was the expected value of the economic loss costs

incurred by customers due to breaks in supply together with the costs of localization.

In [6] it was stated that the process of faulted section localization in power distribution systems can be interpreted as a controlled Markov chain. It was also proved that an optimum strategy of localization existed.

The difficulty in finding the optimum strategy consists in that the decisive function cannot be explained in a simple analytical way. Finally the problem of the faulted section localization is a combinatorial problem connected with the search for the optimum values of discrete variables.

### 2. FORMULATION OF THE PROBLEM

Solution of the decisive process in the uncertainty conditions, which exist in assigning the optimum decision, can be presented by graph called the decisive tree [1]. The decision theory uses the graphs in which the nodes and branches have their separate, conventional meanings.

The choice nodes (drawn as squares) represent the possibilities of the choice of a given decision by a decisive. The chance nodes (drawn as circles) represent the random character of the decision result. The decision result depends entirely on the random factors. The branches which come out of the choice nodes define the possible decision. On the other hand, the branches which come out of the chance nodes, called decision branches, define the results of the decisions made earlier. The results can be random or determined. The chance nodes appear in a particular sequences after the choice nodes. The sequences are completed when all decision possibilities have been considered. In the completed tree, the blocks (drawn as triangles) represent the results of the decision sequence. In the fault localization process the choice nodes project the system state  $x/$  (Figs 1 and 2).

The state  $x$ , of a system in the process of fault localization is described by the vector

$$\mathbf{x}_i^T = [z_i^T, \theta_i^T, \pi_i^T, b_i]$$

The particular components of a vector  $x$ , are defined as follows.

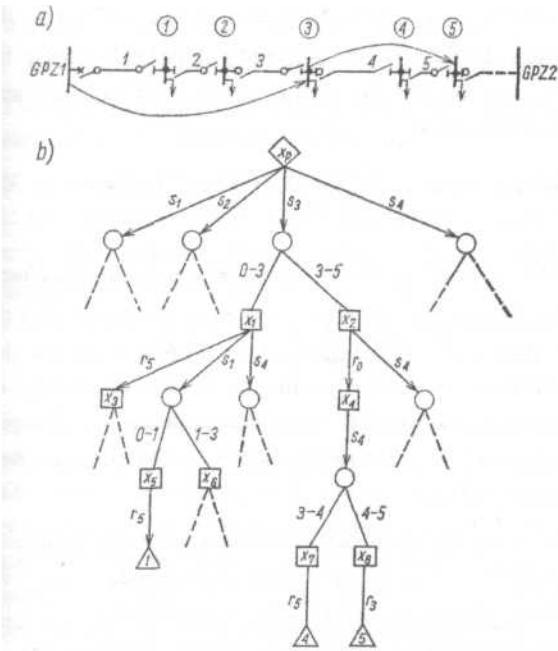


Fig. 1. An example of a decisive tree for a process of fault localization in a cable network: a) sample network; b) decisive tree

Component  $z_i^T$  :

$$z_i^T = [z_1^{(i)}, z_2^{(i)}, \dots, z_k^{(i)}, \dots, z_M^{(i)}] \quad (2)$$

is a vector which shows the state of the circuit switch in the state  $x_i$  of the system where:

$$z_k^{(i)} = \begin{cases} 0 & \text{if the circuit } k \text{ is open in state } x_i, \\ 1 & \text{if the circuit } k \text{ is closed in state } x_i. \end{cases} \quad (3)$$

Component  $\theta_i^T$  :

$$\theta_i^T = [\tau_1^{(i)}, \tau_2^{(i)}, \dots, \tau_j^{(i)}, \dots, \tau_w^{(i)}] \quad (4)$$

is the vector in which component  $T >$  defines the time from the instant of the last switch-off of the node  $y$ , to the moment when the system goes to the state  $x_j$ . After the supply to node  $v$ , is switched on, the component  $\tau_j^{(i)}$  becomes equal to 0.

Component  $\pi_i^T$  :

$$\pi_i^T = [p_1^{(i)}, p_2^{(i)}, \dots, p_j^{(i)}, \dots, p_N^{(i)}] \quad (5)$$

is the vector of the current probabilities of the fault of the particular system branches.

Parameter  $b_i$  defines the position of the working group which localizes the faulted section and is equal to the number of the node in which the group is situated.

Depending on the system state  $x_i$  in the decisive node, generally one of two decisive situations takes place:

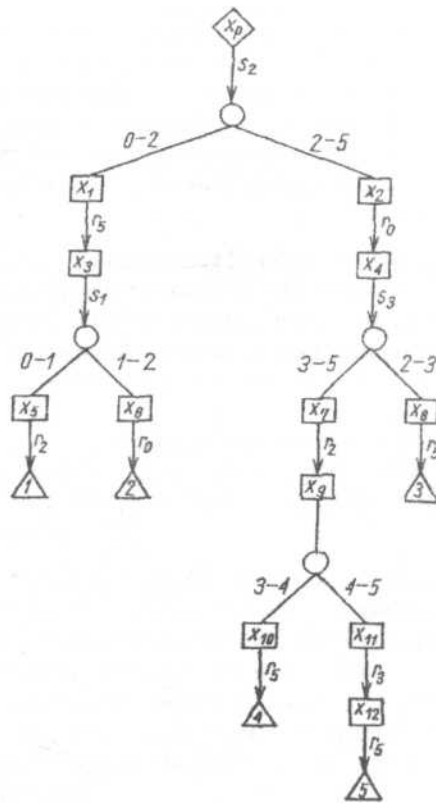


Fig. 2. An example of a strategy of faulty section localization for a network from Fig. 1

a) a decision should be made whether the chosen customers are to be switched on to a reserve supply and a choice made of the variant  $r$ , of the reserve supply from the permissible switching set;

b) a decision and choice should be made of the specified checking  $s_l$  in the system from the permissible checking set

To the branches of the results  $s_l^0$  (meaning that the result of checking is negative) and  $s_l^1$  (meaning that the result of checking is positive) the relevant probabilities  $p_{sl}^0$  and  $p_{sl}^1$  of negative and positive checking results are related by:

$$P_{s_l^0} + P_{s_l^1} = 1 \quad (6)$$

The blocks of results correspond with the final states  $\omega_i, i = 1, \dots, N$  in the localization process and they show the fault of the elements with the indicators / in the system.

The strategy  $\delta^*$  (the sequence of decisions) of the faulted section localization which minimizes the expected value of the total costs of the economic losses  $K$  incurred by the customers as a result of loss of supply should be stated:

$$E[K(\delta^*)] = \min_{\delta \in C} \{E[K(\delta)]\} \quad (7)$$

where  $C$  is the set of permissible strategies.

As the problem of the optimization of the faulted section localization strategy in power distribution systems is large, it is not practicable to build and examine the whole decisive tree of the faulted section localization during an acceptable time, even when a computer is used. Hence methods of building a reduced decisive tree and carrying out reviews and calculations only along chosen branches should be sought.

The concept of the branch and bound method [2] results in a gradual division of the solution set according to the chosen feature and the evaluation of the lower limits of the criterion function for those subsets of solutions (Fig. 3).

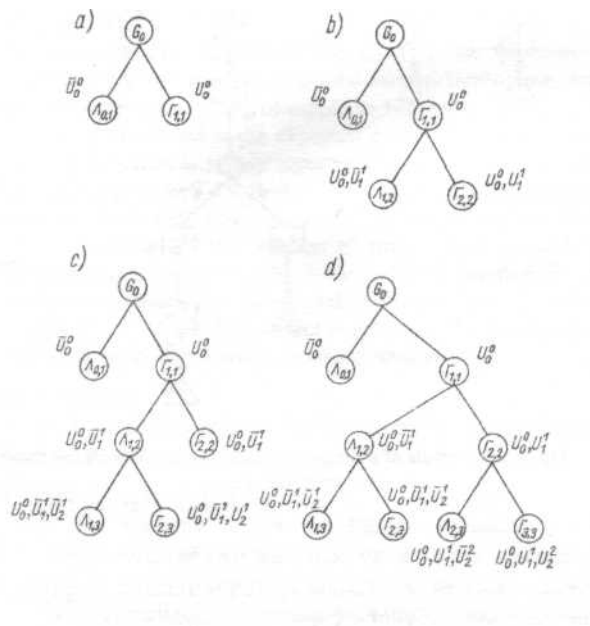


Fig. 3. An example of four successive steps of division of a set of solutions  $G_0$ :  $U_{ij}$  - feature of division of subset  $G_{ij}$

### 3. DIVISION OF THE SOLUTION SET

In the case, where the solution set  $G_0$  is the set of paths in the decisive graph, a certain branch (control)  $U$  can be seen and can be regarded as a feature of division of the solution set. The paths can be divided into those which include that particular branch and those which do not include it. In this way two subsets of the solutions are obtained: the strategies set including control (decision)  $U$  and the strategies set not including this control. The feature of the division  $U_{ij}$  of the subset  $G_{ij}$  is indicated in the following so as to obtain the biggest increase in the value of the lower limit of the criterion function for one of the subsets created by the division of the subset  $G_{ij}$ . The division of sets into subsets is carried out according to the following algorithm.

Using dynamic programming the optimum partial strategies  $\delta^*$  are established. These are the strategies with the minimum cost which lead to the statement that the branch  $i$  has been faulted in the system. The alternative partial strategies are also established. These are to have the least cost from of

all strategies which begin with controls other than the optimal strategy  $\delta_i^*$ . To choose the control  $U_p$  being the feature of the division of the set  $G_0$  the following value should be stated

$$h(U_p) = \max_{\delta_i^* \in C_{ij}} \{ \sum [W^i(\delta_i) - W^i(\delta_i^*)] p_i \} \quad (8)$$

and the control  $U_p$  which fulfills this condition is defined.

In the expression:  $W^i(\delta_i)$  - the costs associated with the fact that for a particular faulted section  $i$  of the line localization is made according to the partial strategy  $\langle \delta_i \rangle$ ;  $C_{ij}$  - the set of partial strategies including the strategies starting with the control  $U_j$ ;  $p_i$  - the probability of a fault in the branch  $i$ .

The control  $U_p$  is regarded as a feature of the set  $G_0$  division and the following solution subsets are defined:  $\Gamma_{1,1}$  - the subset of strategies starting with the control  $U_p$ ;  $A_{0,1}$  - the subset of strategies starting with controls other than  $U_p$ .

Other divisions are carried out in the similar way. At each stage of the division, the lower limit of the criterion function is evaluated for the particular subset  $G_{ij}$  and to further division should first be taken the subset with the smallest lower limit.

### 4. CALCULATION OF LOWER LIMITS OF THE CRITERION FUNCTION

The lower limit of the function of the expected costs of the losses in the section localization process is defined as follows

$$\inf(G_0) = \sum_{i=1}^N p_i W^i(\delta_i^*) \quad (9)$$

The lower limit of the function  $E[K(\delta)]$  for the set  $G_0$  of all admissible localization strategies is indicated by the symbol  $\inf(G_0)$ .

The lower limits of the criterion function for the subsets  $\Gamma_{k,1}$  and  $A_{k-1,1}$  obtained by the division of the subset  $G_{k-1,1}$  according to the feature of the division  $U_{k-1,1}$  is indicated using the dependence

$$\inf(\Gamma_{k,1}) = \sum_{i=1}^N p_i W^i(\delta_i^*(\Gamma_{k,1})), \quad (10)$$

and

$$\inf(A_{k-1,1}) = \inf(G_{k-1,1}) + \Delta(A_{k-1,1}) \quad (11)$$

where  $\Delta(A_{k-1,1})$  - the increase of the value of the criterion function connected with the switch-off from the set  $A_{k-1,1}$  the optimal partial strategies  $\delta_j^*$ .

## 5. THE CONSTRUCTION OF THE OPTIMUM PARTIAL STRATEGIES

The optimum partial strategies are indicated using the rules of dynamic programming (Fig. 4).

If, as a result of the  $s$  control stages carried out according to the partial strategy  $\delta_i$  any of the admissible final states  $w_i \in \Omega_i$  is obtained, then the states  $x$  are excluded from further considerations if

$$W(x_p, x) \geq \min_{\delta_i \in C^i} \{W^i(\delta_i)\} \quad (12)$$

where:  $\omega_i$  - the final state in the fault searching process in which the branch  $i$  of the system was defined as faulted;  $\Omega_i$  - the set of admissible final states  $\omega_i$ ,  $W(x_p, x)$  - the cost of transition of the system from the specified initial state  $X_p$  into the state  $x$ ;  $\delta_i$  - the partial strategy which leads to the statement that the branch  $i$  of the system is faulted;  $C_i$  - the set of admissible partial strategies  $\delta_i$ .

In the decisive tree the paths which connect the root of the tree (state  $x_p$ ) with the final states  $w_i \in \Omega_i$  correspond with the partial strategies  $\delta_i$ .

Calculations are completed after exclusion of all the nodes. The path of the smallest cost of transition of the system from the initial state  $x_p$  to the final state  $w_i \in \Omega_i$

shows the optimum sequence of the controls  $\{u^*_{j}\}$  which defines the optimum partial strategy  $\delta_i = \{u^*_{j}\}$ . In the same way the alternative strategies  $\delta_i$  are defined. From the admissible controls set  $U(x_p)$  only the control  $U^*_{j}$  should be extracted. The procedure presented above may then be followed.

## 6. ALGORITHMS

From of a solution of a model of a localization process of a faulted section in a medium voltage distribution system, presented in the sections 3 to 5, three variants of algorithms of optimization of this process were worked out.

An exact optimization algorithm leads to a globally optimum solution in the set of permissible solutions. At each stage of the division of the solution set the lower limits of the criterion function of all valid solution subsets and the costs of solutions already reached are compared. The results of optimization of schemes of fault localization for particular lines may be determined at an earlier stage by a regional dispatcher center.

An approximate optimization algorithm is now described. The procedure of searching for the optimum strategy of fault localization may be considerably shortened if at each stage of division the subset with the smallest lower limit among the subsets at a given stage is taken. The local minimum is then achieved.

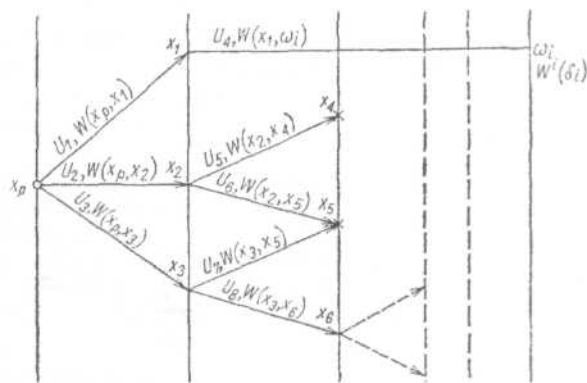


Fig. 4. An example of construction of the optimum partial strategy  $S^*$

Its accuracy can be estimated according to rules presented in the work [6]. The results of approximate optimization can be utilized in the same way as the results of exact optimization.

The on-line localization control algorithm is adapted so that it may be used in a conversational mode. Optimization is made in an approximate way. The maximum error of an approximate solution is estimated. On-line control of the fault localization process is possible in the case where local dispatcher centers are provided with computer workstations with the necessary information on system configuration.

## 7. COMPUTATIONAL EXAMPLE

Calculations were made for a small part of a cable municipal distribution system of medium voltage presented in Fig. 5. The structure of the system makes possible multi-side supplying of the customers. A line with a diversified structure of customers was considered (small industry, commercial, residential). The time characteristics of economic loss costs incurred by the customers because of a break in supply are estimated on the basis of data taken from [7]. Calculations were made according to an exact optimization algorithm of the process of fault localization. The economic losses incurred by the customers during localization of the faulted line section were calculated according to other three different methods: (i) exploitational (normally used in practice), (ii) maximum expected switched load and (iii) maximum effectiveness utilization of a time of localization [3].

It is assumed that:

1. Faulted sections are identified by measurement of insulation resistance.
2. The main supply point has no associated permanent service personnel.
3. The line circuit breaker is not provided with remote control from the local dispatcher center.
4. Other main circuit switches in the system are not equipped with protective automation and remote control.
5. The line is not provided with short-circuit current indicators..

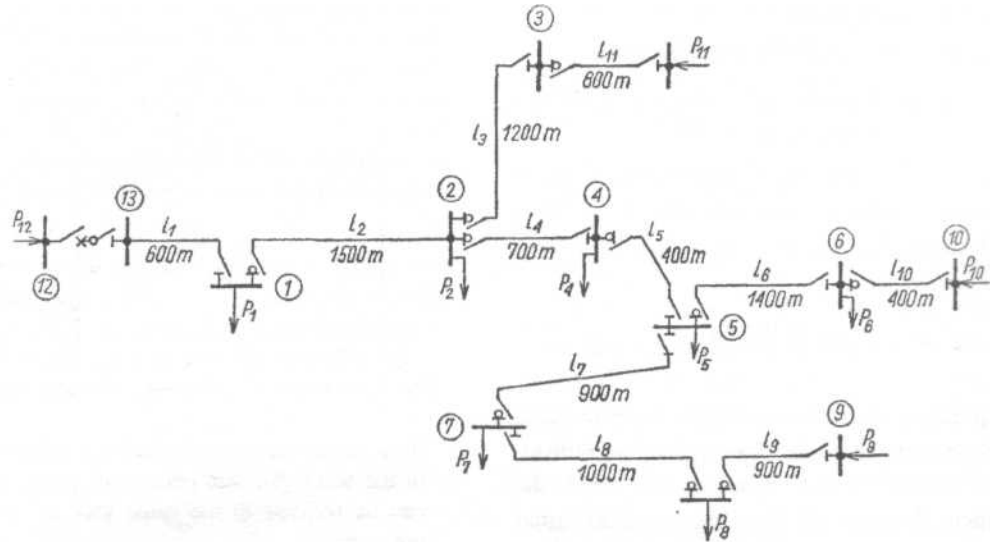


Fig. 5. A sample medium voltage cable urban network

6. After division of the line in a given MV/LV substation into  $n$  parts, all the parts are checked successively.
7. To simplify calculations it is assumed that faults may only occur on sections of a cable line.

The division of the set of solutions into subsets is shown in Fig. 6. The optimum solution is the solution which creates subset  $T/\Lambda$ .

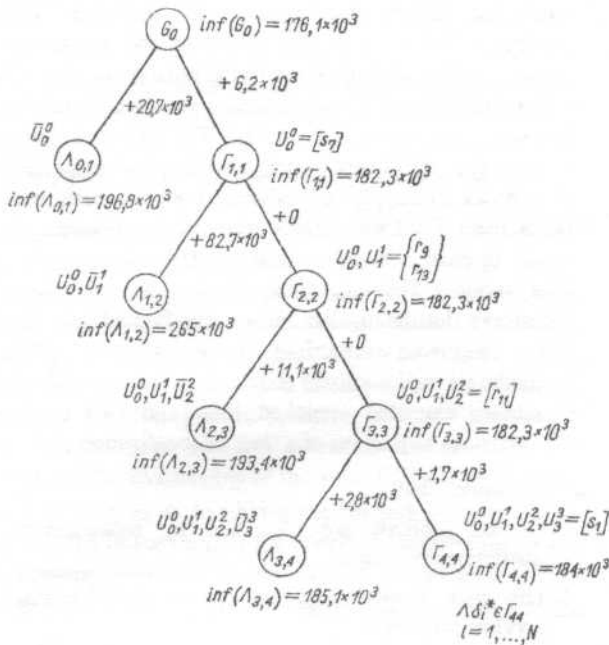


Fig. 6. Division of a set of solutions GQ for a network from Fig. 5

To compare the different strategies of fault localization the expected costs of economic losses incurred by customers were also calculated for other methods. The results of calculations are presented in Table 1.

Table 1. Results of calculations of economic losses during localization of the faulty line section according to different methods

Strategy	Expected value of economic losses	Difference compared to optimal strategy	Relative difference compared to optimal strategy
-	c. u.	c. u.	%
Optimal	184 000	0	-
Exploitational	240 300	56 300	30
Maximum expected load switched on	241 100	57 100	31
Maximum effectiveness utilization of a time of localization	309 000	125 000	68

## 8 CONCLUSIONS

The theoretical considerations and results of the computational example show that in power distribution systems with branched structures it is possible to optimize the process of fault localization with simultaneous re-routing of supply to customers. Optimization is carried out to achieve the minimum economic losses incurred by customers because of loss of supply. It is seen from the computational example that the result of optimization, in the form of decreasing economic losses incurred by customers, may reach 20 - 40 % compared with the costs resulting from present methods of localization.

The developed algorithms can be utilized for optimization of the fault localization and reconfiguration process according to different criteria than the expected costs of economic losses incurred by customers because of loss of supply, e.g. the amount of non-delivered energy. The calculations of the different variants according to the presented method also permit the investigation of the

effectiveness and appropriateness of provision in distribution systems of anti-disturbance automation, switching apparatus, fault-localizers and short-circuit current indicators. The computer program is designed to support utility control engineers, offering advice on fault location and restoration switching strategies.

## 9 ACKNOWLEDGMENTS

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## BIOGRAPHY



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