Fault Section Estimation in Electric Power Plants and Electrical Substations using Fault Trees and Neural Networks with Radial Basis Function

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***Abstract* — In the work reliability modeling with fault trees is implemented in fault section estimation. Finding faulted sections and faulted elements are defined as mathematical abstractions from set theory point of view. Minimal path sets and minimal cut sets are used as patterns in learning process of neural network with back propagation of error (BPNN) and neural network with radial basis function (RBNN).**

Keywords: fault section estimation; reliability; fault trees; minimal path set; minimal cut set; set theory; back propagation; neural network with radial basis function.

I. INTRODUCTION

Fast restoration of transmission and distribution networks during post fault network conditions is one of methods for improvement of the reliable power supply. First step for such process is fast and accurate fault section estimation. Sometimes, during short circuit and earth fault process, there are malfunctions of circuit breakers and/or relay protections and as consequence local faults become major failure. Expert systems usage will facilitate such event analysis and proper operating instructions selection for every particular post fault condition.

The first expert system for dispatchers support was developed by Fukui [1] in 1986 and is written in PROLOG. In 1989 Chan [2] implement neural networks in SCADA alarms. In 1994 Yang [3] published research results for fault section estimation with data from circuit breakers and relay protections. In 1995 Yang [4] used a decision tree as a first step for neural network development based on logical functions. In 2001 Bi [5] used a neural network with radial basis function for fault section estimation. In 2007 Sissoko [6] used a neural network with radial basis function for IEEE 11 bus system fault section estimation. In [7] and [8] Kezunovic and Zhang used event trees for distance protections operation analysis in a small electrical system. In 2008 Meng [9] implemented chaos theory in radial basis neural network learning process.

In all cited articles patterns for neural network education were developed by experts. In this paper fault trees will be used for automatic patterns generation. The article is divided in two parts. In the first part minimal cut sets and minimal path sets usage will be discussed for patterns development. In the second part automatically generated patterns will be used in BPNN and RBNN.

II. PATTERNS DEVELOPMENT USING FAULT TREES MODEL

In [10, 11, 12] path V is defined as a set of elements, which ensure connection between the input and the output of one system. Minimal path T is a path which does not contain other paths. Cut set K [10, 11, 12] is a set of elements whose simultaneous failure leads to the system failure, which is independent of the states of the other components. Minimal cut set C is a cut set that does not contain another cut set.

Let $A = \{x_1,\ldots, x_n\}$ is a set of sections, circuit breakers and relay protections. Let $B = \{V_1,\ldots, V_m\}$ is a set of m paths V, where:

$$V_m = \{\{x_a,\ldots,x_b\} \text{ - path: } 1 \le a < b \le n,\ x_n \in A\} \quad (1)$$

Let $D=\{T_1,\ldots,T_i\}$ is a set of minimal paths T, where:

$$T_i = \{\{x_c,\ldots,x_d\} \text{ – minimal path: } 1 \le c < d \le n,\ x_n \in A\ \} \quad (2)$$

Let $E = \{K_1,\ldots, K_t\}$ is a cut set and $F = \{C_1,\ldots, C_p\}$ is a set of minimal cut sets, where:

$$K_t = \{\{x_e,\ldots,x_f\} \text{ – cut set: } 1 \le e < f \le n,\ x_n \in A\} \quad (3)$$

$$C_p = \{\{x_g,\ldots,x_h\} \text{ – minimal cut set: } 1 \le g < h \le n,\ x_n \in A\} \quad (4)$$

Let $G = \{M_1,\ldots,M_l\}$ is complement of D in B, where M are non-minimal paths:

$$G = B \setminus D =\{M_l\text{: } (M_l \in B) \wedge (M_l \notin D)\} \quad (5)$$

According [10, 11, 12, 13] for every non – minimal path M exist a minimal path T, where $T \subset M$:

$$\forall M\,,\ \exists T : T \subset M \tag{6}$$

In a similar way we can define set H = {$N_1,\ldots,N_s$} of non-minimal cut sets as complement of F in E:

$$H = E \setminus F = \{N_s : (N_s \in E) \wedge (N_s \notin F)\} \tag{7}$$

In [10, 11, 12] mathematically is proved that for every non-minimal cut set N exist a minimal cut set C, where C ⊂ N:

$$\forall N\,,\ \exists C : C \subset N \tag{8}$$

Fault section estimation process can be divided to two major tasks – finding faulted section and finding a faulted relay or a circuit breaker. Furthermore, we can assume “Fault tree analysis” method as acceptable and also minimal paths sets and minimal cut sets are necessary and sufficient condition for expression of all possible fault scenarios, according to basic events which are implemented in a reliability model.

This approach was used for development of a reliability model for a small electric distribution system (Figure 1). In the electrical diagram consumers are 6 kV pumps, which are supplied from three independent power sources. The distribution system consists of six sections, where the first and the second ones are supplied from a transformer T1, the third and the fourth - from a transformer T2, the fifth and the sixth from a transformer T3. There are section breakers between all odd and even sections – between the first, the third and the fifth and between the second, the fourth and the sixth sections. For model simplicity every section supplies only two pumps.

The developed fault trees reliability model was implemented in SAPHIRE IDE. According to [10] (p. 255-256) and [12] (p. 138-139) the fault tree was divided to three branches:

A. Fault in branches, which are between a power source node and the corresponding load node;

B. Fault in branches, which are after the corresponding node, from a power source node point of view;

C. Fault in parallel branches, which has common upper node with the corresponding node, from a power source point of view;

Basic events, from which a fault tree was build, are defined as a state of a circuit breaker, relay protections, sections conditions and transformers conditions.

In this article as example will be presented a pump 1PVBr loss of power supply. Depending on the selected power source transformer T1 (Figure 2), T2 (Figure 3) or T3 (Figure 4), the branches type A, B and C will be different for every power source.

SAPHIRE software generates automatically set F of minimal cut sets C. Set D of minimal paths T can be also generated by software, when in a fault tree every “AND” node is changed with “OR” node and every “OR” node with “AND” node [11].

Let define the following sets:

- Set of sections I = {$x_0,\ldots, x_i$}, where „x“ is the corresponding section from the electrical network.
- Set of unordered pairs of elements –circuit breakers and relay protections – J = {{c_0, r_0},…, { c_m, r_m}}.

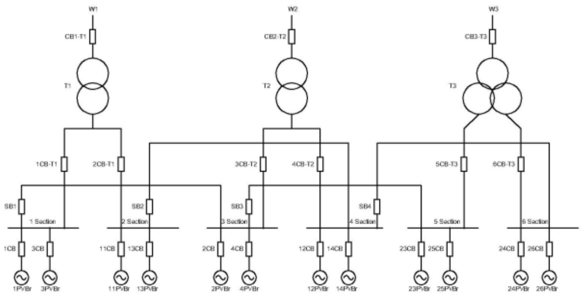

Figure 1. Single line diagram

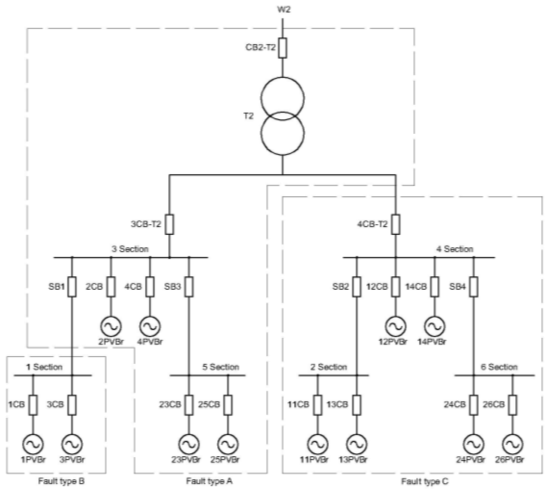

Figure 2. Power supply from T2.

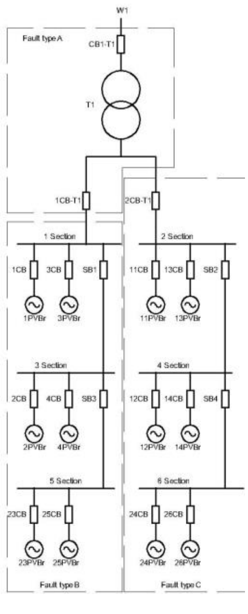

Figure 3. Power supply from T1

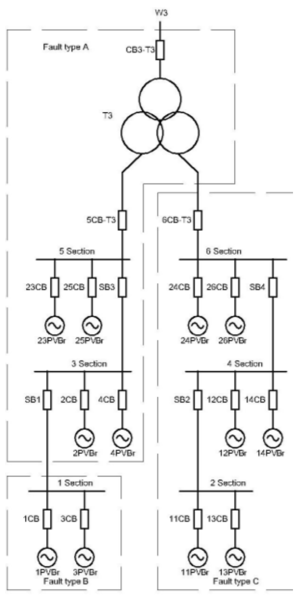

Figure 4. Power Supply from T3

Then can be predicated, that every minimal path consists of the following subsets:

- Set of healthy sections $K = \{y_0, \ldots, y_n\}$, which is a subset of I:

$$K \subset I \because \{(y \in K) \land (y \in I)\} \quad (9)$$

- Set of healthy circuit breakers and relay protections $L = \{\{c_0, r_0\}, \ldots, \{c_p, r_p\}\}$, which is a subset of J:

$$L \subset J \because \{\{\{c_p, r_p\} \in L\} \land \{\{c_p, r_p\} \in J\}\} \quad (10)$$

If we subtract set of healthy sections K, for the corresponding minimal path, from a set of sections I, then set $S = \{z_0, \ldots, z_r\}$ consists potential faulted sections:

$$I \setminus K = S\{z_r : (z_r \in I) \land (z_r \notin K)\} \quad (11)$$

Then the task for finding a faulted section can be written as a definition of the surjective image f of set J, determined by subsets L, in set I, which consists of subsets S:

$$L -^{f}\!\!\rightarrow S : \{S : S = f(L), L \in J\} \subseteq I \quad (12)$$

Every minimal cut set is determined by:

- Set of unordered pairs circuit breakers and relay protections $T = \{\{c_0, r_0\}, \ldots, \{c_r, r_r\}\}$, where one of elements is faulted, which is a subset of J:

$$T \subset J \because \{\{\{c_r, r_r\} \in T\} \land \{\{c_r, r_r\} \in J\}\} \quad (13)$$

- One faulted section, which initiates major fault.

Let see again set S of the potentially faulted sections. It can be represented as a union of the following three sets:

- Set of faulted sections U, for which unordered pairs of circuit breakers and main relay protections are operating properly, or local backup relay protection operates properly:

$$U \subset J \because \{(k \in U) \land (k \in S) \land (k \in I)\} \quad (14)$$

- Set W of faulted sections, where unordered pair for remote backup protection operates properly;
- Set of sections X, which cannot be defined:

$$S \setminus \{U \land W\} = X\{l : (l \in S) \land (l \notin U) \land (l \notin W)\} \quad (15)$$

Then:

- The problem for determination of the set of faulted sections U can be defined as determination of the surjective image g of set J, defined with subsets L in set S, which is a union of subsets U:

$$L -^{g}\!\!\rightarrow U = \{U : U = g(L), L \in J\} \subseteq S \quad (16)$$

- The problem for determination of the set of faulted sections W and malfunction of circuit breaker or/and relay protection can be defined as determination of the surjective image h of set T in set S:

$$T -^{h}\!\!\rightarrow W : \{W : W = h(T), T \in J\} \subseteq S \quad (17)$$

The above presented approach can be used for definition of the pattern inputs and outputs, for neural network training. Furthermore only data from SCADA event recorder is needed. If set X of undefined faulted sections is not empty additional query to database should be send.

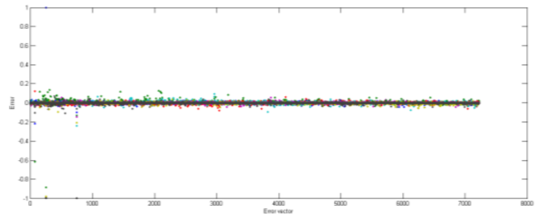

Figure 5. BPNN output error

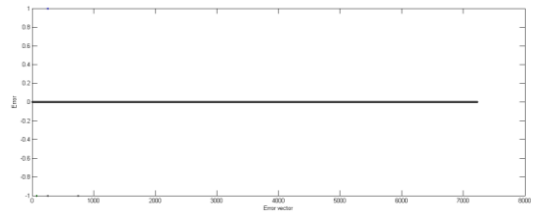

Figure 6. BPNN output error after round finction

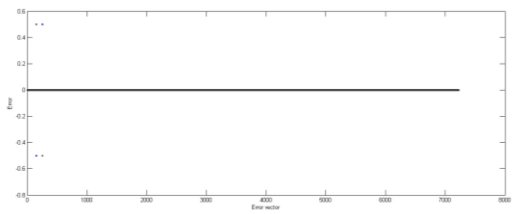

Figure 7. RBNN output error

III. PATTERNS TEST

Proper pattern input and output dataset selection was checked with Matlab standard neural network toolbox. The experiment was developed using a dataset of 7228 patters when power supply was provided by transformer T1. The number of inputs and outputs was 38 and 21 respectively. The number of neurons in the hidden layer was 40. As a result of changes BPNN was trained after 84 epochs for 31 seconds and the error was $0.109 \cdot 10^{-3}$. At Fig. 5 and 6 are presented results from BPNN output error, compared to the pattern output dataset. As it can be seen after round function there are only three unclassified patterns – N 74, N 254, N 747.

Another experiment was made with the same pattern dataset and a neural network with radial basis function. From Matlab neural network toolbox was selected the exact fit RBNN with spread constant 0.001. At Fig. 7 is shown the RBNN output error which is calculated without rounding of the output. There are only two vectors which are unclassified – N 74 and N 254.

- Minimal path N 74: 1T-OK, CB1-1T, CB2-1T, R1-1T, R2-1T, W1-OK;
- Minimal path N 254: W1-TRIP;
- Minimal path N 747: MP-1-1T, R-MP-1-1T, W1-OK.

The minimal path N 74 description is that there is a transformer T1 medium voltage circuit breakers trip. T1 and the supplying feeder W1 are healthy.

The minimal path N 254 represents a fault in the supplying feeder W1. The fault is out of scope of the investigated distribution system relay protections activity.

The minimal path N 747 can be explained as a T1 high voltage circuit breaker trip and healthy supplying feeder W1.

These experiments proof that minimal paths sets and minimal cut sets, for pattern inputs and outputs development, give very good results for BPNN and RBNN networks education.

Set theory gives a possibility for abstract definition of faulted elements and sections estimation problem. The experimental implementation of minimal path sets and minimal cut sets, as patterns in BPNN and RBNN training process, was successful. The presented method solves the problem with dependency of the neural network education quality from the number of vectors in a pattern dataset. In operating condition neural network inputs will get information mainly from a SCADA event recorder. In case of uncertain classification of some sections was presented a way for automatically defined query to database or intelligent electronic devices (IED). The proposed algorithm in this article can be applied to any system, whose behavior can be described as a tree structure.

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