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A Novel Online Multi-section Weighed Fault Matching and Detecting Algorithm Based on Wide-area Information

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Abstract – The large-scale power system blackouts have indicated that conventional protection relays that based on local signals cannot fit for modern power grids with complicated setting or heavily loaded-flow transfer. In order to accurately detect various faulted lines and improve the fault-tolerance of wide-area protection, a novel multi-section weighed fault matching and detecting algorithm is proposed. The real protection vector (RPV) and expected section protection vectors (ESPVs) for five fault sections are constructed respectively. The function of multi-section weighed fault matching is established to calculate the section fault matching degrees between RPV and five ESPVs. Then the fault degree of protected line based on five section fault degrees can be obtained. Two fault detecting criterions are given to support the higher accuracy rate of detecting fault. With the enumerating method, the simulation tests illustrate the correctness and fault-tolerance of proposed algorithm. It can reach the target of 100% accuracy rate under 5 bits error of wide-area protections. The influence factors of fault-tolerance are analyzed, which include the choosing of wide-area protections, as well as the topological structures of power grid and fault threshold.

Keywords: Wide-area Protection, Online fault detection, Fault Matching, Multi-section, Weighed

1. Introduction

In last decade, the large-scale power system blackouts have attracted increasing interests on the improvement of backup protection. The conventional protections using local signals did not fit for modern power grids, and meet some problems on complicated setting, overload and hidden failure. Once main protection failed, conventional backup protection may refuse to trip faulted line and maloperate to cut normal line, expanding the outage area [1-5]. With the development of high-speed and reliable wide-area communication networks, some wide-area protection algorithms have been studied. They use wide-area information to accurately detect the fault and cut the fault with the delays less than those of conventional backup protections, improving the reliability and fault-tolerance of protections in [1-20]. Meanwhile, the unwanted tripping on normal line can be eliminated to avoid the expanding of outage area. The principle of wide-area backup protection (WABP) is gradually accepted by specialists and engineers. In Guangdong province of China, a wide-area backup protection system has been put into operation in 2014.

Some artificial intelligent methods have been applied on WABP [7-23]. The expert system based approaches collect wide-area protection actions of primary, zone II distance and directional protections from local and adjacent lines. The action factors are defined to provide optimal fault detection in [7]. Some expert rules are given to detect the fault [8]. Other artificial intelligent methods were adopted to detect the fault, such as Petri nets in [13, 14], Bayesian networks in [15], multi-agents in [16-19] and genetic evolution in [20]. The genetic evolution is studied to realize the fault-tolerance of WABP system in [20], but genetic evolution is easy to become premature. In order to improve the fault-tolerance of WABP, the authors proposed a fault detecting algorithm with multi-source information fusion. The fitness and state expectation function are established to get fault probability for each line in [21]. A WABP algorithm based on correlation matrix is proposed to realize protection with simple, reliable and high fault-tolerance [22]. The protection fitness function and expectation function are constructed using the distance protection contribution degree as the weight in [23].

With the simulation testing, the high fault-tolerance of WABP algorithms has been tested in [21-23]. However, for some extreme conditions of refusing main and backup protections on faulted line and maloperation protections on normal line caused by overload or hidden failures, the faulted line may not be distinguished by existing literatures. So the fault-tolerance of algorithm needs to be improved. The influence factors of the fault-tolerance for WABP algorithm need to be analyzed intensively.

The development of synchronized Phasor Measurement Units (PMUs) provides new signal resource for fault detection. A new algorithm utilizes PMUs to get fault resistances under faulted conditions and enhance the

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zone third distance protection in [24]. The fault component voltage distribution algorithms can detect faulted line in[25]. However, most existing studies need one PMU on each node. It is not easy to apply to engineering.

In order to accurately detect various faulted lines and improve fault-tolerance of wide-area protection system, a multi-section weighed fault matching and detecting algorithm is proposed. Firstly, the wide-area protections are chosen. Then, the real protection vectors are constructed, as well as the expected section protection vectors of five faults sections on one line. The weighed fault matching function is established to obtain the fault matching degrees between the real protection vector and expected section protection vectors. The fault degree of protected line can be obtained. Two fault detecting criterions are given to support the higher accuracy of the algorithm. The simulation testing illustrates the validity of algorithm.

The paper is organized as follows. Section II presents the wide-area protection vectors. Section III describes the multi-section weighed fault matching model. In section IV, the multi-section weighed fault matching algorithm is given. Some extreme simulation scenarios are given to test the abilities of detecting faulted algorithm in Section V. The analyses of influencing the fault tolerance are given in Section VI. The article concludes in Section VII.

2. The Wide-area Backup Protection Vectors

2.1 The wide-area protection actions

In order to improve the accuracy and fault-tolerance of WABP, some wide-area information based on traditional protection actions are considered to detect the faulted line, according to the protection principles and power grid topology. They include the main protection, zone I, II, III distance protection and directional protection on bilateral sides of faulted line, as well as zone III distance and directional protection from remote ends of adjacent lines.

The primary protections on both sides of the line are used for its high-speed protection on whole line. They are defined as M_n, M_o. M_n means the main protection on near side, meanwhile, M_o is the main protection on opposite side.

The zone I, II, III distance protection on near side of the faulted line, are used for fault detection, as I_n, I_n, III_n, as well as I_o, II_o, III_o for zone I, II, III distance on opposite side of faulted line. The zone I distance protection only protects 80 percent of the line. The zone II distance protection can protect the entire line and 30~40 percent of next adjacent line. The zone III distance protection can protect the entire line and next adjacent line, but its selectivity is weak.

As directional protections on both sides of faulted line can indicate its faulted status, an integrating directional protection variable D is defined to show the faulted status of faulted and normal line, as below.

$$D = \begin{cases} 1 & \text{directional protections on both sides of fault line operate} \\ 0 & \text{others} \end{cases} \quad (1)$$

The zone II distance protection from remote end of adjacent line j can identify part fault section about 30~40 percent, defined as II_{r_j}. As well, the zone III distance protection from remote end of adjacent line j that identified entire line is defined as III_{r_j}. Meanwhile the integrating directional protection on adjacent line j can express as D_j to indicate the fault status of adjacent line.

For the detecting of faulted line i, the real protection vector (RPV) is constructed as P_i for line i:

$$P_i = [M_n I_n \ I_n \ III_n \ M_o I_o \ I_o \ III_o \ D \ \ (II_{r\_j} \ III_{r\_j} \ D_j)_A] \quad (2)$$

In (2), the protection actions are started signals not the tripping signals that have corresponding delays. A is the amount of adjacent lines on both sides of faulted line.

In the topical power grid belong to partial of IEEE 14-bus system, shown in Fig.1, when a fault K_1 on line $L15$ that is near to Bus B9 occurs, the RPV of $L15$ is defined as P_{15}:

$$\begin{array}{c} L_{15} \qquad\qquad\qquad L_{14} \qquad L_{12} \qquad L_9 \\ {\scriptstyle M_n I_n II_n III_n M_o I_o II_o III_o D;\ II_r III_r D_r;\ II_r III_r D_r;\ II_r III_r D_r} \\ P_{15} = [1111 \ \ 1011\,(1); 11\,(0); 11(0); 01(0)] \end{array}$$

To detect the fault on $L15$, the wide-area protections from near and opposite side, zone II, III distance protections from remote ends of adjacent lines $L14$, $L12$, $L9$ are collected from adjacent substations, as well as

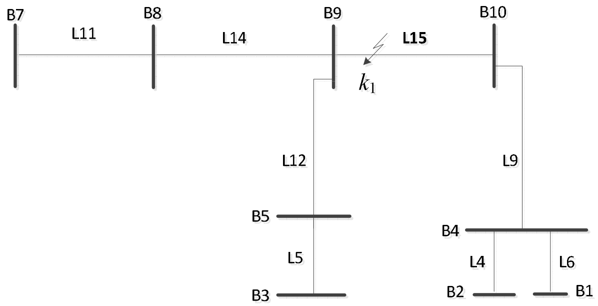

Fig. 1. Partial topical power grid from IEEE 14-bus system

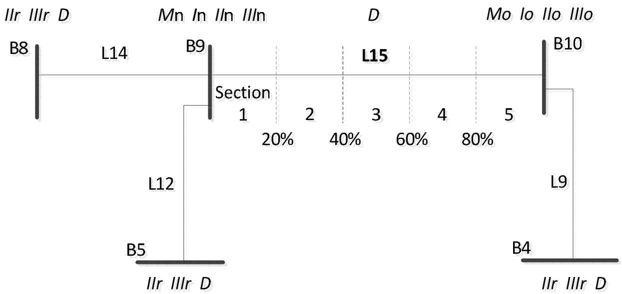

Fig. 2. Wide-area protections used detecting faulted line $L15$

Table 1. The expected protection vectors (ESPVs) of five sections on faulted line $L15$

Section No.	$L15$			$L14$	$L12$	$L9$
	$M_n\ I_nII_nIII_n$	$M_o\ I_oII_oIII_o$	D	$II_r\ III_r\ D$	$II_r\ III_r\ D$	$II_rIII_r\ D$
1	1 1 1 1	1 0 1 1	1	1 1 0	1 1 0	0 1 0
2	1 1 1 1	1 1 1 1	1	1 1 0	1 1 0	0 1 0
3	1 1 1 1	1 1 1 1	1	0 1 0	0 1 0	0 1 0
4	1 1 1 1	1 1 1 1	1	0 1 0	0 1 0	1 1 0
5	1 0 1 1	1 1 1 1	1	0 1 0	0 1 0	1 1 0

integrating directional protections D_j of adjacent lines. The wide-area protections for detecting faulted line $L15$ are shown in Fig. 2.

2.2 Expected protection vectors for multi-section faults

The protections on faulted line and its adjacent lines protect different ranges of this line and next lines. When the fault occurs in different positions on faulted line, the corresponding real protection vector (RPV) on faulted line will vary. So, according to the principles of protections, the faulted line can be divided to five sections per 20%.

The expected section protection vector (ESPV) for faulted section k on faulted line i is defined as P_i^k.

$$P_i^k = [M_n^k\ I_n^k\ I_n^k\ III_n^k\ M_o^k\ I_o^k\ I_o^k\ III_o^k\ D^k\ (II_{r\_j}^k\ III_{r\_j}^k\ D_j^k)_{A_i}] \tag{3}$$

In formula (3), k is the faulted section number on faulted line L_i, from 1 to 5. The components of ESPV are the expected wide-area protection actions. A_i is the amount of adjacent lines on both sides of L_i.

Similar to RPV, ESPV can respond to each faulted section of faulted line, and indicate objective fault section.

The wide-area protections in five ESPVs as P_{15}^1, P_{15}^2, …, P_{15}^5 for line $L15$ are shown in Table 1.

From Table 1, it can be found that there is minor difference of 1, 2 or 3 bits among the five ESPVs.

3. Multi-section Weighed Fault Matching model

3.1 The weighed section fault matching function

The weighed section fault matching function M_i^k is defined to obtain the section fault matching degree between online RPV P_i and kth section's ESPV P_i^k, to detect the faulted statue of section k on line i.

$$M_i^k = 1 - \frac{\sum_{j=1}^{N_i} \omega_{i,j} \left| p_{i,j} - p_{i,j}^k \right|}{T_i^k}, \quad k = 1,2,3,4,5 \tag{4}$$

In formula (4), the parameter vectors used by the function include the weight coefficient vector ω_i, kth section's ESPV P_i^k and expected weight sum T_i^k. k changes from 1 to 5.

N_i is the dimensionality of RPV P_i.

$P_{i,j}$ is the jth vector protection component of RPV P_i.

$p_{i,j}^k$ is the jth vector protection component of kth section's ESPV P_i^k on line L_i.

T_i^k is the expected protection weight sum of wide-area protectionns for the kth faulted section on line L_i, as below.

$$T_i^k = \sum_{j=1}^{N_i} \omega_{i,j}\, p_{i,j}^k, \quad k = 1,2,3,4,5 \tag{5}$$

Where, $\omega_{i,j}$ is the weight coefficient of jth wide-area protection on line L_i.

3.2 The weights of wide-area backup protections

In [21], with the different principles and functions, the weight coefficient values of primary, zone I distance, local backup, directional and remote backup protection, are set to 6, 6, 3, 2 and 2, respectively.

Considering that higher weight coefficient of primary and zone I distance protection may make normal line be misjudged to fault under multiple bits mal-operation protection, we changed weight coefficient values of primary, zone I, II, III distance protection to 3, 3, 2, 2, and added the weight coefficient of integrating directional protection, set it to 3, which also reflects faulted status of faulted or normal line. These weight coefficients of wide-area protections are chosen with analysis of protection principle, as well as by the simulation testing. The selectivity and fault-tolerance of wide-area protection are improved. It has been verified to be reasonable in later section.

3.3 Multi-section weighed fault matching degree

When RPV P_i and kth section's ESPV P_i^k on line L_i are put into (4), the corresponding section fault matching degree M_i^k of kth faulted section on line L_i will be gotten.

The fault matching degree for line L_i is defined as M_i. It is the maximal value of five section fault matching degrees.

Under normal conditions, all of wide-area protections in RPV P_i accurately operate, the section fault matching degree compared with one ESPV will approximate or equal to 1. That means that the RPV is close or equal to the ESPV of faulted section on faulted line.

When there are multiple bits of mal-operation, rejection or missing protection actions on faulted line and adjacent lines, the RPV may be close to one ESPV on faulted line. The faulted line can also be detected by the fault matching degree of line, which exceeds the fault threshold.

On the contrary, five section fault matching degrees on normal line are very small. They indicate that the line is normal.

For example, suppose that A phase ground fault on line $L15$ appears at k_1 near to Bus $B9$ (10%). Assume that main protections on both sides of line $L15$ fail, and the zone I distance backup protection near to $B9$ rejects to operate.

The RPV of line $L15$ is collected as below.

$$\begin{array}{l} \qquad\qquad\qquad L_{15} \qquad\qquad\qquad\quad L_{14} \qquad\quad L_{12} \qquad L_{9} \\ M_n\, I_n\, II_n\, III_n \;\; M_o\, I_o\, II_o\, II_o\, (D);\;\; II_r\, III_r\, (D);\;\; II_r\, III_r\, (D);\; II_r\, III_r\, (D) \\ P_{15} = [\underline{0}\ \underline{0}\ 1\ 1\ \ \underline{0}\ 0\ 1\ 1\ (1)\ ;\ 1\ 1\ (0);\ 1\ 1(0);\ 0\ 1(0)] \end{array}$$

In the vector of RPV, an underlined entry corresponds to a protection rejection, missing or failure occurred, a shaded border means that there was a mal-operation protection. The number in the brackets is integrating directional protection D value of one line.

The weight coefficient vector with 18 components for line $L15$ is given as ω_{15}.

$$\omega_{15}=[\omega_1,\omega_2,\cdots,\omega_{18}]=[3,3,2,2,3,3,2,2,3,2,2,3,2,2,3,2,2,3]$$

The expected protection weighting sum vector T_{15} that has five components for five faulted sections on $L15$, is calculated.

$$T_{15} = [T_{15}^1\ T_{15}^2\ T_{15}^3\ T_{15}^4\ T_{15}^5] = [32\ 33\ 32\ 33\ 31]$$

The five expected section protection vectors (ESPVs) have been given in Table 1.

The RPV P_{15} for line $L15$ is put into formula (4) and five fault ESPVs, the five section fault matching degrees can be respectively obtained as:

$M_{15}^1 = 0.719$, $M_{15}^2 = 0.636$, $M_{15}^3 = 0.500$, $M_{15}^4 = 0.456$, $M_{15}^5 = 0.516$.

The first section fault matching degree M_{15}^1 on $L15$ is the maximum value. It is regard as the final fault matching degree of $L15$, that means $M_{15} = 0.719$. The faulted line can be found as L15.

For the normal line $L14$, The RPV P_{14} of $L14$ is obtained, as well as the expected weight protection sum vector T_{14}.

$$\begin{array}{l} \qquad\qquad\qquad L_{14} \qquad\qquad\qquad\quad L_{11} \qquad\quad L_{12} \qquad L_{15} \\ \mathrm{M_n\, I_n\, II_n\, III_n \;\; M_o\, I_o\, II_o\, II_o\, (D)\, ;\;\; II}_r\,\mathrm{III}_r\,\mathrm{(D)\, ;\;\; II}_r\,\mathrm{III}_r\,\mathrm{(D)\, ;\;\; II}_r\,\mathrm{III}_r\,\mathrm{(D)\, ;} \\ P_{14} = [0\ 0\ 1\ 1\ \ 0\ 0\ 0\ 0\ (0)\ ;0\ 0\ (0);1\ 1\ (0);1\ 1\ (1)] \\ T_{14} = [T_{14}^1\ T_{14}^2\ T_{14}^3\ T_{14}^4\ T_{14}^5] = [31\ 33\ 32\ 33\ 32] \end{array}$$

Similarly, the five section matching degrees of $L14$ can be respectively calculated by formula (4), as below.

$M_{14}^1 = 0.129$, $M_{14}^2 = 0.091$, $M_{14}^3 = 0.125$, $M_{14}^4 = 0.273$, $M_{14}^5 = 0.344$.

The final fault matching degree of $L14$ is obtained as $M_{14} = 0.344$.

From above the process, the fault matching degree of $L15$ is greater than that of $L14$. This fact becomes important basis for detecting faulted line.

3.4 The wide-area backup protection algorithm

The fault detecting criterion 1 of wide-area protection algorithm is given to detect the faulted line:

$$\begin{cases} M_i > \forall M_k, k \neq i \\ M_i > M_{set} \end{cases} \tag{6}$$

As the fault matching degree M_i of one line L_{i} is greater than any fault matching degree M_k of adjacent line L_{k}, and M_i is over the fault threshold M_{set}. The line can be accurately detected to be faulted in most situations.

When there are multiple bits of mal-operation, rejection or missing protections on faulted line and adjacent lines, such as five or more bits protection errors, the fault matching degree M_i of faulted line L_{i} may be equal to fault matching degree M_k of one adjacent line, so fault detecting criterion 1 may fail.

The fault detecting criterion 2 is given for the complementary of criterion 1 under exceptional situations.

$$\begin{cases} M_i = M_k > M_{set} \\ \sum_{j=1}^{9} p_{j,\mathrm{L}i} > \sum_{j=1}^{9} p_{j,\mathrm{L}k} \end{cases} \tag{7}$$

In (7), the nine protections include the main, zone I, II, III distance protection on both sides of the line, and the integrating directional protection D.

When the fault matching degree M_i of line L_{i} is equal to the degree M_k of one adjacent line L_{k}, and over than faulted threshold, meanwhile, the sum of nine protections from both sides of line L_{i} is greater than that of adjacent line L_{k}. Then, L_{i} can be confirmed to be the faulted line.

4. Multi-section Weighed Fault Matching Algorithm Using Wide-area Backup Protections

Step 1: The starting of the wide-area backup protection. When a fault of power grid occurs, one of wide-area backup protection acts, the wide-area backup protection algorithm will be started. The lines with maximal sums of protection actions ranked are regarded as the suspected faulted lines.

Step 2: after collecting wide-area protection actions from local and adjacent substations via local network and wide- area communication network, the RPVs of these suspected faulted lines are obtained.

Step 3: using the RPVs, the ESPVs and other parameters of these suspected faulted lines, the section fault matching degrees between RPV and five sections on the lines can be calculated by formula (4). Then the fault matching degrees of the lines can be gotten with the maximal section fault matching degree.

For each suspected line, if the fault detecting criterion 1 is satisfied on one line, it will be judged to be faulted line. Otherwise, go to step 4.

Step 4: if the fault detecting criterion 2 is satisfied on one line, it will be judged to be faulted line.

Step 5: once the faulted line is detected, its faulted status is transferred to the substations where the faulted line lives, to trip the breaker, and to the adjacent substations to block the incorrect tripping orders from remote backup protection or overload protection on normal line.

5. Simulation Cases

5.1 Case1: All primary protections on fault line fail

Suppose a single-phase ground fault (A phase) k_1 near to Bus *B*9 (10%) occurs on line *L*15 in Fig.1. Assume that the main protections on both sides of line *L*15 fail, the zone *I* distance backup protection near to B9 rejects to operate, the zone *II* distance protection on *L*14 near to *B*9 maloperates.

As there are multiple bits of protections mal-operation on line *L*15*, L*14, *L*12, *L*9, which are ranked as suspected faulted lines.

The RPVs of *L*15*, L*14, *L*12, *L*9 are collected as below.

$$\begin{array}{l}
\qquad\qquad L_{15} \qquad\qquad\qquad\quad L_{14} \quad L_{12} \quad L_{9} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{15}=[\underline{0}\ \underline{0}\ 1\ 1\ \ \underline{0}\ 0\ 1\ 1\ (1)\,;1\ 1\ (0);1\ 1(0);0\ 1(0)]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{14} \qquad\qquad\qquad\quad L_{11} \quad L_{12} \quad L_{15} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{14}=[0\ 0\ 1\ \ 1\ \ 0\ 0\ \boxed{1}\ 0(0)\,;0\ 0(0);1\ 1(0);1\ 1\ (1)]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{12} \qquad\qquad\qquad\quad L_{14} \quad L_{15} \quad L_{5} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{12}=[0\ 0\ 0\ 0\ \ 0\ 0\ 1\ 1(0)\,;1\ 1\ (0);1\ 1(1);0\ 0(0)]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{9} \qquad\qquad\qquad\quad L_{15} \quad L_{4} \quad L_{6} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{9}=[0\ 0\ 0\ 0\ \ 0\ 0\ 0\ 1(0)\,;1\ 1\ (1);\ 0\ 0(0);0\ 0(0)]
\end{array}$$

The RPVs of *L*15*, L*14, *L*12, *L*9 are respectively put into (4). The corresponding fault matching degrees of the suspected faulted lines can be obtained as M_{15}=0.719, M_{14}=0.406, M_{12}=0.344, M_9=0.194.

Using the fault detecting criterion 1, line *L*15 can be detected to the faulted line.

Although there are four mal-operation and rejection protections on *L*15 and *L*14, the detection result is right.

5.2 Case2: Primary protection on faulted line fails and protections on adjacent normal lines misoperate

Suppose a single-phase ground fault (A phase) k_1 near to Bus *B*9 (10%) occurs on line *L*15 in Fig.1. Assume that the main protections on both sides of line *L*15 fail, the zone I distance backup protection near to *B*9 refuses to operate, and the directional protection on *L*15 near to *B*9 rejects (from 1 to 0), directional protection on adjacent line *L*14 near to B9 maloperates (from -1 to 1).

As there are more protection actions on line *L*15*, L*14, *L*12, *L*9, they are chosen as suspected faulted lines.

The RPVs of *L*15*, L*14, *L*12, *L*9 are collected.

$$\begin{array}{l}
\qquad\qquad L_{15} \qquad\qquad\qquad\quad L_{14} \quad L_{12} \quad L_{9} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{15}=[\underline{0}\ \underline{0}\ 1\ 1\ \underline{0}\ 0\ 1\ 1(\boxed{0})\,;1\ 1(\boxed{1});1\ 1(0);\ 0\ 1(0)]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{14} \qquad\qquad\qquad\quad L_{11} \quad L_{12} \quad L_{15} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{14}=[0\ 0\ 1\ 1\ 0\ 0\ 0\ 0\ (\boxed{1})\,;0\ 0(0);1\ 1(0);1\ 1(\boxed{0})]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{12} \qquad\qquad\qquad\quad L_{14} \quad L_{15} \quad L_{5} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{12}=[0\ 0\ 0\ 0\ 0\ 0\ 1\ 1(0);\ 1\ 1(\boxed{1});1\ 1(\boxed{0});\ 0\ 0(0)]
\end{array}$$

$$\begin{array}{l}
\qquad\qquad L_{9} \qquad\qquad\qquad\quad L_{15} \quad L_{4} \quad L_{6} \\
\mathrm{M_n\,I_n\,II_n\,III_n\,M_o\,I_o\,II_o\,II_o\,(D)}\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D})\,;\,\mathrm{II}_r\,\mathrm{III}_r\,(\mathrm{D}) \\
P_{9}=[0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ (0);1\ 1(\boxed{0});0\ 0(0);0\ 0(0)]
\end{array}$$

Similarly, the RPVs of *L*15*, L*14, *L*12, *L*9 are respectively put into formula (4). The fault matching degrees of the suspected faulted lines can be calculated as M_{15}=0.531, M_{14}=0.531, M_{12}=0.344, M_9=0.290.

As there are five bits of mal-operation, rejection protection actions on line *L*15 and *L*14, it makes the two fault matching degrees on *L*15 and *L*14 same. They are over the threshold 0.5.

The fault detecting criterion 1 fails under the scenario, so fault detecting criterion 2 is used to detect the faulted line.

The sum of nine protection operations from both sides of *L*15 is 4; meanwhile the sum of line *L*14 is 3. The sum of nine protection operations on *L*15 is greater than that of *L*14. The fault detecting criterion 2 is satisfied on *L*15.

The *L*15 can be detected to the faulted line. It is consistent with the fault supposition.

5.3 Case3: One protection IED on fault line fails

Suppose a two-phase ground fault (AB phase) on line *L*15 appears at k_1 near to Bus *B*9 (10%) in Fig.1. Assume that the protection device on B9 fails.

The lines $L15$, $L14$, $L12$ and $L9$ are chosen as the suspected faulted lines.

The RPVs of $L15$, $L14$, $L12$ and $L9$ are collected.

$$\begin{array}{lllll}
 & L_{15} & L_{14} & L_{12} & L_{9} \\
 & \mathrm{M_n I_n II_n III_n M_o I_o II_o II_o (D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)} \\
P_{15} = & [\underline{0}\ \underline{0}\ \underline{0}\ \underline{0}\ 1\,0\,1\,1(\boxed{0})\ ; & 1\,1\,(0); & 1\,1(0); & 0\,1(0)]
\end{array}$$

$$\begin{array}{lllll}
 & L_{14} & L_{11} & L_{12} & L_{15} \\
 & \mathrm{M_n I_n II_n III_n M_o I_o II_o II_o (D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)} \\
P_{14} = & [0\,0\,1\,1\ \ 0\,0\,0\,0(0); & 0\,0\,(0); & 1\,1(0); & 1\,1(\boxed{0})]
\end{array}$$

$$\begin{array}{lllll}
 & L_{12} & L_{14} & L_{15} & L_{5} \\
 & \mathrm{M_n I_n II_n III_n M_o I_o II_o II_o (D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)} \\
P_{12} = & [0\,0\,0\,0\ \ 0\,0\,1\,1(0); & 1\,1(0); & 1\,1(\boxed{0}); & 0\,0(0)]
\end{array}$$

$$\begin{array}{lllll}
 & L_{9} & L_{15} & L_{4} & L_{6} \\
 & \mathrm{M_n I_n II_n III_n M_o I_o II_o II_o (D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)}\ ; & \mathrm{II}_r \mathrm{III}_r \mathrm{(D)} \\
P_{9} = & [0\,0\,0\,0\ \ 0\,0\,0\,1(0); & \underline{0}\ \underline{0}(\boxed{0}); & 0\,0(0); & 0\,0(0)]
\end{array}$$

The fault matching degrees of suspected faulted lines can be obtained as M_{15}=0.594, M_{14}=0.438, M_{12}=0.438, M_9=0.161.

Using the fault detecting criterion 1, $L15$ is detected to the faulted line. It is correct.

The failure of protection device made five protections rejected on $L15$, integrating directional protection D on $L15$ changed from 1 to 0. With our multi-section fault matching algorithm, the faulted line can be accurately detected.

6. The Analysis of Fault Tolerance

6.1 Fault-tolerance analysis with enumeration method

For faulted line $L15$ and its adjacent normal line $L14$ in Fig.1, the two RPVs respectively have 18 bits wide-area protections. Except for those repeated, there are 27 bits protections for calculating the fault matching degrees of $L15$ and $L14$.

With the enumeration method, for five faulted sections on $L15$, the different bits errors of protections from 1 to 8 are tested for accuracy rates of wide-area protection algorithm. The fault-tolerance testing results are shown in Table 2.

Table 2. The fault-tolerance testing results of wide-area protection algorithm using enumeration method

Protection error bits	Protection error rate (%)	Combinatorial number	Error judgment number	Accuracy rate (%)
1	5.5	131	0	100
2	11.1	1647	0	100
3	16.7	13241	0	100
4	22.2	76526	0	100
5	27.8	403650	0	100
6	33.3	1480050	6660	99.55
7	38.9	4440150	132784	97.01
8	44.4	11100375	1081135	90.26

From Table 2, we can see that less than 5 bits protection errors, all of faulted lines can be detected with 100% accuracy rates. It means that the algorithm can accurately detect the fault under scenarios less than 5 bits protection errors. For the situations with 6 bits protection errors, the accuracy rate is still higher to be 99.55%. It means that the algorithm has higher fault-tolerance ability.

For the situations of less than 4 bits protection errors, all of the faults can be detected by fault detecting criterion 1.

For the situations with 5 bits protection errors, there are 31 combinations, in which fault degree of $L15$ and $L14$ are same, are detected by fault detecting criterion 2. The percent is 0.0076%.

For the situations with 6 bits protection errors, the combination number accurately detected by fault detecting criterion 2 is 574, the percent as 0.0388%.

The fault detecting criterion 1 can deal with most faulted situations. Few exceptional situations can be handled by fault detecting criterion 2 to find the faulted line.

6.2 The choosing of wide-area protections

The choosing of wide-area protections may influence the effect of the algorithm. There are five kinds of wide-area protections chosen in the paper. In literature [22], three kinds of wide-area protections are adopted, such as zone I and II distance and directional protection.

In order to compare the fault-tolerance ability between proposed and existing algorithm, the contrast experiments are made, shown in Table 3. The "-" in Table 3 means that there no corresponding test from [22].

The first algorithm is from [22]. The second algorithm is our algorithm, in which main protection (M.P.) is taken out to be close to the first algorithm. The third is our algorithm that includes M.P.

Table 3 shows that our algorithm with five kinds of wide-area protections has higher fault-tolerance than that of existing literature.

The weight coefficient values of primary, zone I, II, III distance and integrating directional protection are set to 3, 3, 2, 2, and 3. The weight coefficients of primary and zone

Table 3. The fault-tolerance comparison results of the wide-area protection algorithms

Protection error bits	Accuracy rate of the algorithms (%)		
	with ref[22]	except M.P.	include M.P.
1	100	100	100
2	100	100	100
3	99.79	100	100
4	97.98	99.97	100
5	93.31	96.01	100
6	85.73	95.35	99.55
7	-	86.23	97.01
8	-	70.32	90.26

I distance protection are slightly decreased. As the result, the misjudgments of normal line under multiple bits mal-operation protections on normal line are voided. These coefficients have been tested to be reasonable by the simulation testing.

6.3 The influence of power grid topological structure on the fault-tolerance of algorithm

In Fig. 1, the line numbers of bilateral adjacent lines for faulted line $L15$ are two and one. It may be the minimal topological structure, i.e. left two adjacent lines and right one adjacent line. When one or more adjacent lines are added for faulted line, the wide-area protection components of RPV are increased. The redundant zone II, III distance and directional protection from adjacent lines give more contribution on confirming faulted line.

The comparison testing for three kinds of topological structures is made to check the fault-tolerance performance influenced by topological structure of power grid. The other two kinds of topologies are shown in Fig. 3 and Fig. 4.

The comparison results of accuracy rate for three kinds of topological structures are given in Table 4 and Table 5.

The topological structure in Fig. 1 is the minimal, only two adjacent lines on one side and one adjacent line on another side. Two kinds of topological structures in Fig.3 and Fig. 4 have the higher accuracy rates than the previous.

From Table 4 and 5, we can see that the more adjacent lines, the higher accuracy rate of detecting faulted line. Because redundant wide-area protections from more adjacent lines provide the support on indicating faulted line.

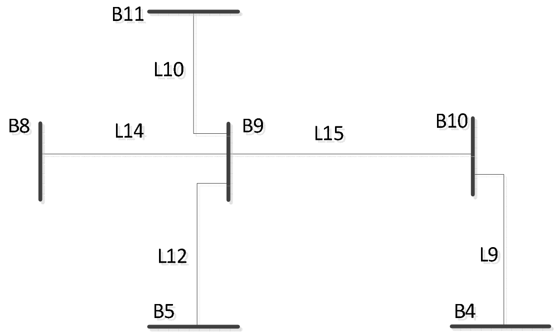

Fig. 3. The topical structure with left three adjacent lines and right one adjacent line on $L15$

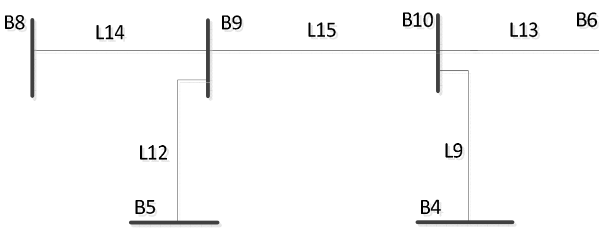

Fig. 4. The topical structure with left two adjacent lines and right one adjacent line on $L15$

Table 4. The comparison results of accuracy rates for three kinds of topological structures (%)

Protection error bits	Left two lines, right 1 line	Left three lines, right 1 line	Left two lines, right two lines
1	100	100	100
2	100	100	100
3	100	100	100
4	100	100	100
5	100	100	100
6	99.55	99.88	99.83
7	97.01	98.33	97.85
8	90.26	93.10	91.48

Table 5. The comparison results of accuracy rates for three kinds of topologies without main protections

Protection error bits	Three kinds of topological structures		
	Left two lines, right one line	Left three lines, right one line	Left two lines, right two lines
1	100	100	100
2	100	100	100
3	100	100	100
4	99.97	100	100
5	96.01	99.88	99.86
6	95.35	99.45	98.87
7	86.23	95.29	92.51
8	70.32	84.02	77.79

6.4 The adaptability of the topological changing

When the topology of power grid has changed, such as one line exited by the fault or maintenance, the formula (4) need to make little adjustment for the calculating of fault matching degree. The dimensionality and components of RPV on other line need to be adjusted to decrease, according to the new topology, as well as ESPVs and T_i.

In order to apply on the engineering, the fault threshold in fault detecting criterion is uniformly set to 0.5. Because the fault degree of most faulted lines will be greater, meanwhile, those of normal lines are less than 0.5 from the simulation.

The fault threshold in the paper is not affected by the topology of power grid and choosing of wide-area protections. The simulation has tested that the fault threshold is appropriate.

7. Conclusion

This article introduces a novel multi-section weighed fault matching and detecting algorithm. Using the traditional primary, zone I, II distance backup protections and remote backup protections from adjacent lines, the model of multi-section weighed fault matching is given to calculate five section fault matching degrees on one line, and fault matching degree of suspected line. The objective of five section fault matching degrees is not to precisely locate the fault section, but to accurately detect the faulted line. Under the multiple bits error wide-area protections, the faulted section may be not located, but the faulted line can be accurately detected. The simulation and experiments have verified the validity of the algorithm, even in the presence of multiple protection errors and device failures. For five bits error wide-area protections, the faulted line can be detected with 100% accuracy rates, which are higher than the existing literatures. Even though primary protections are taken out from the wide-area protections, the accuracy rates of our algorithm are still higher.

The influence factors of fault-tolerance are intensively analyzed, including the choosing of wide-area protections, topological structures and their changing, and fault threshold. The more adjusted lines of faulted line, the higher accuracy rates can be gotten by our algorithm. The unified fault threshold is set to for the application.

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