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Optimal Placement of Traveling Wave Fault Location Equipment in Power Grid Based on Characteristic Non-singular Set

***Abstract**. With the widely use of traveling wave fault location equipment (TWFLE) in power grid, network-based traveling wave fault location (NBTWFL) method has been proposed. To ensure the effectiveness and economy of NBTWFL method, based on the principle of characteristic non-singular set, an optimal placement algorithm of TWFLE is proposed in this paper. The corresponding NBTWFL method based on maximum non-singular subset, additional installation plan of TWFLE and some other related problems are also discussed in this paper.*

***Streszczenie.** W artykule opisano metodą wykrywania awarii w sieci elektroenergetycznej na podstawie analizy fali wędrującej. Proponowane rozwiązanie bazuje na klasycznym algorytmie wykrywania fali wędrującej, w którym zastosowano niesingularne wartości własne. Pozwoliło to na optymalizację rozmieszczenia urządzeń do wykrywania awarii. (**Optymalizacja rozmieszczenia czujników wykrywania fali wędrującej przy awarii w sieci elektroenergetycznej na podstawie niesingularnego ułożenia wartości własnych**).*

Keywords: Optimal placement, Traveling wave, Fault location, non-singular set.
Słowa kluczowe: optymalne rozmieszczenie, fala wędrująca, lokalizacja awarii, niesingularne rozmieszczenie.

1 Introduction

Since the 90's in 20th century, rapid development of modern microelectronics, global position system (GPS), communications and digital signal processing (DSP) technology provides the foundation for research and development of traveling wave fault location equipment (TWFLE). As the major breakthroughs in extraction technology of transient traveling [1-3], the principle and algorithm of traveling wave fault location [4-12] and etc., TWFLE has been widely applied into the power grid.

For traditional both-terminal traveling wave fault location method (BTTWFL) based on single transmission line, any fault in TWFLE like start-up failure and time record error will result in location failure. Field data of B.C Hydro power grid showed that traveling wave could propagate over thousands of kilometres and every substation could detect the fault-generated traveling wave [1]. Meanwhile, theory and practice have proved that speed of aerial-mode traveling wave can basically maintain invariable in a certain range [13]. So the literature [14-16] proposed a network-based traveling wave fault location method (NBTWFL), in which the fault position is located based on all the arrival time of initial wave-fronts of traveling wave recorded by the TWFLE installed at every substation of the power grid.

Compared to the BTTWFL method, NBTWFL method can provide more reliable and accurate location result. However, at present TWFLE is too expensive and modern power grid is too large, it's uneconomical and unnecessary to install TWFLE at every substation. Thus literature [17] proposed the principle of optimal placement of TWFLE in power grid. The method proposed in the paper [17] has a certain value which used simulated annealing algorithm to confirm optimal placement plan, but it needs to be verified by NBTWFL algorithm in the progress. Directly based on NBTWFL algorithm, literature [18] firstly assumed that each transmission line was the fault line, and then optimal placement plan could be obtained from the minimum sharing set which was determined through the substations located at both sides of the fault line. Besides, literature [19] proposed an optimal placement algorithm of TWFLE based on multi-DOF (Degree of Freedom). To obtain the multi-DOF, the principle of maximum non-singular subset is presented. But the algorithm needs to be improved to adapt to ring configu-ration.

Actually NBTWFL method is the extension of traditional BTTWFL method, based on this principle, a new optimal placement algorithm of TWFLE based on characteristic non-singular set is presented in this paper. It proposed a clear physical conception and can be achieved easily.

2 Basic principle

2.1 Extension of traditional BTTWFL method

The principle of traditional BTTWFL method is to use the arrival time difference of the initial wave-fronts of traveling wave recorded by the TWFLE at both sides of the fault line. As shown in Fig. 1(a), a fault happened at point F on line BC, the recorded arrival time of transient traveling wave at substation A,B,C,D and E is T_A, T_B, T_C, T_D, T_E, respectively. Then the basic calculation equation of BTTWFL method is as follows:

(1) $$X_{BF}=\frac{1}{2}[(T_B-T_C)\upsilon+L_{BC}]$$

where: υ – the velocity of traveling wave, L_{BC} – the length of line BC.

Because of the transmission, traveling wave can propagate through substation B to A and propagate through C to D and E. Regard the path A-B-C-D-E as an equivalent extended line, then fault position can be located by the following equation:

(2) $$X_{AF}=\frac{1}{2}[(T_A-T_E)\upsilon+L_{AE}]$$

Equation (2) is the basic calculation formula of NBTWFL method. The basic principle of NBTWFL method is to decompose the whole power grid into serveral extended lines. The extended line is relative to the basic line like line BC.

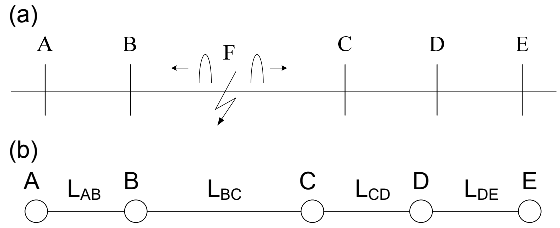

Fig.1. Extension of traditional both-terminal traveling wave fault location method

2.2 Some basic definition

In graph theory, when characteristics of power elements are ignored and only propagation path of the initial wave-fronts is taken into consideration, the power grid can be abstracted as a topological graph G= (V, E) which is constructed by n vertexes and b edges. In graph G, V represented the set of vertexes and E represented the set of edges. Vertexes and edges are corresponding to substations and transmission lines, respectively. The weight of edge e_i represents the length of the corresponding transmission line [20]. The topological graph of the power grid shown in Fig. 1(a) is given in Fig. 1(b).

The adjacency matrix of the simple graph G=(V,E) which is represented by $A(G)=(a_{ij})_{n\times n}$ can be defined as follows:

$$(3)\qquad a_{ij}=\begin{cases}1, & i\neq j \,\&\, (\upsilon_i,\upsilon_j)\in E\\ 0, & \text{otherwise}\end{cases}$$

The weight matrix of the simple graph G=(V,E) which is represented by $W(G)=(\omega_{ij})_{n\times n}$ can be defined as follows:

$$(4)\qquad \omega_{ij}=\begin{cases}0, & i=j\\ f(\upsilon_i\upsilon_j), & (\upsilon_i,\upsilon_j)\in E\\ \infty, & \text{otherwise}\end{cases}$$

where: $f(\upsilon_i\upsilon_j)$ - the weight of the edge $\upsilon_i\upsilon_j$.

In graph G=(V,E), the degree of vertex υ_i which is represented by $d(\upsilon_i)$ is defined as the number of edges related to υ_i:

$$(5)\qquad d(\upsilon_i)=\sum_{j=1}^{n}a_{ij}$$

In graph G= (V, E), assuming P_{uv} represents the minimum path between vertex u and v, P_{rs} represents the minimum path between vertex r and s. If path P_{rs} completely contains P_{uv}, then it is represented by $P_{uv}\subset P_{rs}$. Otherwise they would be regarded as totally different paths and the relationship is represented by $P_{uv}\cap P_{rs}=\Phi$.

The set of minimum path between vertex u and the other vertexes is identified as the minimum path tree of vertex u, represented by $Tree_u$. $CTree_u$ is the maximum non-singular subset of $Tree_u$ if it meets the following conditions: (1) for any two elements P_{uv} and P_{rs}($P_{uv}\in CTree_u$, $P_{rs}\in CTree_u$), $P_{uv}\cap P_{rs}=\Phi$; (2) for any elements P_{uw} ($P_{uw}\in Tree_u$), if there is no P_{ui} ($P_{ui}\in Tree_u$) can meet $P_{uw}\subset P_{ui}$, then $P_{uw}\in CTree_u$.

2.3 Basic principle of optimal placement of TWFLE

In the simple power grid shown in Fig. 1(a), according to equation (2), the progress of optimal placement of TWFLE can be defined as follows: (1) find out the maximum extensive line P_{rs} which contains the fault line BC (for any extensive line P_{uv}, it meets: if $P_{uv}\supset P_{BC}$, then $P_{uv}\subset P_{rs}$); (2) confirm the optimal placement plan which is that two TWFLE are installed at the both terminals of the maximum extensive line P_{rs}.

3 Optimal placement of TWFLE

3.1 Principle of optimal placement of TWFLE

According to the above analysis, the key of optimal placement of TWFLE is how to find out the maximum extensive line. In this paper, it is solved by use of graph theory.

In graph theory, maximum extensive line of vertex u is just the path between the root node and the leaf node in the minimum path tree of u which can be obtained by Dijkstra algorithm [20-22]. Because fault may happen at every basic line, the maximum extensive line set is just the maximum non-singular subset of the maximum non-singular subset of all vertexes, and it is called the maximum non-singular set of the graph in this paper. For the simple power grid shown in Fig. 1(a), the maximum non-singular set of the graph is {A-B-C-D-E}.

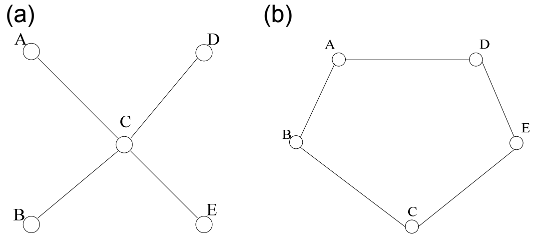

Fig. 2. Star and ring configurations

Besides of linear configuration shown in Fig. 1(a), star and ring configurations also exist in power grid which is shown in Fig. 2. Dimensionality of maximum non-singular set in star or ring configuration is more than 1, so principle of characteristic non-singular set of the edge is proposed to solve the problem of confirming optimal placement plan based on several maximum extensive lines. Set $CTree_G$ as the maximum non-singular set of graph G= (V, E) and assuming that $P_{rs}\in CTree_G$, $P_{uv}\in CTree_G$ and b is one edge of G. Then $CTree_b$ is the characteristic non-singular set of b if it meets the following conditions: (1) if $b\subset P_{rs}$, $P_{rs}\in CTree_b$;(2) any $P_{uv}\notin CTree_b$, $b\not\subset P_{uv}$.

In addition, the following principle is used in optimal placement of TWFLE:

(1)TWFLE must be installed at the vertex whose degree equals 1, in this paper it is called must-be-installed vertex (MBIV).

(2)TWFLE is unnecessary to be installed at the vertex which is related to MBIV and its degree is more than 1. In this paper it is called unnecessary-be-installed vertex (UBIV).

The MBIV and UBIV can be identified based on equation (5): vertex i would be MBIV if the following condition is met: $\sum a_{ij}=1(1\le j\le n)$; vertex i would be UBIV if the following condition is met: $\sum a_{ij}>1(1\le j\le n)$ and there exists at least one element which meets $a_{ip}=1$(p is MBIV).

3.2 Optimal placement of TWFLE

The optimal placement algorithm of TWFLE can be derived as follows:

(1) Based on the structure of the power grid, obtain the corresponding topological graph, adjacency matrix and weight matrix.

(2) Identify the MBIV and UBIV.

(3) Figure out the maximum non-singular subsets of all vertexes except for the UBIV by use of Dijkstra algorithm.

(4) Obtain the maximum non-singular set of the graph and the corresponding characteristic non-singular set of each edge. Smaller dimensionality of the characteristic non-singular set is according to the smaller number of maximum extensive lines which contain the basic line, so TWFLE would be more necessary to be installed at the endpoints of the elements belonging to the characteristic non-singular set whose dimensionality is smaller.

(5) In ascending order, sort edges by the dimensionality of the corresponding characteristic non-singular set. When the breaker status is unknown, the corresponding edge will not be taken into consideration in the next progress if there exists at least one element of its characteristic non-singular set on which two TWFLE have been installed and they are on both sides of the edge; when the breaker status is a known quantity, the corresponding edge will not be taken into consideration in the next progress if two TWFLE have been installed at the nodes of the elements which belongs to characteristic non-singular set of the edge, and they can't be located at the same side of the edge in the traveling wave propagation path.

(6) Select the characteristic non-singular set whose dimensionality is the minimum as the TWFLE-prior-installation unit. If the breaker status is unknown, two TWFLE should be installed at the both endpoints of one element and the element whose one endpoint has installed TWFLE takes priority of selection. If the breaker status is a known quantity, Two TWFLE should be installed at any two endpoints of elements but need to be on both sides of the corresponding edge.

(7) Repeat step (5) and (6) until there exists no edge to be sorted.

From step (6), it can be inferred that the optimal placement plan may not be unique if the number of characteristic non-singular sets which has the minimum dimensionality is more than 1 or the alternative nodes which need to install TWFLE are not unique.

4 Case study

As shown in Fig. 3, take the 500kV power grid in Hunan Province of China mentioned in literature [14] as an example, the progress of confirming optimal placement plan is as follows:

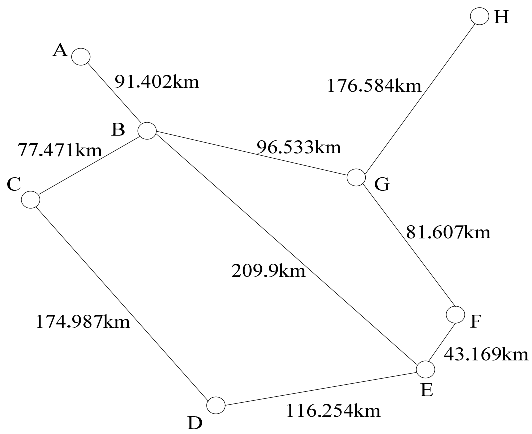

Fig. 3. 500kV power grid in Hunan province, China

(1) Obtain the corresponding adjacency matrix A(G) and weight matrix W(G).

(2) The MBIV is vertex A and H; the UBIV is B and G.

(3) Maximum non-singular subsets of all vertexes except for the UBIV are shown in Table 1.

(4) The maximum non-singular set of the graph and the corresponding characteristic non-singular set of each edge are shown in Table 2.

(5) If the breaker status is unknown, the iterative progress of the optimal placement is shown in Table 3. If the breaker status is known, similar iterative progress is used to get the optimal placement plan.

Results show that the optimal placement plan with the breaker status in 500kV power grid in Hunan Province of China is the same as the optimal placement plan without the breaker status. It is as follows: Four TWLFE should be installed at substation A, H, D and E separately. The effectiveness of the optimal placement algorithm mentioned above is obvious, it can meet the requirements of reliability and economy. When a fault happened on any transmission line, at least one element of maximum non-singular set of the graph on which TWFLE have been installed can be used to locate the fault position; meanwhile, the installation number of TWFLE is the minimum. The optimal placement plan in literature [17] is P= [A, B, D, E, H], obviously it is not optimal. The optimal placement plan obtained in this paper is the same as the result in literature [18], but the algorithm proposed in this paper is simpler, more convenient and supported by adequate evidence. Meanwhile, through combination of the optimal placement algorithm and the NBTWFL method based on maximum non-singular set mentioned below, the fault position can be located without breaker status.

Table 1. Maximum non-singular subsets of all vertexes except for the UBIV in power grid shown in Fig. 3

Vertex	Maximum non-singular subset	Vertex	Maximum non-singular subset
A	A-B-C-D A-B-E A-B-G-F A-B-G-H	E	E-D E-B-C E-B-A E-F-G-H
B	UBIV	G	UBIV
C	C-B-A C-B-E C-B-G-F C-B-G-H	F	F-E-D F-G-B-C F-G-B-A F-G-H
D	D-C-B-A D-E-F-G-H	H	H-G-B-C H-G-B-A H-G-F-E-D

Table 2. Maximum non-singular set of the graph and the corresponding characteristic non-singular set of each edge in power grid shown in Fig. 3

Maximum non-singular set of graph	Edge	Characteristic non-singular set
A-B-C-D A-B-E A-B-G-F A-B-G-H C-B-E C-B-G-F C-B-G-H D-E-F-G-H	AB	A-B-C-D A-B-E A-B-G-H
	BC	A-B-C-D C-B-E C-B-G-F C-B-G-H
	CD	A-B-C-D
	DE	D-E-F-G-H
	EF	D-E-F-G-H
	BE	A-B-E C-B-E
	FG	A-B-G-F C-B-G-F D-E-F-G-H
	BG	A-B-G-F A-B-G-H C-B-G-F C-B-G-H
	GH	A-B-G-H C-B-G-H D-E-F-G-H

Table 3. The iterative progress of the optimal placement without breaker status in power grid shown in Fig. 3

	The vertexes which install TWFLE	Sort of edges	Number of elements	If or not to be considered in next step
Initial Status	A, H	CD DE EF BE AB FG GH BC BG	1 1 1 2 3 3 3 4 4	Yes Yes Yes Yes No Yes No Yes No
First step	A, H, D	CD DE EF BE FG BC	1 1 1 2 3 4	No No No Yes No No
Second step	A, H, D, E	BE	2	No

In order to compare with the algorithm proposed in literature [19], take the power grid mentioned in literature [19] as an example which is shown in Fig. 4.

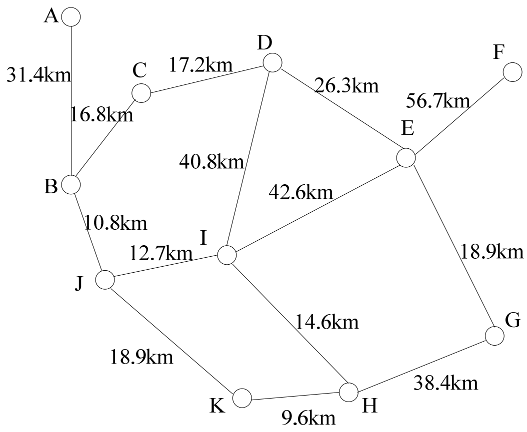

Fig.4 one typical power grid for simulation

Similar progress is used to obtain the optimal placement without breaker status and optimal placement with breaker status. The result shows that the optimal placement plan with breaker status for the power grid shown in Fig. 4 is the same as the optimal placement plan without breaker status. It is as follows: six TWFLE are installed at A, F, H, D, K and G separately. The optimal placement plan for the power grid shown in Fig. 4 based on multi-DOF is P= [A, F, K] which is presented in literature [19], obviously it is not optimal. For example, when a fault *f* happened on line ID and is 5km from I (the characteristic non-singular set of ID is {H-I-D}, the recorded time at A, F and K would be:

$$(6)\qquad \begin{cases} T_A = T_f + (L_{fI} + L_{IJ} + L_{JB} + L_{BA}) / \upsilon \\ T_K = T_f + (L_{fI} + L_{IH} + L_{KH}) / \upsilon \\ T_F = T_f + (L_{fI} + L_{IE} + L_{EF}) / \upsilon \end{cases}$$

where: T_f – fault time, unknown, T_A, T_K, T_F – the recorded time at A, F and K separately, υ –velocity of traveling wave.

Based on equation (6), the fault position can't be located. For the optimal placement plan obtain in this paper, the fault position can be located using the arrival time difference recorded by the TWFLE installed at both endpoints of element H-I-D.

5 Concrete realization of NBTWFL method

5.1 Additional installation plan of TWFLE

The optimal placement plan is to confirm a plan which keeps installation number of TWFLE to minimum. But when conditions permit, additional TWFLE will improve the reliability of fault location system. Based on the progress of optimal placement and the characteristics of traveling wave propagation, the principle of additional installation of TWFLE is as follows:

(1) If an additional TWFLE has been installed at vertex *u*, flags of some elements belonging to the maximum non-singular set of the graph will change to 1 (flag 1 of one element represents that both endpoints have installed TWFLE, otherwise the flag equals 0). The additional installation plan should keep number of the elements whose flag has changed to maximum. When the plan is not unique, select the plan which guarantees that the elements whose flag has changed contain the maximum number of edges.

(2) The bigger degree of vertex is, the smaller the transmittance is, which means the amplitude of transmitted wave is smaller. So the maximum degree of vertex has priority to install TWFLE.

According to the principle (1), the prior vertex to install TWFLE in the power grid shown in Fig. 3 is C; according to the principle (2), the prior vertex is B.

5.2 NBTWFL based on maximum non-singular set

When the operation of breaker is correct and its status can be obtained by the NBTWFL system, fault position can be located by the TWFLE installed at the endpoints of the elements belonging to the graph maximum non-singular set. However, the used TWFLE can't be located on the same side of the fault line in traveling wave propagation path.

Assuming a fault happened on line $u\upsilon$ and the TWFLE installed at substation r and s are used (traveling wave propagates through u to r and propagates through υ to s), then

$$(7)\qquad X_{uf} = \frac{1}{2}[\upsilon(T_r - T_s) + L_{u\upsilon} + L_{\upsilon s} - L_{ru}]$$

Take the power grid shown in Fig. 3 as an example, when a fault happened at *f* on line CD and is 30km from vertex D, recorded arrival time of wave-front is shown in Table 4 and it is benchmarked by the arrival time of substation D which traveling wave arrived at first [17].

Since traveling wave propagates through C to A, the fault position can be located using the recorded arrival time at A and D shown in Table 4 based on the equation (7).

$$X_{Df} = \frac{1}{2}[\upsilon(T_D - T_A) + L_{DC} + L_{CA} - L_{DD}] = 29.884 \text{ km}$$

The error of the fault location is -0.116km. Because fault location method doesn't use the arrival time recorded by the other installed TWFLE, the NBTWFL method based on the maximum non-singular set can simplify the calculation procedure and inherently eliminate the virtual fault positions.

Table 4. The wave-fronts arrival time recorded at A, H, D and E

Substation	Arrival time/μs	Substation	Arrival time/μs
A	959.77	D	0
H	1412.41	E	393.35

In the industry field, TWFLE may detect the traveling wave when the breaker doesn't act [1]. For this situation, the fault position located by the TWFLE usually indicated the weaknesses of the system. In addition, transmission error of breaker status or malfunction of breaker may happen. So it's necessary to study the NBTWFL method without the breaker status.

According to the characteristics of traveling wave propagation, the nearest substation *u* would detect the wave-fronts of traveling wave first and the fault position can be located on the extensive lines which contain the substation *u*. Only when the arrival time of wave-fronts recorded by the TWFLE installed at both endpoints of the extensive lines which contain the fault line is used, fault position can be located correctly. Otherwise the result of fault location would be actually at the transmission point in the traveling wave propagation which is the substation *u*.

When considering the error of the recorded time, fault position *f* would be equivalently located at the substation *u* if the following condition is met:

$$(8)\qquad |[L_{rs} + \upsilon(T_r - T_s)] / 2 - L_{ru}| < \upsilon|\Delta t|$$

Δt represents the error of the recorded time difference at both endpoints of the line and can be set as ±2μs [22].

Assuming a fault happened at *f* on line CD and is 30km from vertex D in power grid shown in Fig.3 again, the progress of fault location is as follows:

(1) D is the substation which traveling wave arrives at first and the corresponding maximum extensive lines which contain the substation D have A-B-C-D and D-E-F-G-H.

(2) The result of fault location is shown in Table 5.

The final result of fault location proved that fault line can be identified correctly and the error of fault location is only -0.116km. The NBTWFL method without breaker status based on the maximum non-singular set can work effectively.

Table 5. The result of fault location without the breaker status

The maximum extensive line	If or not at the substation	Virtual fault location/km	Final result
A-B-C-D	No	X_{Df}= 29.884	On line CD and is 29.884km from D
D-E-F-G-H	Yes	X_{Df}= -0.230	

5.3 Limitation of NBTWFL method

A. NBTWFL method in ring configuration

When a fault happened at position F shown in Fig. 5(a), the propagation path of initial wave-fronts of traveling wave may change because of the different relative lengths of the edges. Unlike the situations shown in Fig. 5(b) and Fig. 5(c), fault positions in Fig. 5(d) and Fig. 5(e) are not on the extensive line any more, and fault location will fail based on equation (2). So the fault position needs other measures to be located [4-12].

The situations shown in Fig. 5(d) and Fig. 5(e) may happen in the ring configuration when the following conditions are met:

$$\begin{cases} \Delta l < [L_{BC} - (L_{AB} + L_{AC})]/2 \\ L_{BC} > L_{AB} + L_{AC} \end{cases} \tag{9}$$

where: Δl – the distance between fault position and the terminal of faulty line, L_{BC} – the length of faulty line. L_{AB} & L_{AC} – The length of healthy line.

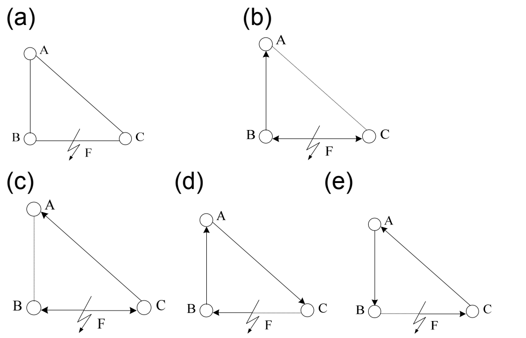

Fig. 5 Different propagation paths in ring configuration

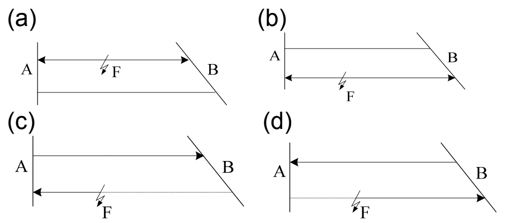

Fig. 6 Different propagation paths in double circuit lines

B. NBTWFL in double circuit lines

If lengths of double circuit lines are the same, the double circuit lines can be equivalent to one line in fault location. However, when lengths of double circuit lines are different, propagation path of initial wave-fronts of transient traveling wave may change because of different fault positions. In Fig. 6(a) or Fig. 6(b), fault position is still on the line AB and it can be located. In Fig. 6(c) and Fig. 6(d), fault positions are not on the line AB any more, and fault location will fail based on equation (2). So the fault position needs other measures to be located [4-12].

The situation shown in Fig. 6(c) and Fig. 6(d) may happen in the double circuit lines configuration when the following conditions are met:

$$\begin{cases} \Delta l < (L_1 - L_2)/2 \\ L_1 > L_2 \end{cases} \tag{10}$$

where: Δl – the distance between fault position and the terminal of faulty line, L_1 – the length of the longer line, L_2 – the length of the shorter line.

6 Conclusion

This paper proposed an optimal placement algorithm of TWFLE in power grid. It can keep the installation number of TWFLE to minimum and locate the fault position on any transmission line. The conclusion of this paper is as follows:

(1) The maximum non-singular set of the topological graph can be obtained by use of Dijkstra algorithm and power grid can be decomposed into several maximum extensive lines based on it. Then optimal placement plan can be confirmed according to this principle.

(2) The optimal placement algorithm based on characteristic non-singular set can work well whether or not breaker status is known.

(3) The optimal placement algorithm based on characteristic non-singular set can be completely combined with the NBTWFL method based on maximum non-singular set in principle. This not only can simplify the calculation procedure and inherently eliminate the virtual fault positions, but also can locate the fault position correctly without breaker status.

(4) The proposed optimal placement algorithm of TWFLE can be achieved easily and satisfy the requirement of power grid's operation.

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