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Fast Search Algorithm for Key Transmission Sections Based on Topology Converging Adjacency Matrix

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ABSTRACT The traditional method of searching transmission section generally has the problem of omission and time-consuming. A topology converging algorithm of power grid adjacency matrix is proposed in this paper. It aggregates neighboring buses based on a simple matrix transformation rule, and identify key transmission sections based on matrix operations and power flow distribution factors. This method has the advantage of no presetting the sub-zone, which can avoid the simplification of the grid topology in the sub-zone and improve the calculation accuracy. The complex logical operations of the traversal algorithm adopted by most of traditional methods can be avoided, and the calculation speed can be effectively improved. Besides, the algorithm also has a memory characteristic which can be applied to the online search of key transmission sections. The results of several IEEE test systems show the effectiveness of the proposed algorithm.

INDEX TERMS Key transmission sections, power grid operation monitoring, adjacency matrix, topology converging, blackouts.

ABBREVIATIONS

TS	Transmission Section
KTS	Key Transmission Section
TCAM	Topology Converging Adjacency Matrix
PFDF	Power Flow Distribution Factor

NOMENCLATURE

ΔP_k^l	variation of active power of line k after the outage of line l
P_l	active power before the outage of line l
α_{k-l}	PFDF of line k after the outage of line l
X_{k-l}	mutual impedance between port k and port l, and the port k and l is the pair of nodes connecting the line k and l to the power grid respectively
X_{l-l}	self-impedance of port l
X	node impedance matrix of the power grid
M_l	column vector corresponding to line l in node-line incident matrix
M_k	column vector corresponding to line k in node-line incident matrix
x_l	line reactance of line l
x_k	line reactance of line k
α_{set}	preset threshold value between 0.2 to 0.3
$G(V, E)$	graph with vertex vector V and edge vector E
V	vertex vector with vertex elements $v_1, v_2, \ldots, v_n$
E	edge vector with edge elements $e_1, e_2, \ldots, e_m$
$A(G)$	adjacency matrix of graph G
a_{ij}	element of row i and column j in the adjacency matrix $A(G)$
D	distance index of the adjacency matrix
ψ	set of subscripts with a_{ij} value of 1 in the adjacency matrix
D_{af}	distance index in D after exchange operation
A	adjacency matrix

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B topology converging adjacency matrix
S sub-matrix
v_t starting bus of a sub zone
v_{t+b} ending bus of a sub zone
n_{ts} number of transmission lines in the sub-matrix S corresponding to a sub zone
N_{ts} preset upper limit number of lines in the TS
R connectivity judgment matrix for the adjacency matrix Z of order n of a sub zone
r_{ij} number of paths from bus v_i to v_j in matrix R

I. INTRODUCTION

Many blackouts in the world have caused serious consequences. On August 14, 2003, the North American blackout cost nearly 40 billion dollars [1]. On November 4, 2006, the blackout in Western Europe led to darkness in many important cities in France, Germany, Italy, Spain and Austria [2]. On July 30, 2012, the blackout in India spread to three regional power grids in the north, East and northeast of India, affecting about 600 million people [3]. Although the causes are different, they have a similar evolutionary process of cascading failures. The power grid is under heavy load and multiple components are scheduled outage. After an occasional failure of a component, it is cut off by the protection device. The power flow carried by this component is transferred to the adjacent transmission lines, which make the power flow on the originally heavy loaded adjacent lines break through the thermal stability limit rapidly, and causes the overload protection devices to trip successively, leading to cascading failures.

Large scale blackout exposes the following problems in the current power grid operation monitoring,

1) The high proportion of new energy and increasing load increase the complexity of power grid operation [4]. The load area and power generation area of the system change repeatedly with the operation mode of the power grid, causing heavy-load transmission lines to continuously shift. System security monitoring becomes more and more difficult.
2) The correlation of the components in the power grid has not been paid enough attention. If the adjacent lines do not have sufficient transmission margin to absorb the transferred power flow [5], [6], the outage of a heavy-load line will lead to cascading failure [7], and eventually develop into a large-scale serious accident.

Therefore, finding a fast algorithm to identify the lines with strong correlation and further analyzing the impact of outages on other lines is particularly important in formulating more reasonable fault handling strategies to prevent the occurrence of blackouts [8], [9]. According to the operation experience of the power grid, there are weak links in the power grid that are easy to exceed the power flow limit [10], and the weak links are often the connecting lines between the power supply area and the load area [11]. To solve this problem, a concept called "Key Transmission Section (KTS)" is proposed [12]–[26]. But its definition is different for different application purposes. The stability constrained KTS is mainly used for power grid stability research [12], while the static physical relationship KTS studied in this paper focuses on prevent large-scale cascading overload fault caused by power flow transfer. The KTS embodies the weak link in the power grid. Due to the large scale of power grid interconnection, high proportion of new energy access, random failure of equipment, planned outage and other variables, the KTS changes frequently. In the initial stage of overload, KTS composed of lines affected greatly by power flow transfer should be searched quickly. Then emergency control measures such as adjusting generator output or load cutting are adopted to eliminate overload. How to quickly identify the KTS on line with the change of power grid operation is the core technology to prevent power grid disaster.

Traditionally [13], [14], TS is subjectively identified by experts based on personal experience and cannot adapt to the complexity of modern power grid operations affected by multiple uncertainties. Decisions cannot be made quickly and accurately when grid operations are facing urgent evens.

In order to monitor the power flow transfer caused by equipment outage, reference [15] considers that the line affected by the outage line is directly or indirectly connected to the terminal of the outage line. But only the shortest path for power flow transfer is searched, and the key transmission lines in other paths are easily missed. The shortest path method is improved in [16], [17], and the K shortest path is searched by the deviation path method or the improved Dijkstra method. But this kind of method needs to check the power flow of each line in the system, which is not only computationally intensive, but also unable to search for the KTS when there is no topology change but only power change. A data driven method is proposed in reference [18], which can train KTS search model offline and apply them online. But the accuracy of KTS search model depends on a large number of high-quality samples.

To make up for the above defects, the method of graph theory to search the TS is proposed in [19]. But before searching, it is necessary to determine the set of power supply buses for each generator, and then the generators are assigned to sub zone by group, determine the chain between sub-zones, and then build a state transition diagram. The idea in [19] was further developed in [20]. KTS is searched by clustering the power components of line. But the power contribution of each generator to each transmission line needs to be calculated in advance. In order to reduce the amount of calculation, the power grid needs to be divided into several sub zones according to generators and loads. The complex preparation before searching makes these algorithms unable to adapt to the flexible operation of power grid. The method of searching the key TS using the traversal algorithm is proposed in [21], but the traversal algorithm is a typical NP problem with heavy calculation burden as the scale of the power grid increase. In order to meet the needs of online application, this paper uses electrical distance to partition the power grid to reduce the computational complexity. In [22], [23], the power grid is pre zoned by geographical division to simplify the network. And in [24], [25], the power grid is pre zoned by GirvanNewman algorithm. Then, the complex network theory is used to construct index of transmission betweenness to identify the key TS. All the above methods need to partition the power grid in advance in order to quickly search the key TS. With the increase of power grid scale, if the preset sub zone is too small, the calculation time cannot be effectively controlled. If the preset sub zone is too large, the characteristics of the network topology within the sub zone will be eliminated, resulting in the omission of KTS. It is difficult for such algorithms to guarantee both speed and accuracy.

In summary, the main obstacles to the online search of key TS are the slow calculation speed caused by the traversal algorithm and the omission caused by the pre zoning of power grid. Aiming at this problem, a fast search algorithm for key TS based on the Topology Converging Adjacency Matrix (TCAM) is proposed in this paper. The main contributions of the algorithm are as follows:

1) This algorithm uses a simple matrix exchange rule to transform the adjacency matrix of the power grid into TCAM, which can rearrange neighboring buses according to their distance in the topology.
2) There is no need to use a fixed preset sub zone, and the simple operation of the sub-matrix on TCAM is used to identify the key TS, avoiding the heavy calculation burden of the traversal algorithm.
3) The algorithm proposed in this paper also has the memory property. When a line is out of service with the change of power grid operation mode, it does not need to calculate from the beginning like the traditional method, only needs to modify the last TCAM locally, which can save a lot of calculation time.

The calculation results of multiple IEEE test systems show that the proposed algorithm is accurate and efficient.

The rest of the paper is organized as follows. The definition of KTS is given in Section II. The two forms of adjacency matrix of power grid are presented in Section III. Topology converging algorithm of adjacency matrix is proposed in Section IV, and the search method for KTS is given in Section V. The overall process of the algorithm is presented in Section VI. A case study is given in Section VII, followed by conclusions in Section VIII.

II. DEFINITION OF THE KEY TRANSMISSION SECTION

In the actual operation of the power grid, the dispatcher divides the power grid into several sub zones according to the geographical location of the main power supply and load. Based on the analysis of the historical operation data of the power grid, the connecting lines with strong correlation between sub zones are identified as the TS. There are two main characteristics of the TS. First, the TS is a group of tie lines between a connected sub zone and an external grid. When all the connecting lines are removed, the sub zone will become an isolated network. Secondly, the direction of power flow of all lines included in the TS should be the same. This reflects the power transmission characteristic of TS from the generation zone to the load zone. When the transmission power of the opposite direction is less than 10% of TS, it is still approximately considered that the power flow direction of the TS is the same [23]. The above characteristics of TS are accepted by many scholars [12], [19], [24]–[26], which can be used to prevent cascading overload faults caused by power flow transfer of component outage. In summary, the definition of TS is as follows,

Definition of TS: a group of transmission lines connected between two connected zones with the same direction of power flow and having cut set property in the network topology diagram under a certain reference power flow.

The number of TS is huge and the operation mode of power grid is complex. Due to the nonlinearity of the power grid model, the outage of lines in different TS will have different effects for other lines. Only TS containing strongly correlated lines should be monitored. When a line included in this kind of TS is out of service, the power flow on the line will transfer to others in the TS, resulting in cascading failure. The definition of KTS is given as follows [19],

Definition of KTS: For a certain TS, the power flow of the remaining lines is greatly affected by the disconnection of any line, which is called the key transmission section.

Whether TS is the KTS is determined by the PFDF [27] of the remaining lines in the TS after any line outage. Suppose there are m ($m = 1,2,\ldots, l, \ldots, k, \ldots, m$) lines in a TS. When line l is out of service, the active power on line l will be transferred to the remaining lines in the TS. The variation of active power on line k can be expressed as follows,

$$\Delta P_k^l = \alpha_{k-1} P_l \tag{1}$$

where, P_l is the active power before the outage of line l; ΔP_k^l is the variation of active power of line k after the outage of line l; α_{k-l} is the PFDF of line k after the outage of line l, which is the proportion of active power transferred from line l to line k.

α_{k-l} can be derived from DC power flow formula [28] as follows,

$$\alpha_{k-l} = \frac{X_{k-l}/x_k}{1 - X_{l-l}/x_l} \tag{2}$$

$$X_{k-l} = M_k^T X M_l \tag{3}$$

$$X_{l-l} = M_l^T X M_l \tag{4}$$

X_{k-l} represents the mutual impedance between port k and port l, where the port k and l is the pair of nodes connecting the line k and l to the power grid respectively; X_{l-l} indicates the self-impedance of port l; X is the node impedance matrix of the power grid; $\mathbf{M}_l$ and $\mathbf{M}_k$ are the column vectors corresponding to line l and line k in node-line incident matrix respectively; x_l and x_k are the line reactance of line l and k respectively.

The index of α_{k-l} can reflect the correlation degree between lines in the TS. A TS can be identified as the KTS when α_{k-l} is greater than the preset threshold value α_{set} under the circumstance of line k outage.

$$\alpha_{k-l} > \alpha_{set} \tag{5}$$

Usually, the value of α_{set} is determined according to the experience of power grid operation experts, and the range is set between 0.2-0.3. It can also be dynamically adjusted according to the operation state of the power grid. For example, a smaller α_{set} can be selected when the grid is heavy loaded, a larger α_{set} can be selected when the grid is lightly loaded.

III. TWO FORMS OF ADJACENCY MATRIX OF POWER GRID

The identification of the KTS depends on the fast searching of the TS of the power grid. The power system can be abstracted into a graph when only the topological structure of the network is studied without considering the electrical characteristics of the network components. The bus in the power grid is represented by vertex v, where the branch is represented as edge e. For a power grid with n buses and m lines, its topology can be represented by graph $G(V, E)$. where, $V = \{v_1, v_2, \ldots, v_n\}$, $E = \{e_1, e_2, \ldots, e_m\}$. The topology model of the power grid can be constructed as undirected graph. After cut sets of the topology are searched and determined as the sub zones of the power grid, the direction of the line power flow is used to verify whether the cut set can be identified as the TS. For a graph G with n nodes, its adjacency matrix is an n-order 0-1 symmetric matrix. The adjacency matrix of graph G can be expressed as follows [28]:

$$A(G) = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & \ddots & & & \vdots \\ a_{i1} & & a_{ij} & & a_{in} \\ \vdots & & & \ddots & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \tag{6}$$

where a_{ij} is the element of row i and column j in the adjacency matrix $A(G)$. When there is an edge between vertex v_i and v_j, the value of a_{ij} is 1, otherwise 0.

For a network topology with 12 nodes as shown in Fig. 1, the adjacency matrix can be obtained according to the sequence of node numbers, as shown in Fig. 2 (a). The node number $V = \{v_1, v_2, \ldots, v_{12}\}$ is displayed on the left side and the upper side of the matrix respectively. For the sake of clarity, the color block is used to represent the adjacency matrix. The black blocks indicate that the elements in the matrix have a value of 1, and the white blocks indicate that the elements have a value of 0.

According to the definition of the TS of the power grid, the lines included in the TS of the power grid must be the cut sets of the two interconnected zones of the topology diagram, and their power flow directions must be consistent. It can be known from the topology of Fig. 1 that the graph

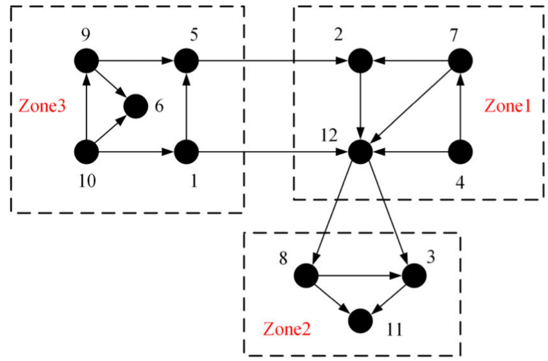


FIGURE 1. **The 12-bus network topology diagram.**

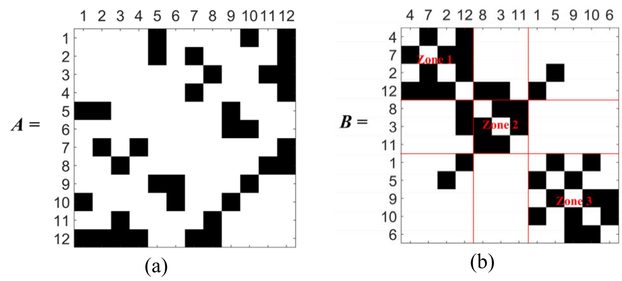


FIGURE 2. **Two forms of adjacency matrix of the 12-bus network topology diagram.**

can be divided into three zones, each zone's external connecting lines is a cut set. If the cut sets have the same flow direction, they can be considered as TS. Experienced experts can aggregate buses with relatively close electrical distances into a sub zone, and then select their external connection lines as the cut set. This process depends on the expert's familiarity with the power grid, cannot handle emergencies and may miss important TSs. But the existing computer traversal algorithms to search cut sets are NP-hard problem with a heavy computation burden and cannot be used directly for large-scale power grids.

The adjacency matrix shown in Fig. 2(a) is arranged according to the natural sequence of the bus numbers. The distribution of the elements with a value of 1 in the matrix is irregular, and it is difficult to directly divide the sub zones from the matrix. If there is an algorithm that can change the form of Fig. 2(a) to Fig. 2(b) by exchanging the sequence of node numbers, so that the nodes are arranged according to the principle of near-to-far in the topology graph, then the problem of cut set searching in the topology graph can be converted to the problem of element partition of 1 in the adjacency matrix, which can greatly reduce the computational complexity. As shown in Fig. 2(b), three zones can be easily divided. The topology converging algorithm of adjacency matrix given in the next section can achieve this goal.

IV. TOPOLOGY CONVERGING ALGORITHM OF ADJACENCY MATRIX

Fast and accurate search of KTS depends on accurate power grid sub-zone's division. The sub zone division of power grid refers to the division of buses with adjacent electrical distance into a group which is regarded as virtual buses in the entire

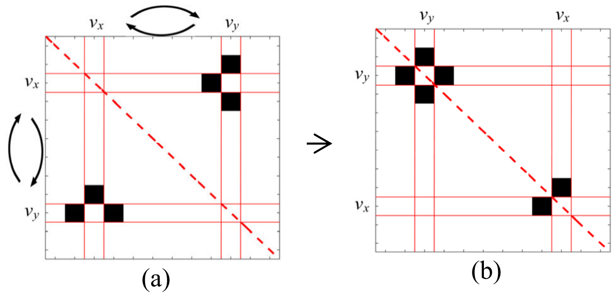


FIGURE 3. Operation ($V_x \leftrightarrow V_y$) between bus V_x and V_y.

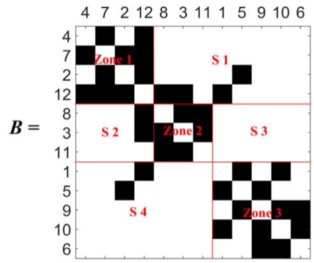


FIGURE 4. Sub matrix about TS in B.

topology. The external connection lines of the virtual bus are the KTS of the corresponding sub zone. Each bus number in the power system does not consider the mutual connection relationship between the buses. The element distribution in the adjacency matrix arranged by the bus number is scattered and disorderly. It is impossible to divide the sub zone directly on such adjacency matrix. The sequence of the buses of the adjacency matrix shown in Fig. 2(a) is adjusted to artificially bring adjacent buses together and arrange them into a pattern shown in Fig. 2(b). It is found that the elements with a value of 1 in the matrix are converged near the diagonal. So a conclusion can be drawn that as long as the elements with the value of 1 in the adjacency matrix are concentrated near the diagonal as much as possible, the numbers of adjacent buses in the topology can be gathered together in the matrix. If the adjacent buses in the adjusted adjacency matrix are interconnected, they can be divided into a sub zone.

Based on this idea, the topological converging algorithm of adjacency matrix is proposed in this paper. The elements with value of 1 in the adjacency matrix are converged to the main diagonal by simple row and column exchange operation. The adjacency matrix after operation is denoted as B, which is called topological converging adjacency matrix. In order to quantitatively measure the distance between the elements and the main diagonal, the distance index of the adjacency matrix is defined as follows,

$$D = \sum_{i,j \in \Psi} |i - j| \tag{7}$$

where, ψ is the set of subscripts with a_{ij} value of 1 in the adjacency matrix. The smaller the value of D, the more the elements with a value of 1 in the adjacency matrix converge toward the main diagonal.

The main operation of adjacency matrix topology converging algorithm is to exchange rows and columns. Because it is a symmetric square matrix, rows and columns need to be exchanged synchronously. Define the exchange operation $(v_x \leftrightarrow v_y)$ between buses v_x and v_y in the adjacency matrix, which means that the corresponding rows and columns of the buses numbered v_x and v_y in the adjacency matrix are exchanged respectively. The process is shown in Fig. 3.

The steps of topology converging algorithm of adjacency matrix with n buses are as listed below:

1) For the adjacency matrix A, calculate the distance index D before the exchange operation.
2) For bus v_x ($1 < x < n$), perform $(v_x \leftrightarrow v_{y(\min)})$ operation, in which $v_{y(\min)}$ ($1 < y < n$, $x \neq y$) is a bus that can minimize the distance index D_{af} after exchange with bus v_x.
3) Store the distance index D_{af} in D after the exchange operation, that is, $D = D_{af}$.
4) Repeat steps 2)-3) for bus v_{x+1} until all n buses are exchanged.
5) Repeat steps 1)-4) until there are no new exchange operations. The adjacency matrix A is transformed into the topology converging adjacency matrix B.
6) Output the topology converging adjacency matrix B.

As a result of the given steps, the sequence of the buses of the adjacency matrix is rearranged according to the topological structure. For the 12-bus network shown in Fig. 1, its adjacency matrix is transformed from Fig. 2(a) to Fig. 2(b). Buses that are closely related in the network topology are aggregated together, and buses that are more distantly connected are assigned to farther away locations. Compared with the original adjacency matrix A, the topology converging adjacency matrix B reflects the characteristics of the network topology.

V. SEARCH METHOD FOR KTS

The topology converging algorithm proposed in Section IV provides conditions for grid partitioning and search of KTSs. Fig. 4 shows the topology converging adjacency matrix in Fig. 1. The sequence of its buses has been transformed from {1,2,3,4,5,6,7,8,9,10,11,12} to {4,7,2,12,8, 3,11,1,5,9,10,6}. The sub zones 1, 2 and 3 can be divided intuitively. In fact, the transmission lines included in the sub-matrix composed of the rows of each sub-zone except for itself is the TS. This sub-matrix of the TS is represented by S.

As shown in the Fig. 4, the bus set {4,7,2,12} can be divided into sub zone 1. The TS of sub zone 1 refers to the connection lines outside the zone 1, corresponding to the elements with value 1 contained in sub matrix S1. Similarly, the bus set {8,3,11} can be divided into sub zone 2, and its TS is the connection lines contained in the sub-matrices S2 and S3. The bus set {1,5,9,10,6} can be divided into sub zone 3, and its TS is the connection lines contained in the sub-matrix S4. The sub zones and their TS can be easily searched based on the main diagonal of the TCAM. After all TSs are found, the distribution factors among lines in each TS can be calculated to determine which the KTSs are. It should be noted that, the zone is different from that of the traditional algorithm. The zone is searched on the diagonal of TCAM and is not fixed. Each zone corresponds to a matrix S, and the lines included in the S matrix are the TS.

The steps of the KTS search algorithm are as follows,

1) All sub zone with buses set $\{v_\zeta,\ldots, v_\eta\}$ and its corresponding sub-matrix S are searched from the TCAM with the buses sequence of $\{v_1, v_2,\ldots, v_\zeta,\ldots, v_\eta,\ldots, v_n\}$. where, $1 \le \zeta \le (n-1)$, $\zeta < \eta \le n$. The number of buses included in the sub zone can be specified according to the scale of the power grid.
2) Suppose the number of transmission lines in the sub-matrix S corresponding to a sub zone is n_{ts}, and when $n_{ts} \le N_{ts}$, the lines included in the S are considered as the initial TS. Where, N_{ts} is the preset upper limit number of lines in the TS. This index is used to avoid too many unnecessary TS, especially those with enough interconnection lines that will not cause risks to the power grid.
3) Verify the power direction of connection lines in the initial TS, and keep all connection lines in the initial TS with the same power direction. The undirected graph adjacency matrix is upgraded to the adjacency matrix with power direction. The value in the adjacency matrix is specified 1 when the power direction of the branch is from the column bus points to the row bus, otherwise −1. For the 12 buses network topology shown in Fig. 1, the adjacency matrix with power direction is shown in Fig. 5.
Elements with the value 0 in Fig. 5 are omitted. Whether the power direction of the TS is consistent is determined by whether the signs of the non-zero elements contained in the sub-matrix S are consistent. All of them are positive indications that the power flows from the sub zone to the power grid, and all of them are negative indicate that the power flows from the power grid to the sub zone. As shown in Fig. 5, the four non-zero values of S1, two positive and two negatives, indicating that the four connection lines have opposite power direction, so they are not TS of zone 1. And the signs of non-zero value in the sub-matrices corresponding to zone 2 and zone 3 are the same, so they are TS.
4) Verify the connectivity of the remaining sub zones. Keep the connected sub zones and remove the non-connected sub zones. This is because it is possible to divide a non-connected sub zone when performing a search according to the bus sequence in step 1). Calculate the matrix R for the adjacency matrix Z of order n of sub zone [28],

$$R = Z + Z^2 + \cdots + Z^{n-1} \tag{8}$$

The element r_{ij} in matrix R represents the number of paths from bus v_i to v_j. If all of the elements in matrix R are non-zero, then the sub zone can be judged to be connected.

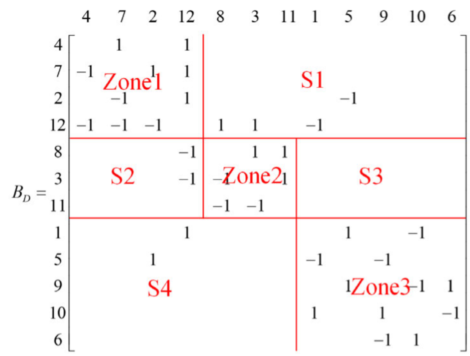


FIGURE 5. Adjacency matrix with power direction.

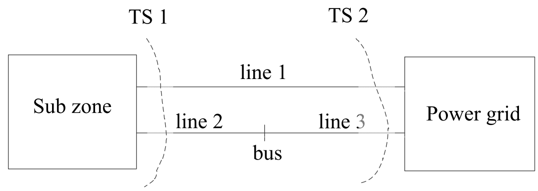


FIGURE 6. KTS combining schematic.

5) The PFDF among the lines in each reserved TS are calculated according to (2) - (4). If one of the PFDF meets the conditions of (5), the corresponding TS is considered as the KTS.
6) Combine the same KTS. As shown in Fig. 6, it is possible to determine TS 1 and TS 2 as KTS simultaneously according to the above steps. Obviously, since line 2 and line 3 are connected by a unique bus in the middle, they can actually be regarded as one line. And the PFDF between line 1 and line 2 in TS 1 is exactly the same as that between line 1 and line 3 in TS 2. Therefore, the KTS with the same PFDF can be determined as the same, only one of them is kept.
7) Output the KTS.

The sub zones and its corresponding sub matrixes searched in step 1) must meet all conditions specified in steps 2) - 6), and the corresponding TS can be determined as the KTS. Steps 2) - 5) have no sequence requirements. In order to save time the steps with short calculation time should be put in the front, while the steps with more calculation time should be put in the back as above present.

VI. THE OVERALL PROCESS OF THE ALGORITHM

The overall process of searching KTS based on TCAM is shown in Fig. 7. The steps are as follows.

1) Collect power grid operation and topology data online.
2) Construct the adjacency matrix A of power grid.
3) The adjacency matrix A is transformed to TCAM B using the algorithm described in Section IV.
4) Search all sub zones and its corresponding sub-matrixes S according to the buses sequence in B.
5) Select one of the sub zones and its corresponding sub-matrix S for the next calculation from the searching results of step 4).

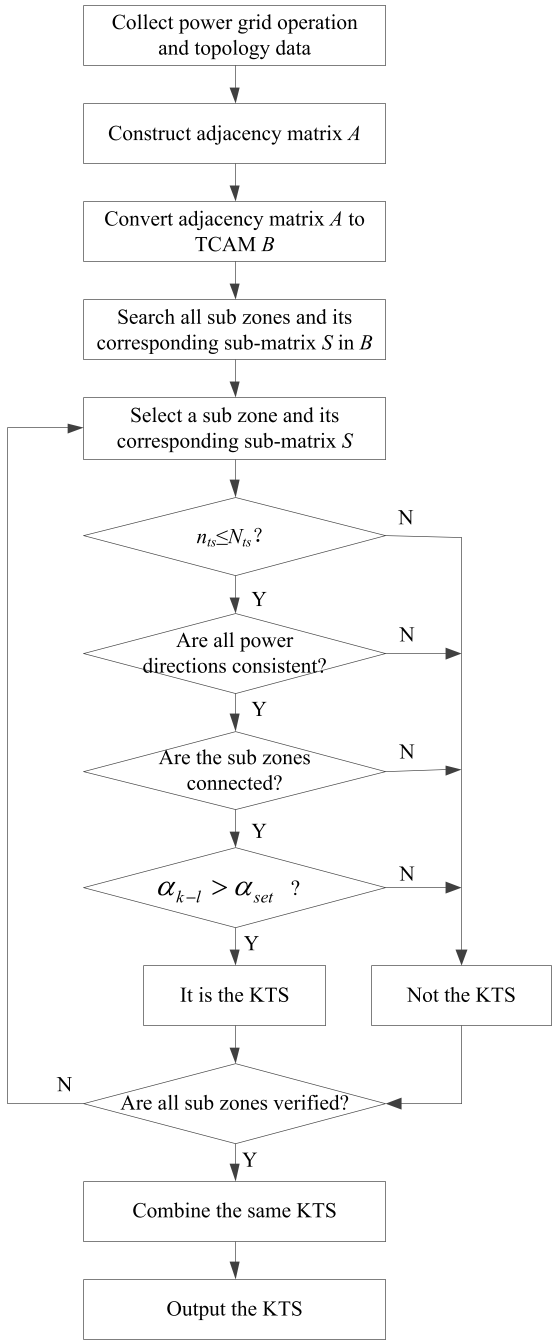


FIGURE 7. The flow chart of KTS search.

6) Verify the condition $n_{ts} \leq N_{ts}$ for the selected sub-matrix S. if it is satisfied, continue to the next step. Otherwise the connection lines included in S is not the KTS, go to step 10).
7) Verify whether the power direction of the connection lines of the selected S is consistent. If the direction is consistent, continue to the next step. Otherwise, it is not a KTS, and go to step 10).
8) Verify the connectivity of the selected sub zone. If it is a connected area, continue to the next step. Otherwise, it is not the KTS, and turn to step 10).
9) Verify whether the index of PFDF between lines of selected sub-matrix satisfy the condition in (5). If it is satisfied, it is the KTS. Otherwise, it is not.
10) Are all sub zones and corresponding sub-matrix verified? If all are verified, go to the next step, otherwise go to step 5).
11) Combine the same KTS.
12) Output the KTS.

Most of the calculation of the algorithm is based on the adjacency matrix, and the calculation speed has obvious advantages compared with the traditional method.

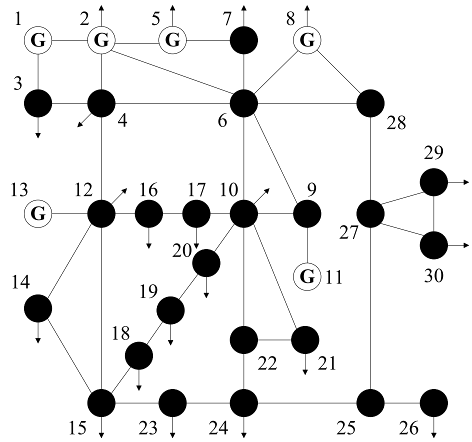


FIGURE 8. Topology diagram of IEEE 30 bus system.

VII. CASE STUDIES

The IEEE 30 bus test system is taken to verify the proposed algorithm. There are 30 buses and 41 transmission lines in the system, and its topology is shown in Fig. 8. According to the sequence of bus numbers, its adjacency matrix A can be obtained as shown in Fig. 9. The order of the buses does not reflect the distance between the buses, so it can not directly partition the power grid on the adjacent matrix.

A. ADJACENCY MATRIX CONVERTED TO TCAM

The adjacency matrix shown in Fig. 9 is reconstructed with the topology converging algorithm in Section IV to obtain the TCAM B, as shown in Fig. 10. It can be seen from Fig. 10 that the values in B are converged to the vicinity of the main diagonal. The buses that are more closely related in topology are gathered together, which provides the possibility to partition the power grid on the adjacency matrix and search for KTS.

B. SEARCH OF KTS ON TCAM

KTS is searched on TCAM with the algorithm described in Section V. When the number of buses in the sub zone is not less than 4 and maximum number of connection lines in TS is 4, 29 TS candidates are found. Among them, 11 meet the power direction consistency conditions, and 11 meet the connectivity conditions in the power grid sub zone. Calculate the PFDF between the lines in the remaining KTS candidates. When the PFDF threshold α_{set} in the KTS is 0.25 and the

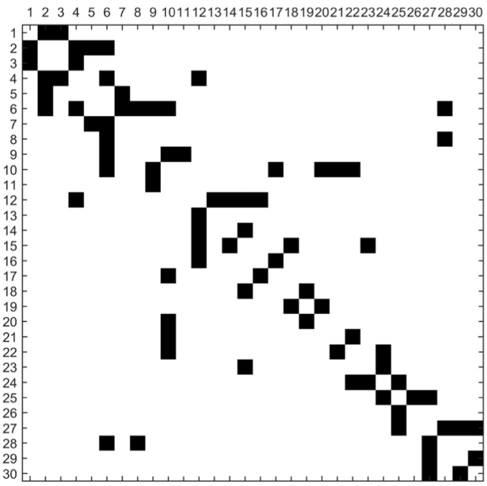


FIGURE 9. Adjacency matrix of IEEE 30-bus system.

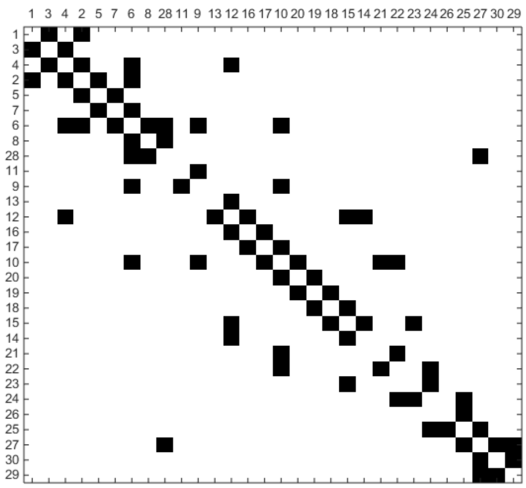


FIGURE 10. TCAM of IEEE 30 bus system.

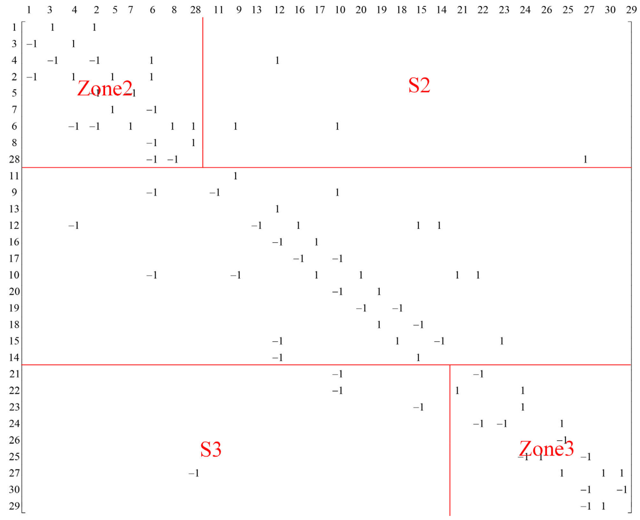


FIGURE 11. TCAM with power direction of IEEE 30 bus system.

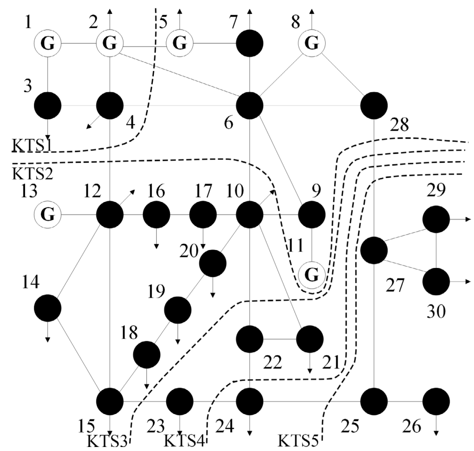


FIGURE 12. Topology diagram of KTS of IEEE 30 bus system.

TABLE 1. KTS and its corresponding sub zones of IEEE 30 bus systems.

sub zone	Buses included in sub zone	KTS
zone 1	1,2,3,4	$l_{2\text{-}5}$、$l_{2\text{-}6}$、$l_{4\text{-}6}$、$l_{4\text{-}12}$
zone 2	1,2,3,4,5,6,7,8,9,11,28	$l_{6\text{-}10}$、$l_{9\text{-}10}$、$l_{4\text{-}12}$、$l_{27\text{-}28}$
zone 3	21,22,23,24,25,26,27,29, 30	$l_{10\text{-}21}$、$l_{10\text{-}22}$、$l_{15\text{-}23}$、$l_{27\text{-}28}$
zone 4	23,24,25,26,27,29,30	$l_{15\text{-}23}$、$l_{22\text{-}24}$、$l_{27\text{-}28}$
zone 5	25,26,27,29,30	$l_{24\text{-}25}$、$l_{27\text{-}28}$

same KTS is combined, 5 KTS are finally determined in the IEEE 30 bus system. The 5 KTS and their corresponding sub zones are shown in Table 1. The PFDF calculation results of KTS of IEEE 30 bus system are shown in table 2. It can be known from Table 2 that disconnecting any one of the lines will greatly increase the power of other lines in the KTS. When the power grid operates under heavy load, the line outage may lead to chain failure and increase the risk of system operation. Therefore, the KTS should be strictly monitored.

The TCAM with power direction of IEEE 30 bus system is shown in Fig. 11. Zone 2 and its corresponding sub-matrix S2, zone 3 and its corresponding sub-matrix S3 are shown in the figure respectively. It can be seen from Fig. 11 that there are four connecting lines between zone 2 and the external power grid, i.e. l_{6-10}, l_{9-10}, l_{4-12} and l_{27-28}, and the four element values in sub-matrix S2 are all $+1$. This means that the power direction of the KTS2 is from sub zone 2 to the external grid. Zone 2 should be an area with many generators.

All KTS are drawn with dashed lines in Fig. 12. As can be seen from Fig. 12, zone 2 separated by KTS2 contains most of the generator buses of the system, which is consistent with the conclusion in Fig. 11.

As shown in Fig. 11, there are l_{10-21}, l_{10-22}, l_{15-23} and l_{27-28} connecting lines between sub zone 3 and external power grid, and the corresponding element values of sub-matrix S3 are all -1. Sub zone 3 should be dominated by load and absorb power from the external grid. It can be seen from Fig. 12 that the sub zone 3 separated by the KTS3 does not include any generator bus. The TCAM which buses have

TABLE 2. PFDF of KTS of IEEE 30 bus system.

KTS	Outage line	PFDF
KTS1	$l_{2\text{-}5}$	$l_{2\text{-}6}$=0.446, $l_{4\text{-}6}$=0.521, $l_{4\text{-}12}$=0.033
	$l_{2\text{-}6}$	$l_{2\text{-}5}$=0.266, $l_{4\text{-}6}$=0.691, $l_{4\text{-}12}$=0.043
	$l_{4\text{-}6}$	$l_{2\text{-}5}$=0.228, $l_{2\text{-}6}$=0.506, $l_{4\text{-}12}$=0.266
	$l_{4\text{-}12}$	$l_{2\text{-}5}$=0.046, $l_{2\text{-}6}$=0.102, $l_{4\text{-}6}$=0.853
KTS2	$l_{6\text{-}10}$	$l_{6\text{-}9}$=0.546, $l_{6\text{-}10}$=0.321, $l_{28\text{-}27}$=0.133
	$l_{9\text{-}10}$	$l_{4\text{-}12}$=0.407, $l_{6\text{-}10}$=0.419, $l_{28\text{-}27}$=0.174
	$l_{4\text{-}12}$	$l_{4\text{-}12}$=0.294, $l_{6\text{-}9}$=0.515, $l_{28\text{-}27}$=0.191
	$l_{27\text{-}28}$	$l_{4\text{-}12}$=0.232, $l_{6\text{-}10}$=0.406, $l_{6\text{-}9}$=0.362
KTS3	$l_{10\text{-}21}$	$l_{10\text{-}22}$=0.810, $l_{15\text{-}23}$=0.120,$l_{27\text{-}28}$=0.070
	$l_{10\text{-}22}$	$l_{10\text{-}21}$=0.877, $l_{15\text{-}23}$=0.078,$l_{27\text{-}28}$=0.045
	$l_{15\text{-}23}$	$l_{10\text{-}21}$=0.489, $l_{10\text{-}22}$=0.293,$l_{27\text{-}28}$=0.218
	$l_{27\text{-}28}$	$l_{10\text{-}21}$=0.423, $l_{10\text{-}22}$=0.254,$l_{15\text{-}23}$=0.323
KTS4	$l_{15\text{-}23}$	$l_{22\text{-}24}$=0.782, $l_{27\text{-}28}$=0.218
	$l_{22\text{-}24}$	$l_{15\text{-}23}$=0.631, $l_{27\text{-}28}$=0.369
	$l_{27\text{-}28}$	$l_{15\text{-}23}$=0.323, $l_{22\text{-}24}$=0.677
KTS5	$l_{24\text{-}25}$	$l_{27\text{-}28}$=1.000
	$l_{27\text{-}28}$	$l_{24\text{-}25}$=1.000

been rearranged provides a very good tool for the topology analysis of power grid.

Some of the KTS marked in Fig. 12 are obtained by combining the same KTS. Taking KTS2 as an example, it includes four lines, l_{6-10}, l_{9-10}, l_{4-12}, and l_{27-28}. However, according to the analysis of the topology in Fig. 12, the transmission section composed of lines l_{6-10}, l_{6-9}, l_{4-12} and l_{27-28} also play the same role in separating the generator buses with the external power grid. The difference between the two KTS is that the lines l_{6-9} and l_{9-10} are different. These two lines share the same bus 9. And the PFDF of the two KTS is equal, so they can be regarded as the same KTS. Only KTS2 is reserved.

C. COMPARISON OF CALCULATION TIME

Traditional KTS search mostly adopt traversal algorithm [19]. But as the number of buses of the power grid increases, the calculation time will increase exponentially. In order to make the traversal algorithm adapt to the on-line search of KTS, some fixed sub zones have to be preset to simplify the topology. The topology in the sub zone is simplified to a fixed virtual bus, which may lead to the omission of KTS search. Different from that, most of the calculations in the algorithm proposed in this paper are data exchange or addition and subtraction operations on the matrix, which can avoid the complex logical judgment of the traversal algorithm, so it has obvious speed advantages. And it does not need to preset fixed sub zones, which has high accuracy. In order to compare the calculation speed of the proposed algorithm with the traversal algorithm [19], the calculation times of the six IEEE test systems are shown in Table 3 and Fig. 13. For the comparability, the IEEE test systems do not partition in advance.

TABLE 3. Comparison of calculation time between traversal algorithm and proposed algorithm.

Test system	traversal algorithm /s	algorithm proposed in the paper/s
IEEE 9	0.056	0.085
IEEE 14	0.287	0.132
IEEE 24	13.033	0.282
IEEE 30	38.158	0.507
IEEE 39	86.365	0.743
IEEE 118	>10min	10.673

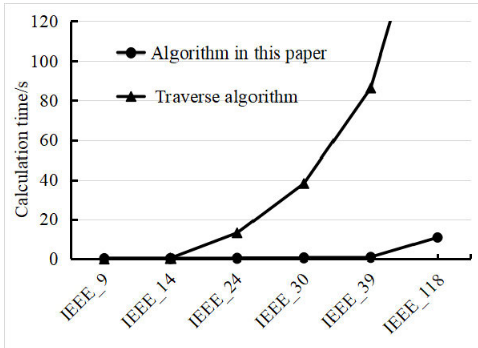


FIGURE 13. Comparison of calculation time.

The computer configuration used is: Intel(R) core (TM) i5, 8G memory, 1TB mechanical hard disk. The operating system is windows 10 64bit, and all programs are run by Matlab R2014b.

As shown in table 3 and Fig. 13, the calculation time of the traversal algorithm increases rapidly with the increase of the number of buses. The calculation time of IEEE 118 test system with traversal algorithm is more than 10 minutes and no result been obtained, the program is terminated artificially. When the number of buses reaches 118, it is difficult for the computer to calculate the results in a short time, which cannot be used for online monitoring of power grid directly. However, the algorithm proposed in this paper has obvious speed advantage and can quickly and efficiently search out KTS of the power grid. This calculation time will increase exponentially with the increase of the number of buses. Due to the memory characteristic of the algorithm, TCAM can be saved during each search. When the grid topology change in local location, only a few modifications on the previous TCAM are needed, and then the TCAM of new grid topology can be obtained by a few iterations, which can save more time.

D. COMPARISON WITH PRE-ZONED METHOD

When the scale of power grid is large, it is time-consuming to search KTS by traversal algorithm. Usually, the number of traversal buses is reduced by pre zoning the power grid. In order to compare with the algorithm in this paper, the

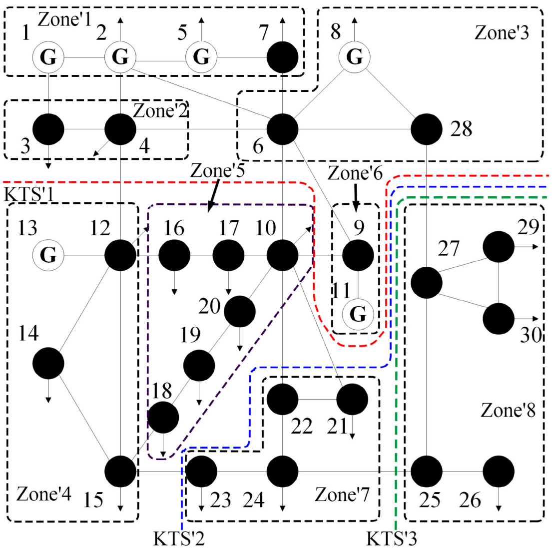


FIGURE 14. KTS of pre-zoned method.

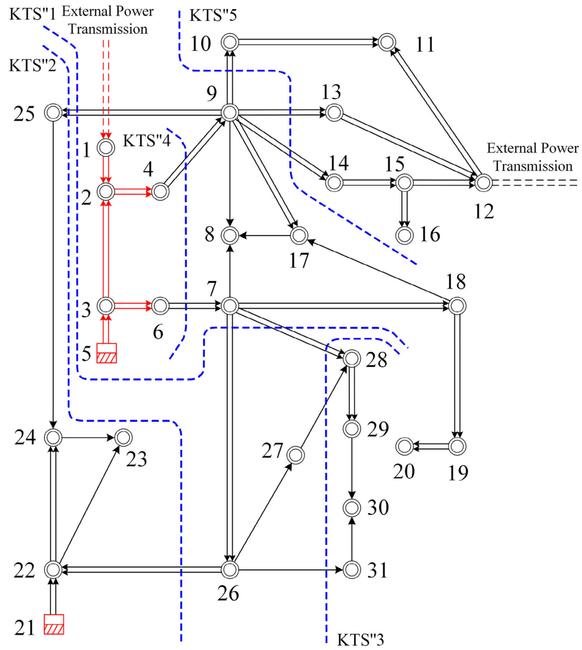


FIGURE 15. Topology diagram of actual power grid.

IEEE 30 bus system is calculated by the method proposed in reference [12].

The main principle of the algorithm is that the zone is usually connected by long-distance high-voltage transmission lines, and its electrical distance is larger than the lines in the zone. Therefore, the tie lines between zones can be found according to the electrical distance between buses, and the power grid can be divided into several sub zones by disconnecting these tie lines. Then, the sub zone of power grid is regarded as a bus. Then, the KTS search is carried out by the traversal algorithm. All lines in the zone do not participate in KTS search. The calculation results are shown in Fig. 14.

It can be seen from the results that the IEEE 30 bus system is divided into 8 sub zones and 3 KTSs are searched out. Compared with the search results of the algorithm presented in this paper shown in Fig. 12, KTS1 and KTS4 are omitted. Because bus 1, 2, 5 and 7 are divided into zone'1, all lines in zone'1 cannot participate in the KTS search. However, there is a strong correlation among the lines l_{2-5}, l_{2-6}, l_{4-6} and l_{4-12} in KTS1. When any of the lines in KTS1 is cut off, the power on the line will be transferred to other lines in large proportion, which may cause cascading overload fault. Similarly, KTS4 is missed because the lines in zone'7 could not participate in KTS search.

The calculation time of the algorithm in reference [12] is 0.274 seconds, while that of the algorithm in this paper is 0.507 seconds. The calculation time of the two algorithms is slightly different. When the system scale increases, the computing speed of the algorithm proposed in this paper will have more advantages. But the algorithm based on TCAM has better calculation accuracy, can search more KTS, and is more meaningful for the safety of power grid.

E. CASE STUDY OF ACTUAL POWER GRID

Part of the actual power grid in Central China is analyzed as an example as shown in Fig. 15. There are 31 buses and 39 transmission lines in the power grid, including 12 single circuit transmission lines and 27 double circuit transmission lines. The voltage level of bus 1, 2, 3, 4, 5 and 6 is 500kV which is denoted in red, and the rest buses are 220kV which is denoted in black. Bus 5 and bus 21 are power plant, in which the output of bus 21 is 192MW and the output of bus 5 is 1516MW.

The calculation time of searching KTS with algorithm proposed in this paper is 0.563 seconds, and 5 KTSs are obtained. The l_{4-9} and l_{6-7} included in KTS"4 connect 500kV substation and 220kV substation, which is the main channel for power transmission of the power grid. All the KTSs searched by the topology converging algorithm of power grid adjacency matrix proposed in this paper is completely consistent with the empirical analysis of experts, which verifies the effectiveness of this algorithm in the actual power grid.

F. DISCUSSION OF CALCULATION RESULTS

1) After analyzing the adjacency matrix, an important law is found in this paper. When the elements in the adjacency matrix are as close to the main diagonal as possible, the sequence of the buses will be rearranged according to their distance in the topology. According to this law, a fast KTS search algorithm using TCAM was proposed. The proposed algorithm can overcome the shortcomings of the traditional traversal algorithm about time-consuming and omission.
2) Once the topology of the power grid changes, the traversal algorithm must restart to calculation. However, the algorithm proposed in this paper has the memory feature of historical operation. When the grid topology is changed due to random fault or planned outage, the corresponding buses of the outage line can

be modified based on the previous TCAM. After a few buses exchange operations, the TCAM can be reconstructed. Then the KTS under the new topology are searched again. Because the modified part can be easily distinguished on the TCAM, the calculation time can be greatly saved. The calculation time of the proposed algorithm shown in Table 3 and Fig. 13 can be further reduced in the actual online application of the power grid. This feature is not available in the traditional search methods. The algorithm proposed in this paper has good scalability.

3) The algorithm proposed in this paper does not need to set the sub zones in advance. Sub zones separated by KTS are found during the search. The sub zones are not fixed, and its internal topology will not be simplified, so the algorithm can more accurately identify weak parts in the power grid. Taking KTS 4 and KTS 5 in Fig. 12 as an example, the sub zone 5 separated by the KTS 5 is actually contained inside the sub zone 4. The algorithm proposed in this paper does not directly simplify the sub zone into a fixed virtual bus, so these two KTS can be identified. However, the sub zones in the traditional search algorithm are preset. Once it is simplified into fixed virtual buses, the topology inside the sub zone no longer participates in topology analysis. This may lead to the omission of the KTS search.

VIII. CONCLUSION

The uncertain output of high proportion of new energy results in frequent power fluctuation between the load zone and the generation zone. The operation mode of power grid is very complex due to the random failure of components, planned outage and other variables, and the KTS changes frequently in the power grid. With the change of the operation mode of the power grid, it is the key technology to quickly identify the KTS.

Aiming at the shortcomings of time consuming and omission of current methods, a KTS search algorithm based on TCAM is proposed in this paper. This method can concentrate the elements of the adjacency matrix near the main diagonal by simple matrix exchange rule, so that the buses are arranged according to the topological distance in the adjacency matrix. This algorithm does not partition the power grid in advance, and can directly identify the sub zone and KTS on the TCAM. In this way, it can avoid the topology simplification of sub zone, and the accuracy is higher than the traditional pre partition method.

Most of the calculation of the algorithm in this paper depends on matrix exchange and matrix addition and subtraction. The method is simple and has obvious speed advantage over the traditional method. And the proposed method has memory characteristics, when the topology changes, it does not need to be calculated from the beginning. It can save a lot of computing time by simply modifying the last TCAM and then searching the KTS. The results of several IEEE test systems show the effectiveness of the proposed algorithm.

The TCAM proposed in this paper represents the topology of the power grid in the sequence of matrix elements. It provides a new idea for the analysis of power grid topology. The KTS search algorithm based on TCAM is fast and accurate, and has broad application prospects in the prevention of grid disasters, grid operation congestion management, and wide area protection.

REFERENCES

[1] D. Novosel, M. M. Begovic, and V. Madani, "Shedding light on blackouts," *IEEE Power Energy Mag.*, vol. 2, no. 1, pp. 32–43, Jan. 2004, doi: 10.1109/MPAE.2004.1263414.

[2] C. Li, Y. Sun, and X. Chen, "Analysis of the blackout in Europe on November 4, 2006," in *Proc. IPEC*, Singapore, Dec. 2007, pp. 939–944.

[3] V. Rampurkar, P. Pentayya, H. A. Mangalvedekar, and F. Kazi, "Cascading failure analysis for Indian power grid," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 1951–1960, Jul. 2016.

[4] A. Ahmadi-Khatir, A. J. Conejo, and R. Cherkaoui, "Multi-area energy and reserve dispatch under wind uncertainty and equipment failures," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4373–4383, Nov. 2013.

[5] W. Li, P. Wang, and Z. Guo, "Determination of optimal total transfer capability using a probabilistic approach," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 862–868, May 2006.

[6] G. C. Ejebe, J. G. Waight, M. Sanots-Nieto, and W. F. Tinney, "Fast calculation of linear available transfer capability," *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 1112–1116, Aug. 2000.

[7] Y. Susuki and I. Mezic, "Nonlinear koopman modes and power system stability assessment without models," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 899–907, Mar. 2014.

[8] Y. Li, B. Hu, K. Xie, L. Wang, Y. Xiang, R. Xiao, and D. Kong, "Day-ahead scheduling of power system incorporating network topology optimization and dynamic thermal rating," *IEEE Access*, vol. 7, pp. 35287–35301, Mar. 2019.

[9] N. Honeth and L. Nordstrom, "Distributed topology inference for electric power grids," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3206–3215, Dec. 2017.

[10] S. S. Halilcevic, A. F. Gubina, B. Strmcnik, and F. Gubina, "Multiple regression models as identifiers of power system weak points," *IEE Proc. Gener., Transmiss. Distrib.*, vol. 153, no. 2, pp. 211–216, Mar. 2006.

[11] M. Girvan and M. E. J. Newman, "Community structure in social and biological networks," *Proc. Nat. Acad. Sci. USA*, vol. 99, no. 12, pp. 7821–7826, Jun. 2002.

[12] J. Liu, X. Li, C. Wang, L. Xu, and H. Gan, "A method of searching multi-type transmission sections based on hierarchical split," *Power Syst. Technol.*, vol. 41, no. 2, pp. 566–573, Feb. 2017.

[13] L. Min and A. Abur, "Total transfer capability computation for multi-area power systems," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1141–1147, Aug. 2006.

[14] X. Zhang and S. Grijalva, "Decentralized total transfer capability evaluation using domain decomposition methods," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3349–3357, Sep. 2016.

[15] W. Zhang and Z. C. Pan, "An automatic shedding decision system for the backup protection of a transmission network," in *Proc. Int. Conf. Power Syst. Technol.*, Chongqing, China, Oct. 2006, pp. 1–6.

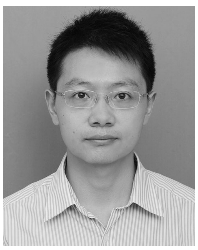
[16] J. Ren, G. Li, Z. Wang, and X. Zhen, "New algorithm for searching tie lines based on deviation path," *Power Syst. Technol.*, vol. 36, no. 4, pp. 121–127, Apr. 2012.

[17] Z. Wang, G. Li, and J. Ren, "A new search algorithm for transmission section based on K shortest paths," *Trans. China Electrotech. Soc.*, vol. 27, no. 4, pp. 193–201, Apr. 2012.

[18] T. Huang, Q. Guo, H. Sun, N. Zhao, B. Wang, and W. Guo, "Hybrid model and data driven concepts for power system security feature selection and knowledge discovery: Key technologies and engineering application," *Autom. Electr. Power Syst.*, vol. 43, no. 1, pp. 95–101, Jan. 2019.

[19] D. Zhou, B. Zhang, F. Yao, L. Wang, B. Zou, and Y. Zhao, "Fast search for transmission section based on graph theory," *Proc. Chin. Soc. Elect. Eng.*, vol. 26, no. 12, pp. 32–38, Jun. 2006.

[20] L. Cheng, B. Zhang, Z. Hao, P. Li, C. Wang, and Z. Bo, ''Fast search for key transmission section based on power component of line,'' *Proc. Chin. Soc. Electr. Eng.*, vol. 30, no. 10, pp. 50–56, Apr. 2010.
[21] F. Zhao, H. Sun, and B. Zhang, ''Electrical zone division based automatic discovery of flowgates,'' *Autom. Electr. Power Syst.*, vol. 35, no. 5, pp. 42–46, Mar. 2011.
[22] B. Xue and J. Duan, ''Typical transmission section searching method considering geographical attributes for large power grids,'' *J. Eng.*, vol. 2019, no. 16, pp. 3051–3055, Mar. 2019.
[23] T. Wang, Y. Li, X. Gu, and J. Jia, ''Identification of the key transmission sections considering optimization of geographical partition boundary for power grids,'' *Trans. China Electrotech. Soc.*, vol. 29, no. 4, pp. 220–228, Apr. 2014.
[24] G. Luo, J. Chen, D. Shi, X. Duan, X. Wu, and W. Ju, ''Key transmission sections analysis based on complex network theory,'' *Proc. Chin. Soc. Electr. Eng.*, vol. 33, no. 25, pp. 147–155, Sep. 2013.
[25] L. Gang, C. Jinfu, D. Xianzhong, and S. Dongyuan, ''Automatic identification of transmission sections based on complex network theory,'' *IET Gener., Transmiss. Distrib.*, vol. 8, no. 7, pp. 1203–1210, Jul. 2014.
[26] P. He and X. Fang, ''Fast search of the key transmission sections based on clustering algorithms,'' *Power Syst. Protection Control*, vol. 45, no. 7, pp. 97–101, Apr. 2017.
[27] B. Zhang, S. Cheng, and Z. Yan, ''Special solution of power flow equation,'' in *Advanced Power System Analysis and Dynamics*, 2ed ed. Beijing, China: Tsinghua Univ. Press, 2007, pp. 208–216.
[28] J. L. Gross, J. Yellen, and M. Anderson, ''Structure and representation,'' in *Graph Theory and Its Applications*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2018, pp. 100–105.



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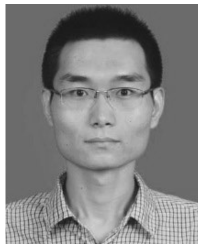

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