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Research Article

Research on the Structural Characteristics of Transmission Grid Based on Complex Network Theory

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Reasonable and strong structure is an important foundation for the smart transmission grid. For vigorously promoting construction of the smart grid, it is of great significance to have a thorough understanding of the complex structural characteristics of the power grid. The structural characteristics of several actual large-scale power grids of China are studied in this paper based on the complex network theory. Firstly, the topology-based network model of power grid is recalled for analyzing the statistical characteristic parameters. The result demonstrated that although some statistical characteristic parameters could reflect the topological characteristics of power grid from different ways, they have certain limitation in representing the electrical characteristics of power grid. Subsequently, the network model based on the electrical distance is established considering the limitation of topology-based model, which reflects that current and voltage distribution in the power grid are subject to Ohm's Law and Kirchhoff's Law. Comparing with the topology-based model, the electrical distance-based model performs better in reflecting the natural electrical characteristic structure of power grid, especially intuitive and effective in analyzing clustering characteristics and agglomeration characteristics of power grid. These two models could complement each other.

1. Introduction

In recent years, the smart grid has become a new trend development of the power grid in the world. Although the definition of the smart grid is different, essentially the smart grid is based on the original transmission and distribution grid and electrical equipment, using modern information, communication, and control technologies to attain its information, intelligence, and electricity markets to solve the issues of renewable energy applied to network and rational utilization of energy [1, 2]. The smart grid can improve the security and reliability of the power grid, promote the development of new and renewable energy, and improve the quality of power, so as to meet user demand for the security of the grid and help solve the global energy shortages, environmental pressures, and other major problems. At the same time, operating environment of the electricity networks becomes more complex due to wind, solar renewable resources which are combined to the grid, or other new problems; obviously the traditional grid structure and operation mode have not adapted the development [3, 4]. Reasonable frame structure is closely related to the operation of the power grid, and strong frame structure is an important foundation for the development of the smart grid. Structure of the power grid and system operating mode are facing another change. Many studies have demonstrated the close relationship between the structure and characteristics of power grid [5–8], therefore have a thorough understanding of the power grid topology as well as its impact on the secure and stable operation of power grid has important significance for enhancing the awareness of weak links of power grid structures, ensuring the secure and stable operation of power grid and promoting the construction of smart grid.

The emergence and continuous development of complex network theory enables us to study the power grid as a "global" complex network [9]. General characters of power grid can be described by comprehensive analysis on the statistical characteristics of complex network, such as degree, degree distribution, clustering coefficient, and characteristic path length of the network [10]. Based on the comparison of clustering coefficient and characteristic path length between the power grid and its random graph with same nodes and sides, [11–13] discovered that the power grid in Western United States, power grid in Northern Europe, and power grid in Northern China are small-world network, while [13, 14] discovered that China's Sichuan-Chongqing power grid and Anhui power grid are more proximate to random network. Many researches on the characteristics of degree distribution concluded exponential distribution [15, 16]. However, power-law distribution was observed in some researches [5, 17]. To explain such different distributions, [18] compared the statistical characteristic parameters of the topological graphs of large power grids in three North America regions with the corresponding statistical characteristic parameters of same-size random graph, small-world graph, and scale-free graph. The comparison result demonstrated that these power grids are neither small-world network nor scale-free network and their degree distributions are more proximate to exponential distribution rather than power-law distribution. [13] analyzed the impact of small-world characteristics on the cascading failure propagation qualitatively, finding that the unique shorter mean distance and higher clustering coefficient of small-world power grid facilitated the failure propagation.

Complex network theories and methods are widely applied for vulnerability analysis of power grid. However, people discovered in these studies that it is difficult to depict the operation characteristics of power grid accurately only through the topological structure. Based on the centrality indexes of element importance analysis in graph theory and the electrical characteristic parameters of power grid and [19] put forward the electrical centrality index which was used to search important nodes and lines of power grid. Reference [20] established the weighted topological model of power grid based on the wire reactance which was confirmed through practical power grid to be better in reflecting the node importance and operating state of practical electric power system comparing with the unweighted model. Reference [21] put forward 4 vulnerability indexes of system structure under the consideration of system operation constraint. Reference [22] suggested using electrical betweenness as the criteria of critical line, which covered the shortage of weighted betweenness model in which it supposes the currents between buses only flow through the shortest path. Reference [18] put forward the electrical distance-based power grid model and compared it with the topology-based model, finding significant difference between the topological structure and electrical structure of power grid.

This paper aims to carry out a deep analysis on the complex structure of practical large power grids in China through the complex network theory and methods. In this paper, several typical large-scale transmission grids are simplified to different extents and the graph theory model based on the topology relation as well as the graph theory model based on electrical distance is established for discussing the representation of their complex network statistical characteristic parameters to the topological structure and operating characteristics of practical power grid.

2. Topological Structural Characteristics of Power Grid Based on Topology-Based Model

Power grid is a network composed of various electrical elements like power transmission lines and transformers through certain way for delivering and distributing electric energies. The topology-based model of power grid is easy to be established according to the topological relationship between its transmission elements. In other words, all buses are abstracted as the nodes of topology-based model, whereas the transmission lines and windings of transformers are abstracted as edges (in this paper, the three-winding transformer applies Y-connection with virtual intermediate node. The virtual node also is abstracted as the node of topology-based model). All nodes and edges are treated in the same way. Consequently, the topology-based model of power grid represented by the unweighted and undirected graph ($G = (V, E)$) containing n nodes and e edges was gained, where V is the node set and E is edge set. The adjacency matrix of node is recorded as A_t and the matrix element is

$$a_{ij} = \begin{cases} 1 & \text{if } (i, j) \in E \\ 0 & \text{if } (i, j) \notin E. \end{cases} \quad (1)$$

2.1. Power Grid Data. The analysis objects of this paper are several typical large-scale transmission grids in China, including NX Grid, TJ Grid, TJ220 Grid, CS Grid, NW Grid, and NC Grid. The topology-based model sizes of these grids after data processing are $G_{\text{NX}} = \{155, 176\}$, $G_{\text{TJ}} = \{597, 648\}$, $G_{\text{TJ220}}\{151, 167\}$, $G_{\text{CS}} = \{328, 371\}$, $G_{\text{NW}} = \{1840, 2162\}$, and $G_{\text{NC}} = \{4828, 5666\}$. Their nodes vary from hundreds to thousands.

2.2. Topology Analysis of Power Grids. The major statistical characteristic parameters of network models of the abovementioned power grids were calculated and analyzed, including various parameters and methods widely applied in various researches currently, such as degree (k), degree distribution ($P(k)$), clustering coefficient (C), and characteristic path length (L). The results were listed in Table 1, where n is the number of nodes and e is the number of edges, $\langle k\rangle$ is the average node degree and C_{random} is the clustering coefficient of random network with same nodes and sides as corresponding practical network, D is the network diameter which is the maximum distance between any two nodes. The representation of these parameters to the structure of power grids will be analyzed one by one in the following text.

2.2.1. Node Degree (k). Node degree (k) refers to the edge amount connected to one node. The larger the node degree (k) is, the more important the node is in the network. Take TJ220 Grid for example. Its topology-based model is $G_{\text{TJ220}}\{151, 167\}$ and its average node degree $\langle k\rangle$ values 2.21. Table 2 is the node degree statistics of TJ220 Grid under different voltage levels. To ensure the power distribution reliability within the whole city, 500 kV nodes are connected with each other in the grid to form the backbone ring. These

Table 1: Statistical characteristic parameter values of power grids.

Grid	n	e	k_{max}	$\langle k \rangle$	C	C_{random}	L	D
TJ	597	648	13	2.17	0.0009	0.00036	10.281	20
TJ220	151	167	11	2.21	0.0135	0.01463	7.6037	16
NX	155	176	9	2.27	0.0212	0.01464	8.7566	19
CS	328	371	9	2.26	0.0181	0.00689	11.8725	32
NW	1840	2162	11	2.35	0.0170	0.00127	15.4676	39
NC	4828	5666	14	2.35	0.0037	0.00048	16.3647	43

Table 2: Node degree statistics of TJ220 Grid.

Node degree (k)	Voltage level	
	500 kV	220 kV
1–3	25%	84%
4–11	75%	16%

nodes have large degree and 75% of them have 4–6 degrees, fully demonstrating the importance of 500 kV substations as load-center substations in the grid. In contrast, only 16% of 220 kV nodes have large node degree ($k > 4$), while the rest 84% have smaller node degree, ranging from 1–3.

2.2.2. Degree Distribution (P(K)). Degree distribution ($P(K)$) is a general description of node degree in the network. The basic topological characteristics of power grid can be evaluated by analyzing whether the degree distribution was subjected to some specific probability distributions. This paper applies cumulative degree distribution which was defined as $P(K \geq k) = \sum_{K \geq k} P(K)$. The cumulative degree distribution curves of power grids are shown in Figure 1, which reveals that the degree distributions of all power grids are approximately subjected to exponential distribution with the maximum node degree $k_{max} \leq 14$.

If the substations are viewed as nodes during the network abstract modeling, the new network model will involve fewer nodes but higher degree of some nodes. Take NC Grid for example. The new topology-based model after abstracting the substations as nodes is $G'_{NC} = \{871, 1199\}$ (the original model is $G_{NC} = \{4828, 5666\}$). The cumulative degree distribution curve is shown in Figure 2. It can be known from Figure 2 that the maximum node degree of the new analysis model increases ($k'_{max} = 16$) and the cumulative degree distribution is also subjected to exponential distribution without power-law distribution observed. This is because the outlet lines of substation are restricted by the capacity and floor space of outlet intervals of the substation, thus making it impossible to involve node with large node degree in the topology-based model.

2.2.3. Clustering Coefficient (C). Many large-scale complex networks in the real world have obvious clustering effect (or known as aggregation effect), which means that nodes to the same node in the network are closely related with each other. The clustering coefficient of network can represent the cluster degree of nodes. Suppose node i has k_i adjacent nodes, then there may be $k_i(k_i - 1)/2$ edges among these k_i adjacent nodes to the maximum. The $E_i/(k_i(k_i - 1)/2)$ ratio is defined as the clustering coefficient (C_i) of node i, where E_i is the practical edges existed among k_i adjacent nodes:

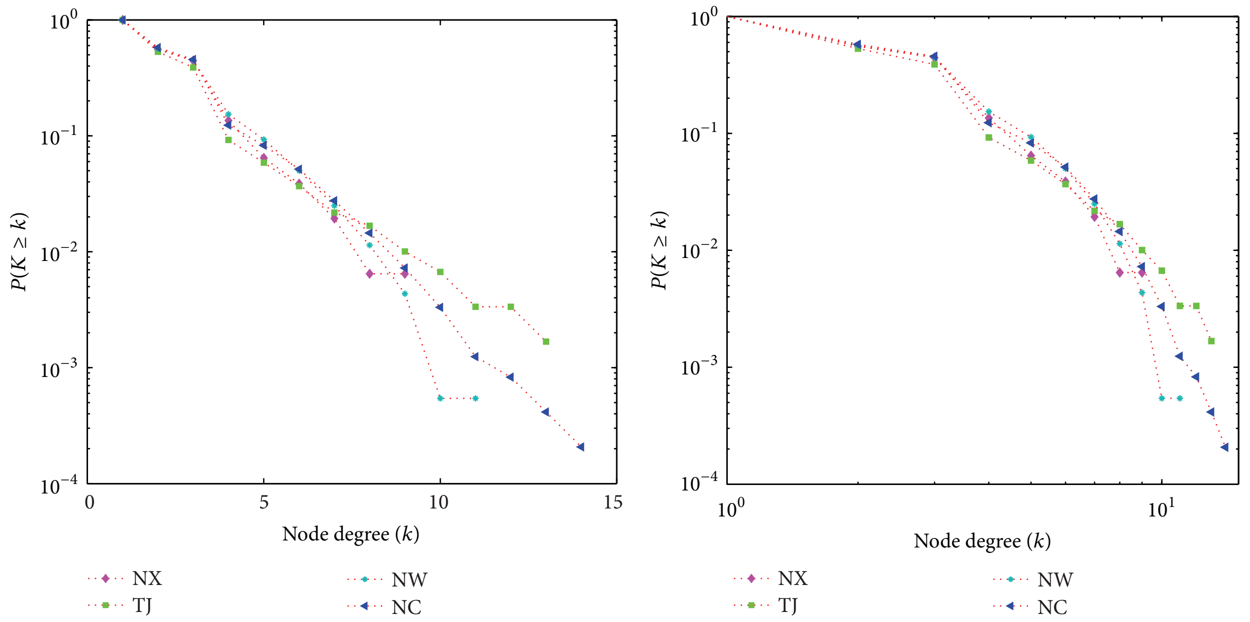
$$C_i = \frac{E_i}{k_i (k_i - 1)/2}. \quad (2)$$

The clustering coefficient of network is defined as the mean clustering coefficient of all nodes:

$$C = \frac{1}{N} \sum_{i=1}^{N} C_i. \quad (3)$$

According to Table 1, the clustering coefficients of topology-based model of all power grids are relatively small. It can be known from the definition of clustering coefficient that the clustering coefficient of nodes, in fact, reflects the existence of delta connection in network. However, such delta connection is rare in practical power grid since the cyclic network is generally connected by more than 3 nodes. Take TJ220 Grid for example. It has very low clustering coefficient since there is only one group of nodes that formed delta connection. Therefore, the network represents no obvious aggregation effect when viewed from the clustering coefficient of its topology-based model. However, this conclusion contradicts with the zoning operation of power grid which has obvious cluster effect viewed from the electrical characteristics of power grid. For example, 500 kV wires in TJ220 Grid formed a dual-ring network basically, which are connected with external wires and accept electric power transmission. On the other hand, the 220 kV Grid forms three power-supply regions for receiving powers from 500 kV Grid (Figure 3) [23]. In such power grid, every zone has independent close electrical relationships and zones are connected through interval connection wires, thus achieving the layering and zoning operation of power grid and improving the overall power distribution reliability and security of urban power grid maximumly. However, for topology-based modeling method, the clustering coefficient (C) is difficult to reflect such structural characteristics of power grid.

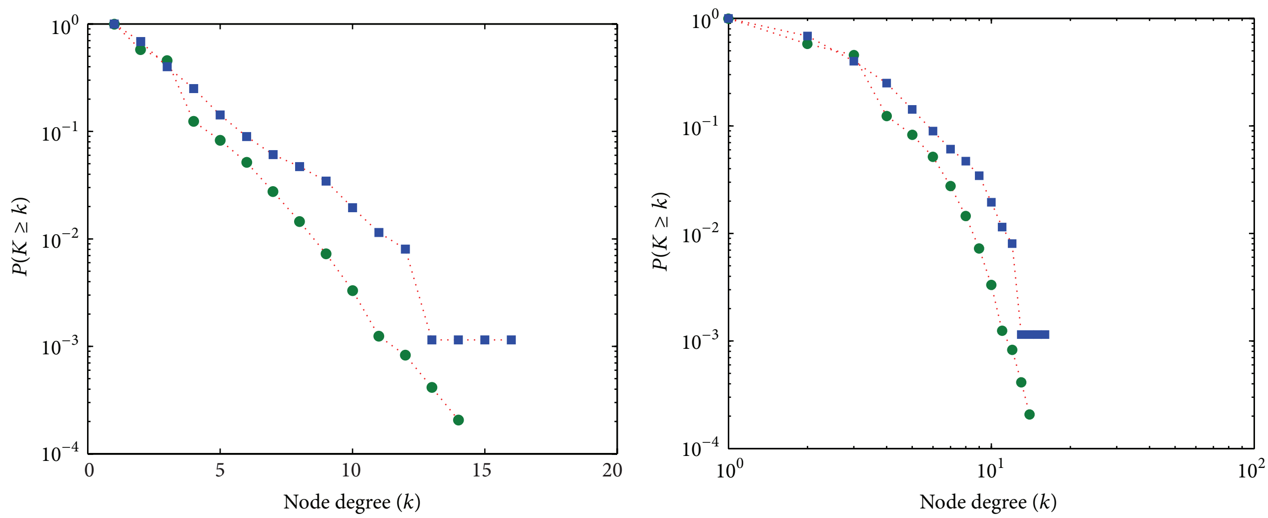
2.2.4. Structural Visualization of Power Grid Based on K-K Layout Algorithm. Rational visualization enables us to represent the power network structure intuitively. The geographical wiring layout shown in Figure 3 is a common visualization method of power network structure. However, such wiring layout is formed by the geographic information



(a) Semilogarithmic coordinates

(b) Logarithmic coordinates

FIGURE 1: Cumulative degree distribution of topology-based model of power grids.



(a) Semilogarithmic coordinates

(b) Logarithmic coordinates

FIGURE 2: Cumulative degree distribution curves of NC Grid model G_{NC} and G'_{NC}.

of substation and wires and fails to reflect the practical electrical distance between nodes in the power grid. To gain a better observation on the overall power network, this paper proposed to using the Kawai-Kamada (K-K) algorithm in the complex network theory [24] to achieve the visualization of power network structure.

The Kamada-Kawai Algorithm is a force directed layout algorithm. The nodes are represented by steel rings and the edges are springs between them. The basic idea is to minimize the energy of the system by moving the nodes and changing the forces between them. When the system finally reaches the optimal layout, distances between nodes are close to their ideal distances, while the total energy of the system (E) hits the bottom value:

$$E = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{1}{2} k_{ij} \left(\left| p_i - p_j \right| - l_{ij} \right)^2, \tag{4}$$

where P_i and P_j are the position coordinates of nodes i and j in the wiring layout, l_{ij} is the ideal distance between nodes i and j, $k_{ij} = K/d_{ij}$ represents the elastic coefficient of the spring between nodes i and j, K is a constant, and d_{ij}

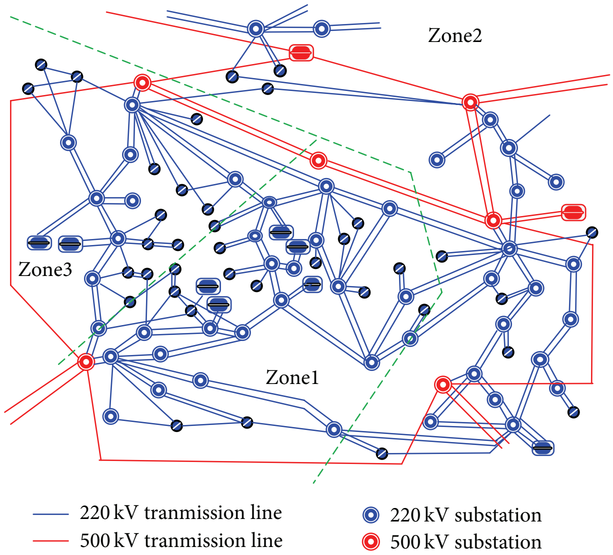


Figure 3: Geographical wiring layout of TJ220 Grid.

is the shortest distance between nodes i and j. Hence, the optimal layout can be gained by seeking the minimum total energy of the system.

The weighted topology-based model of power grid can be gained by assigning weights to the connecting edges between nodes in the topology-based model. Edge weights set according to the impedance module ($|z_{ij}|$) of the wire ($i-j$) can represent the electrical connection between nodes. The larger the weight is, the weaker the electrical connection will be. In other words,

$$a_{ij} = \begin{cases} |z_{ij}| & \text{if } (i,j) \in E \\ 0 & \text{if } (i,j) \notin E. \end{cases} \tag{5}$$

According to the principle of K-K layout algorithm, the optimal layout based on the weighted topology-based model will reflect the electrical closeness between different nodes thoroughly. Larger geometrical distance between nodes in the wiring layout represents the weaker electrical connection, while shorter geometrical distance represents stronger electrical connection.

Figures 4(a) and 4(b) represent the K-K optimal layout of TJ220 Grid based on topology-based model and weighted topology-based model, respectively. Comparing with the geographical wiring layout, the visualization of power grid based on K-K layout algorithm enjoys obvious superiorities in representing the electrical connection: node distribution fully represents the electrical connection between nodes with evident zoning characteristics, especially the 500 kV nodes. These 500 kV nodes have longer geographical distance between each other (Figure 3); they have very close electrical connection practically. For this reason, 500 kV nodes are positioned on the core areas in Figure 4. Both geographical wiring layout and K-K optimal layout based on weighted topology-based model can represent the overall layout and structure of power grid from different perspectives. The former emphasizes on the regional features of electric power transmission, whereas the latter is superior for its intuitive representation of electrical connection between nodes.

2.2.5. Network Diameter (D) and Characteristic Path Length (L). The distance (d_{ij}) between nodes i and j is defined as the number of edges on their shortest connecting path. The maximum distance between any two nodes in the network is called as the network diameter (D):

$$D = \max d_{ij}. \tag{6}$$

The characteristic path length (L) in the network is defined as the mean distance between any two nodes:

$$L = \frac{1}{n(n+1)/2} \sum_{i \geq j} d_{ij}, \tag{7}$$

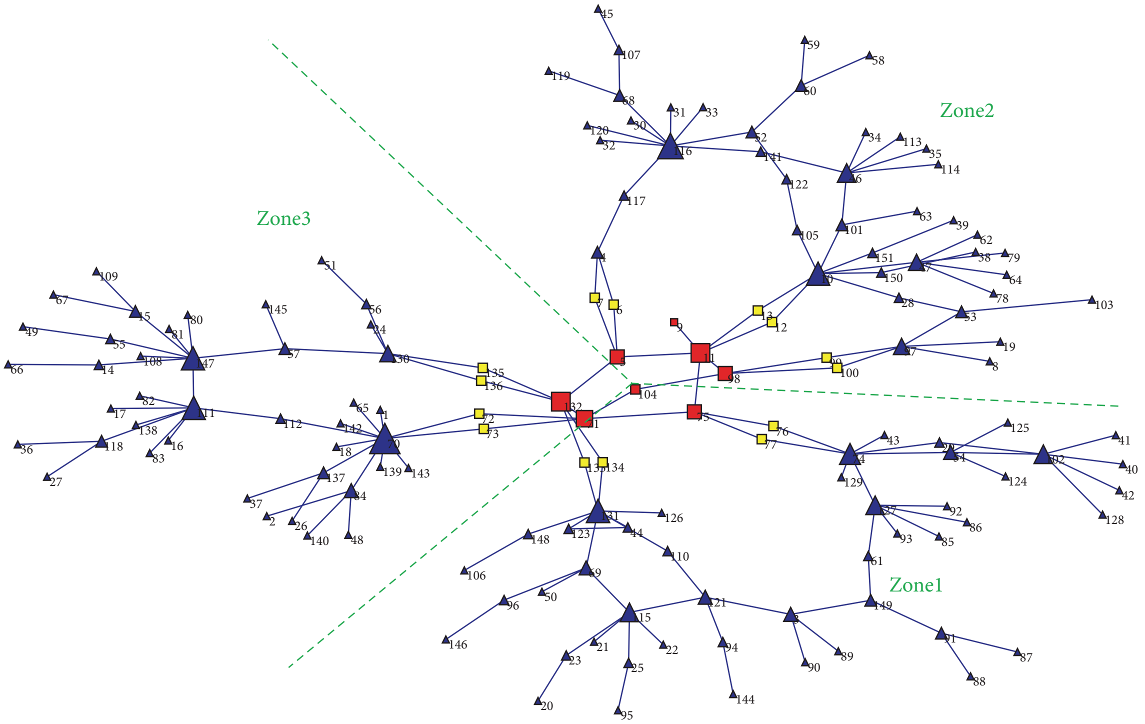
where L reflects the connecting closeness between nodes. The combination of L and D can reflect the overall layout of the network. Although TJ220 Grid and NX Grid have similar nodes and size, their structures are significantly different from each other. As shown in Figures 4(a) and 5, the backbone network of TJ220 Grid is a compact cyclic structure and supplies powers to zone load, whereas the NX Grid represents a loose long and narrow dendritic-distribution structure. Their different structures result in their different L and D: $L_{\text{TJ220}} = 7.6037 < L_{\text{NX}} = 8.7566$ and $D_{\text{TJ220}} = 16 < D_{\text{NX}} = 19$. Radial network has both larger L and D than the cyclic network. Therefore, L and D can reflect the loose degree of network structure.

3. Complexity of Power Grid Based on Electrical Distance Model

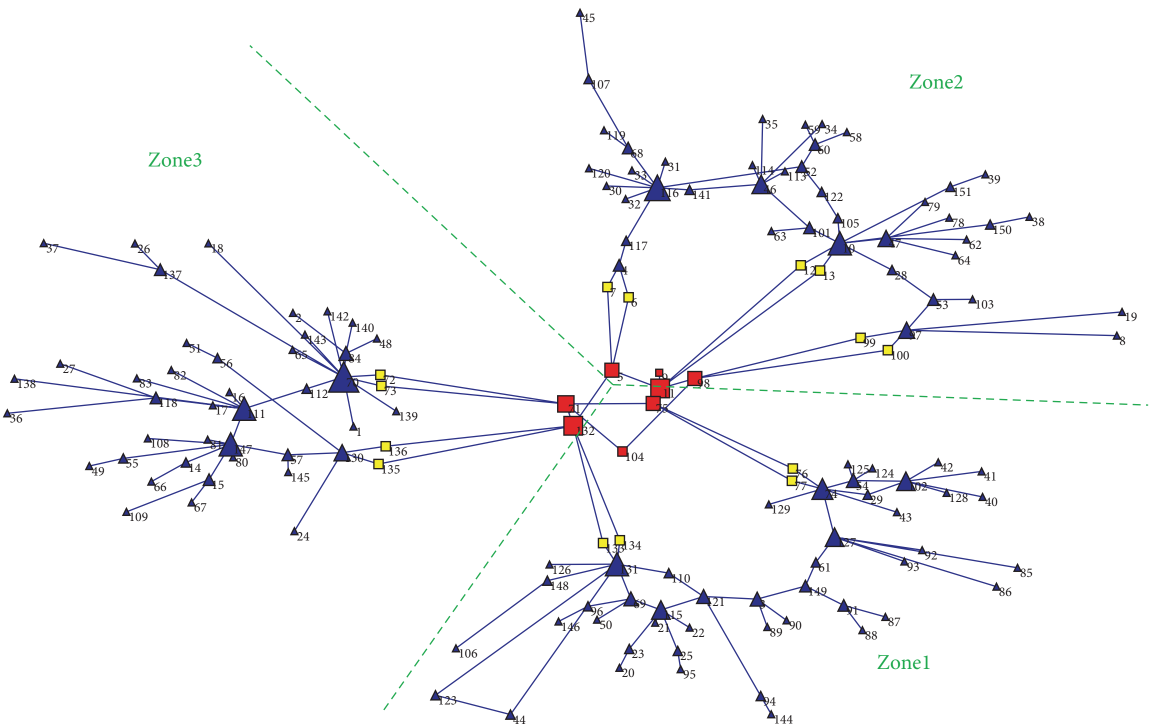
According to the analysis in Chapter II, the analysis on the abovementioned statistical characteristic parameters of topology-based model of power grid enables us to gain a lot of information about the structural characteristics of the power grid. However, such power grid model fails to represent the electrical characteristics completely. Therefore, the conclusion about the structural characteristics of power grid drawn from the topological relation has certain limitations. For example, the clustering coefficient (C) can only declare the delta connection amount in the power grid but fails to represent its real zoning characteristic. For this reason, the power grid model based on electrical distance is established in this paper.

3.1. Graph-Theory Modeling of Power Grid Based on Electrical Distance. The voltage and current distribution in the power grid follows Ohm's Law and Kirchhoff's Law. Therefore, strong or weak electrical connections exist between indirectly connected nodes except for that between directly connected nodes. The strength of electrical connection between nodes can be measured by electrical distance.

Take a power grid with n nodes for example. $\dot{I}_i$ and $\dot{U}_i$ represent the injection current and voltage of node i,



(a) K-K optimal layout based on topology-based model



(b) K-K optimal layout based on weighted topology-based model

Figure 4: Optimal layout of TJ220 Grid.

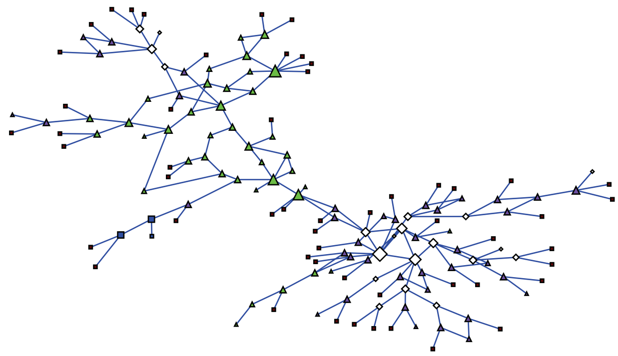


Figure 5: Topology layout of NX Grid.

respectively. According to the Kirchhoff's Law, the network equation expressed by the nodal impedance matrix (**Z**) is

$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1n} \\ \vdots & & \vdots & & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{in} \\ \vdots & & \vdots & & \vdots \\ Z_{n1} & \cdots & Z_{ni} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \vdots \\ \dot{I}_i \\ \vdots \\ \dot{I}_n \end{bmatrix} = \begin{bmatrix} \dot{U}_1 \\ \vdots \\ \dot{U}_i \\ \vdots \\ \dot{U}_n \end{bmatrix}. \quad (8)$$

When $\dot{I}_m \neq 0$ and $\dot{I}_i \neq 0$ $(i = 1, 2, \ldots, n; i \neq m)$, the mutual impedance (off-diagonal element of the matrix) between any two nodes is

$$Z_{im} = \frac{\dot{U}_i}{\dot{I}_m}, \quad i = 1, 2, \ldots, n. \quad (9)$$

Elements in the nodal impedance matrix are the open-circuit parameters of power grid, including information of the whole network. In this paper, the module of mutual impedance ($|Z_{ij}|$) is defined as the electrical distance between node i and j, expressed as $d_{e(i,j)} = |Z_{ij}|$. Higher $|Z_{ij}|$ represents longer electrical distance and weaker electrical connection, whereas lower $|Z_{ij}|$ represents shorter electrical distance and stronger electrical connection. The electrical distance matrix ($\mathbf{D_e} = |\mathbf{Z}|$) between nodes in the power grid can be gained through the modules of elements in the impedance matrix. For interconnected networks, the impedance matrix is a full matrix. Therefore, the electrical distance matrix ($\mathbf{D_e}$) is a full matrix too. During the network modeling based on $\mathbf{D_e}$, the electrical connection in the network is simplified by setting the electrical distance threshold ($d_{e(\text{th})}$) in order to prevent the model from becoming a complete graph. In other words, elements (electrical distance $> d_{e(\text{th})}$) in the $\mathbf{D_e}$ are set as 0 and only elements (electrical distance $\leq d_{e(\text{th})}$) are kept. Under this circumstance, the adjacency matrix of electrical distance-based power grid model is $\mathbf{A_e}$, and its elements are

$$a_{e(i,j)} = \begin{cases} d_{e(i,j)} & \forall d_{e(i,j)} \leq d_{e(\text{th})} \\ 0 & \forall d_{e(i,j)} > d_{e(\text{th})}. \end{cases} \quad (10)$$

Under different thresholds, connection between nodes in the corresponding power grid model based on electrical distance will be different. In the following text, different $d_{e(\text{th})}$ will be set according to the distribution characteristics of electrical distance between nodes and then the electrical structure of power grid will be analyzed based on the established different network models.

Table 3: Electrical distance between nodes.

Grid	$\lvert Z_{\text{average}}\rvert$	$\lvert Z_{\min}\rvert$	$\lvert Z_{\max}\rvert$
NX	0.2484	0.0309	1.4555
TJ220	2.1073	1.7394	2.1331
CS	0.0167	0.0001	0.0900

3.2. Structural Analysis of Power Grid Based on Electrical Distance Model. Table 3 lists the maximum, minimum, and average electrical distances between nodes in TJ220 Grid, NX Grid, and CS Grid. Figure 6 represents the probability distribution of electrical distance between nodes in all these three grids. It can be known from Figure 6 that although these three grids have different electrical distance ranges and distributions, their electrical distances demonstrate concentrating distributions. Shorter electrical distance may exist between nodes indirectly connected, which may be shorter than that between nodes directly connected. This indicates that similar electrical characteristics may be observed between nodes indirectly connected, which cannot be reflected by the topology-based model.

According to the above mentioned modeling idea based on electrical distance, the structural characteristics of TJ220 Grid are analyzed. The cumulative probability distribution of electrical distance between nodes is analyzed to set the electrical distance threshold reasonably, as shown in Figure 7. When $d_{e(\text{th})} > 2.11$, weak connections in the network decrease quickly with the decreasing of $d_{e(\text{th})}$. When $d_{e(\text{th})} = 2.107$, 72.51% weak connections are deleted and the electrical distance model can just maintain connected. With the further decreasing of $d_{e(\text{th})}$, the network diagram is divided into several independent subblocks, accompanied with isolated nodes and slowed decreasing of weak connections. When the electrical distance model has same edges with the topology-based model ($e = 167$), 98.53% relative weak connections have to be deleted. In this case, the corresponding threshold $d_{e(\text{th})}$ is 2.04.

Table 4 lists some statistical characteristic parameters of TJ220 Grid under different thresholds. Obviously, under the modeling based on electrical distance, the edges of graphical model will increase, which leads to the increase of average and maximum node degree to different extents. However, the cumulative degree distribution of TJ220 Grid still fails to represent power-law distribution under different thresholds (Figure 8).

Table 4 reveals the biggest difference between the electrical distance-based network model and topology-based model. The clustering coefficient of the network remains at higher level regardless of the threshold variation, indicating obvious clustering effect of nodes in the power grid. Figures 9(a) and 9(b) represent the structures of electrical distance-based model of TJ220 Grid at $d_{e(\text{th})} = 2.107$ and $d_{e(\text{th})} = 2.07$, where the blue squares represent 500 kV nodes and green

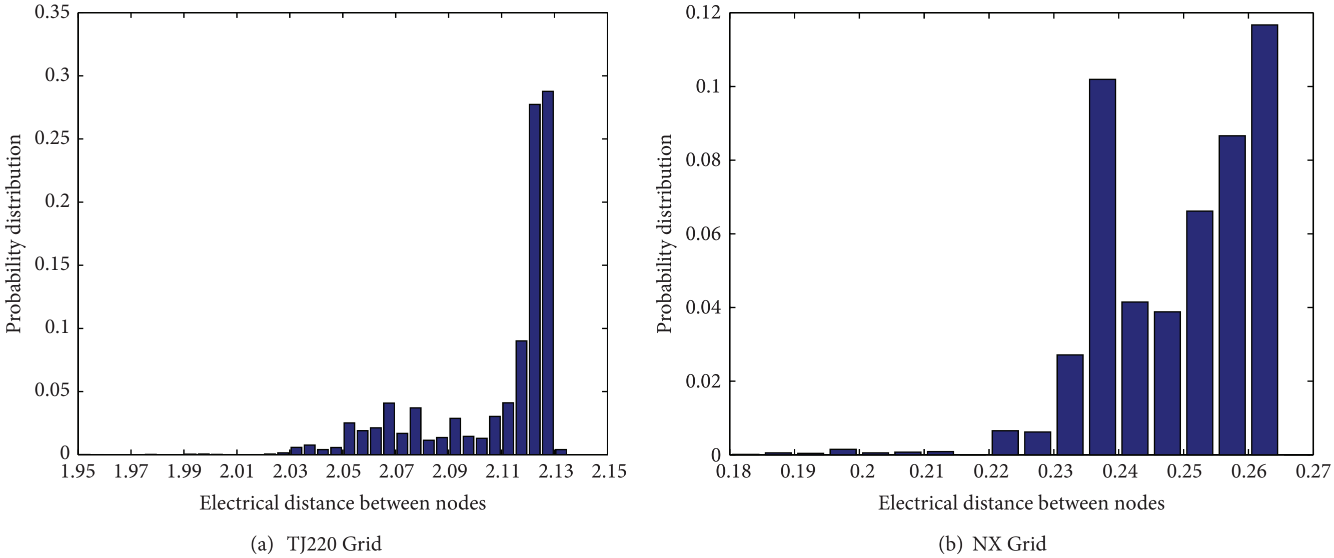


Figure 6: Probability distribution of electrical distance between nodes in power grids.

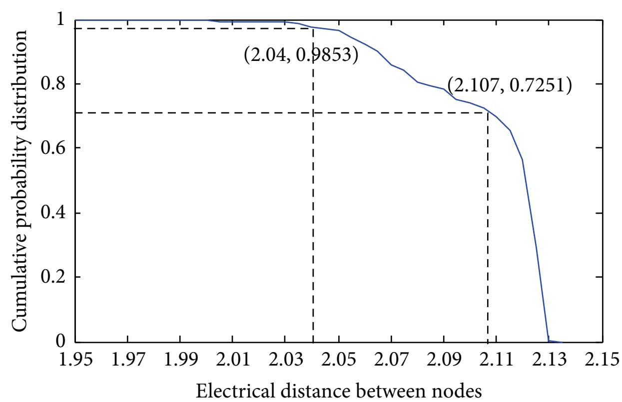
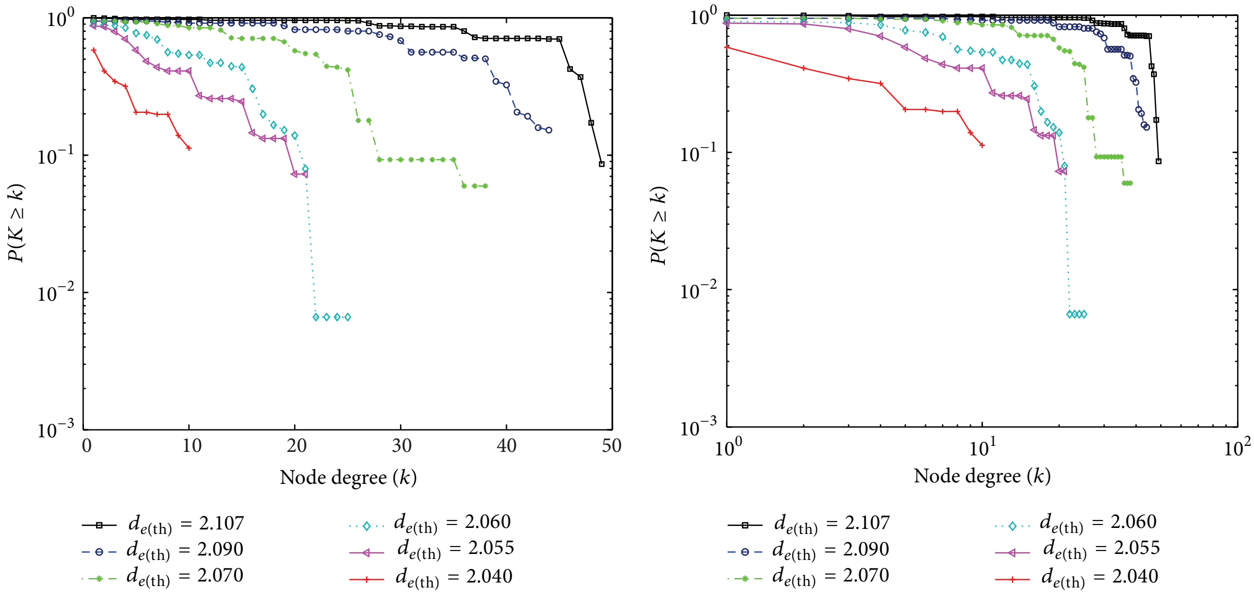


Figure 7: Cumulative Probability distribution of electrical distance between nodes in TJ220 Grid.



(a) Semilogarithmic coordinates

(b) Logarithmic coordinates

FIGURE 8: Cumulative degree distribution of electrical distance-based network model of TJ220 Grid.

TABLE 4: Statistical characteristic parameters of electrical distance-based network model of TJ220 Grid.

$d_{e(th)}$	e	$\langle k \rangle$	k_{max}	C
2.107	3113	41.23	49	0.9416
2.090	2414	31.97	44	0.8785
2.07	1520	20.13	38	0.8469
2.06	816	10.81	25	0.8220
2.055	600	7.95	21	0.8203
2.04	167	2.72	10	0.3938

triangles represent 220 kV nodes. Under different thresholds, the electrical distance-based models of power grid have closely connected clusters with abundant delta connections, representing close electrical connections. Furthermore, when $d_{e(th)} = 2.107$, the TJ220 Grid forms three obvious clusters according to the closeness between nodes, which echoes with its zones basically. In other words, the clustering coefficient (C) of the electrical distance-based power grid model can accurately and effectively reflect that power grid has obvious clustering effect in electrical connection.

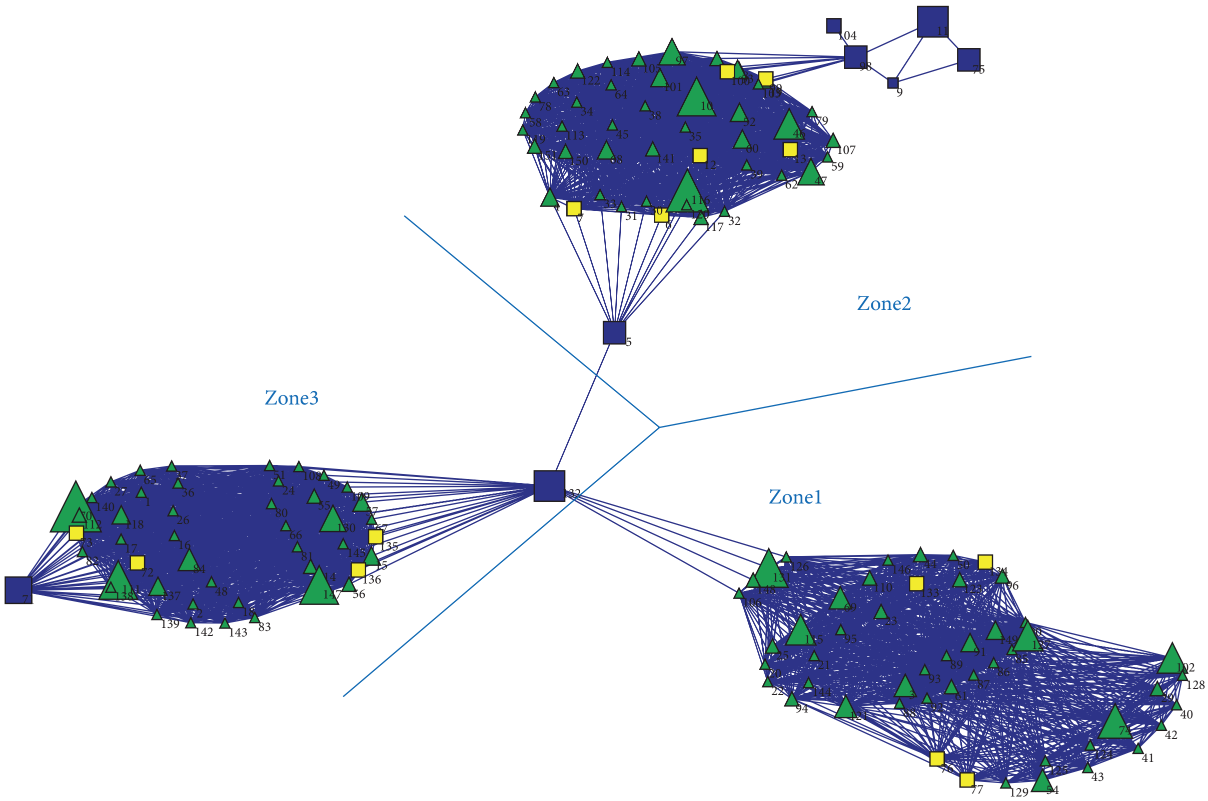
To verify the above analysis, three typical nodes (V1, V2, and V3) are selected in Zone1, Zone2, and Zone3, respectively, and their electrical distances with nodes in different zones are drawn (Figure 10). It can be seen from Figure 10 that nodes within the same zone have the shortest electrical distance and two nodes in different zones have longer electrical distance. Therefore, with the decreasing of $d_{e(th)}$, although the connections between nodes of different zones are deleted gradually, nodes within the same zone still remain closely connected and finally form the three zoning layout (Figure 9(a)).

When the $d_{e(th)}$ decreases from 2.107 to 2.07, zones separate from each other as the connections between them are deleted gradually. Meanwhile, a lot of weak connections in same zone are deleted and Zone3 has been separated into two sub-zones (Figure 9(b)). Abundant isolated nodes can be observed in the electrical distance-based model of the power grids when $d_{e(th)}$ decreases to 2.04. Although edges decreases continuously with the decreasing of $d_{e(th)}$, the model still maintains several closely connected clusters. In other words, the network still has evident clustering characteristics, thus endowing the network with larger clustering coefficient (Table 4).

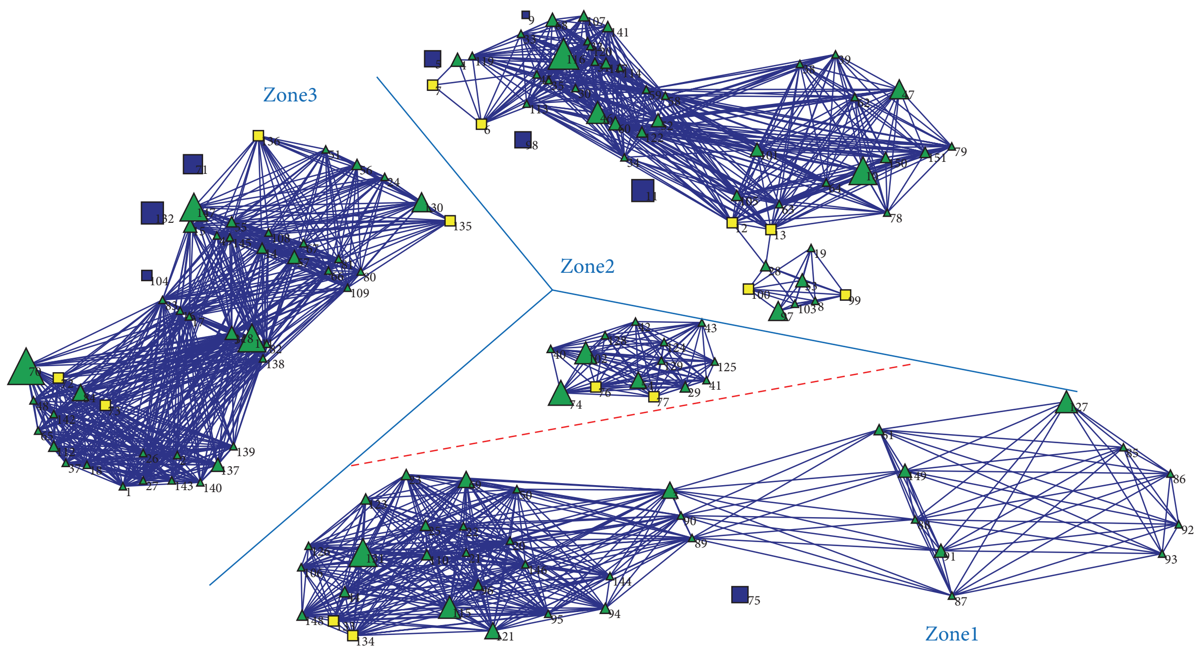
4. Conclusions

This paper analyzes the structural characteristics of several large-scale practical power grids based on the complex network theory and compares the analysis results of their complex network parameters under different modeling methods as well as the power network structural information these parameters could provide.

Firstly, the network model based on practical topological structure is established and the statistical characteristic parameters of topology-based models of all involved power grids are analyzed. The results demonstrate that these parameters can reflect the topological characteristics of power grids to certain extent from different sides. (1) The statistical analysis of node degree of power grid under different voltage levels can disclose different structural characteristics of grids structure under different voltage levels caused by their different role in power supply. (2) The comparison of characteristic path length (L) and network diameter (D) of different power grids can reveal the tightness of power network structure. (3) The node degree distribution



(a) $d_{e(\text{th})} = 2.107$



(b) $d_{e(\text{th})} = 2.07$

Figure 9: Structure of electrical distance-based model of TJ220 Grid.

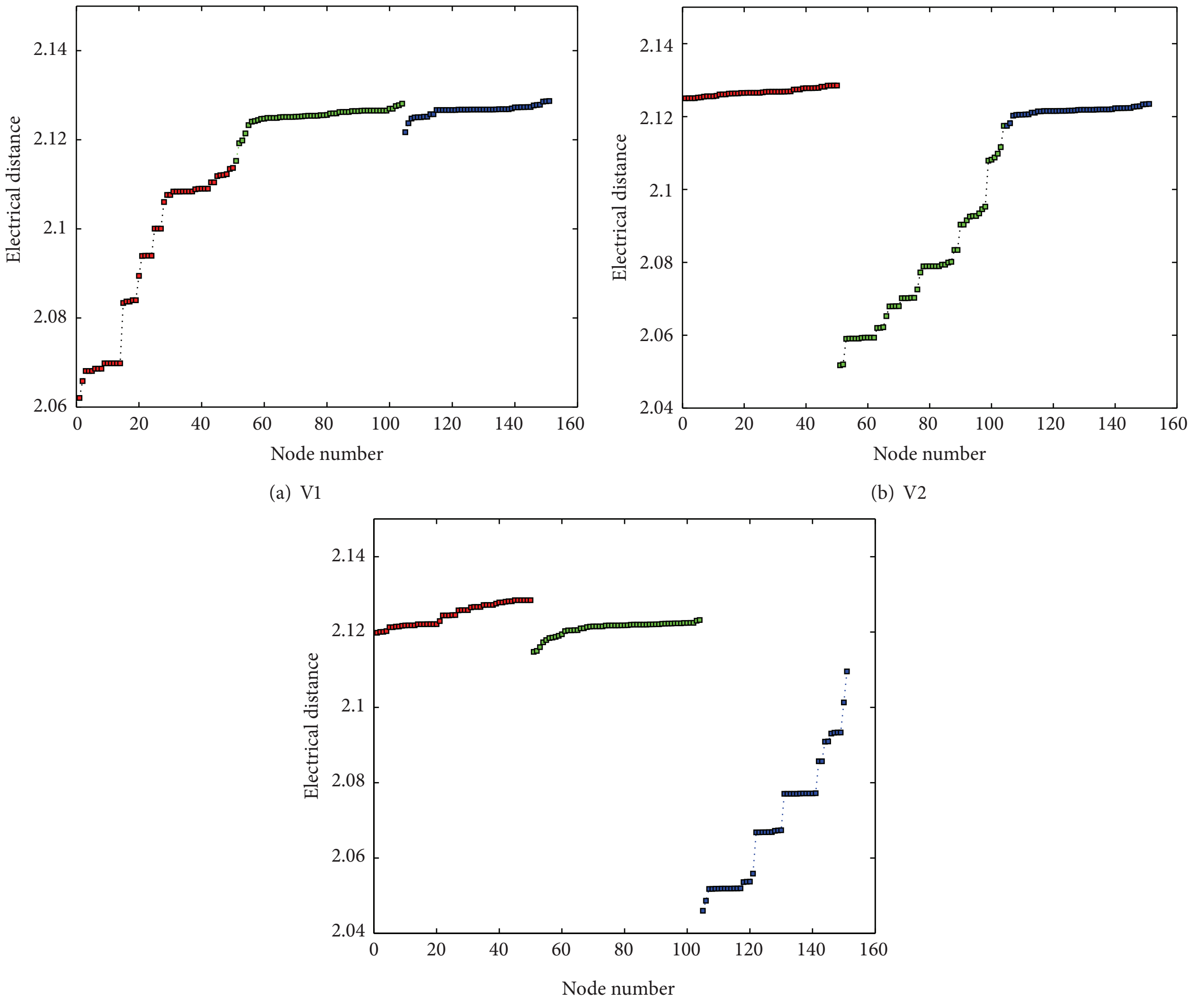


FIGURE 10: Electrical distance distribution between V1, V2, and V3 and other nodes. Red squares represent the electrical distance between the selected node and nodes in Zone1. Green squares represent the electrical distance between the selected nodes and nodes in Zone2. Blue squares represent the electrical distance between the selected node and nodes in Zone3.

of power grids generally represents exponential characteristic. However, since the topology-based model neglects the electrical characteristics of power grid components, it fails to reflect the Ohm's Law and Kirchhoff's Law in which voltage and current distribution in power grid has to be followed. Consequently, the conclusion concerning the structural characteristics of power grid may have certain limitations, that is, clustering coefficient (C) fails to represent the zoning and clustering characteristics of power grid accurately.

This paper establishes the power grid model based on electrical distance in order to offset the shortages of topology-based model. This model can reflect that current and voltage distribution in power grid are subject to Ohm's Law and Kirchhoff's Law, which is in accordance with the practical running of power grid. The analysis of several different power grids demonstrates a relative concentrate distribution of electrical distance between nodes in power grids and close electrical connections between nodes without direct topological relationship. Under different thresholds of electrical distances, electrical distance-based models maintain higher clustering coefficient, which indicates the obvious clustering effect of power grid in electrical connection. Therefore, the electrical distance-based model can analyze the agglomeration characteristics and clustering characteristics accurately and thoroughly.

Both topology-based model and electrical distance-based model can be used to analyze different aspects of power grid structure effectively, thus enabling us to gain a more comprehensive and accurate understanding of the structural characteristics of power grid. Additionally, the structural visualization of power grid based on K-K layout algorithm can provide a clear and intuitive representation of the electrical connections between nodes in power grid.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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