LETTER

An Evolving Network Model for Power Grids Based on Geometrical Location Clusters

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SUMMARY Considering that the traditional local-world evolving network model cannot fully reflect the characteristics of real-world power grids, this Letter proposes a new evolving model based on geographical location clusters. The proposed model takes into account the geographical locations and degree values of nodes, and the growth process is in line with the characteristics of the power grid. Compared with the characteristics of real-world power grids, the results show that the proposed model can simulate the degree distribution of China's power grids when the number of nodes is small. When the number of nodes exceeds 800, our model can simulate the USA western power grid's degree distribution. And the average distances and clustering coefficients of the proposed model are close to that of the real world power grids. All these properties confirm the validity and rationality of our model.

key words: *power grid, complex network, modeling, evolving network, local-world*

1. Introduction

Power grid [1] is a strong nonlinear large-scale dynamic system, it can be regarded as a large-scale complex network composed of power stations, high-voltage transmission lines and other abstract network nodes, and connected through different types of connections. The development of complex network modeling methods opens up a new way for the analysis of the operating state of power systems, providing a new perspective and a new research method. Using the perspective of complex networks [2]–[5] to analyze and study power grids can help to grasp the complexity of power grids and the dynamic characteristics of the whole network response as a whole. In the complex network theory [6], the modeling method is also called model analysis method, which regards the large system in nature as a network of interactions between a large number of individuals, and then studies its statistical characteristics and its evolution property.

In order to use the complex network theory, it is necessary to establish a reasonable power grid model first. As the time goes on, the establishment of the model has gone through three stages [7]. The first stage is to generate the undirected unweighted topological structure. The second stage considers the edge weight and other indicators on the basis of the first stage model, so that the topology of the power grid is more accurate. The third stage establishes the grid model according to the electrical connection, which makes the power grid model closer to the real power grids, so that the complex characteristic analysis will be more and more accurate.

Considering the prevalent local-world phenomenon in the real network, a local-world evolution model was proposed in [8]. This model uses a random strategy in selecting the local world. Another neighborhood model established by the literature [9] also randomly selects the neighborhood center, but the definition of neighborhood is based on the depth and the concept of local-world is explained more concretely. Inspired by the local evolution model of power grid [9], taking into account the geographical locations of the power network nodes, this Letter constructs a power network evolving model based on geographical location clusters. This model views the power grid as a network consisting of multiple clusters connected to the network. In the evolution process, the degree values of new nodes, the distance values between every node to the cluster center and the distance values between cluster centers are together considered. Our model is more realistic than previous models since both location clustering and neighboring topological information are considered during the evolution process.

The remainder of this paper is organized as follows. Section 2 introduces the classical power grid local-world evolving network model [9]. And then we introduce our power grid evolving network model in Sect. 3. Section 4 compares the characteristics of these two models with the characteristics of three real power grids respectively.

2. Power Grid Local-World Evolving Network Model

The power grid local-world evolving network model [9] is a kind of evolving model for complex power grids proposed by Cao et al. on the basis of the local-world network evolving model [8]. The model proposed in [9] considers the random connection outside the local-world, and thus to a certain extent it is in line with the evolution mechanism of real power grids. The specific construction algorithm is as follows:

1) Initialization: in the initial network, there are fewer nodes and links (here, a link means an edge connecting two nodes), i.e., m_0 nodes and e_0 links;

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2) Growth: in every time interval, among the positions that are not utilized by other nodes, randomly select a position as the location of the newly-joined node;

3) Determining the local world: among all the nodes of the original network, randomly select M nodes as the local world of the newly-joined node;

4) Connection: Set the parameter value p, $0 \le p \le 1$ when the program is initialized, as the probability that the newly added node is connected to the local world determined in Step 3. Thus the probability that the newly added node is connected to the node outside the local world is $1-p$. Here, both the number of connected nodes outside the local world and the number of connected nodes inside the local world are m ($M > m$). For the nodes inside the local world, the newly added node is connected according to the principle of probability priority, and the preferred connection probability is as follows:

$$P_{local}(k_i) = p \cdot \frac{k_i}{\sum\limits_{j \in local} k_j} \tag{1}$$

where k_i denotes the degree of node i, i.e., the number of direct neighbors of node i. For the nodes outside the local world, the new node is randomly connected to them according to the principle of equal probability. The connection probability is as follows:

$$P_{nonlocal}(k_i) = (1-p) \cdot \frac{1}{m_0 + t - M} \tag{2}$$

In this way, after t time intervals, the original small network can be evolved into a new network containing $N = m_0 + t$ nodes and $M = mt + e_0$ edges.

3. Proposed Evolving Network Model

With the socio-economic development and increased demand for electricity, many new power plants and substations have been added to the power system. In the process of power network development, the transmission distance greatly affects the economic cost of power grid construction. Therefore, the power is generally input from the adjacent substation to the new power plants and substations, and they are connected to the surrounding substations in a certain geographical area, and thus the growth of the grid shows a certain neighborhood evolution characteristics. In order to maintain the stable operation of the power system (the $N-1$ principle, transient stability, etc.) [10], the new plant will need to be connected with the substations that are important and often have a high capacity and have more connections. In the process of power network evolution, the position of the new substation or power plant node which directly joins the power grid directly affects the network topology and network performance. Therefore, the evolution model of the power grid should have a certain geographical area as a "neighborhood" range. Based on this, this paper presents a power grid evolving model based on Geographical Location Clusters (GLC). The basic algorithm is given as follows:

1) Initialization: randomly generate or fix K locations (nodes) as cluster centers (e.g. $K = 20$). This to some extent reflects the power plant sites.

2) The rules for network growth are as follows:

i) Join a new node at each time interval.

ii) The probability that this new node falls within a cluster is proportional to the number of nodes in the cluster.

iii) Once a new node belongs to a cluster, a random location is generated within the cluster as the location of the new node.

iv) randomly assign (uniformly) a degree value to the new node, either 1, or 2, or 3.

v) If the degree value of the new node is 1: select a node within the cluster to be connected to the new node with the probability proportional to the node degree;

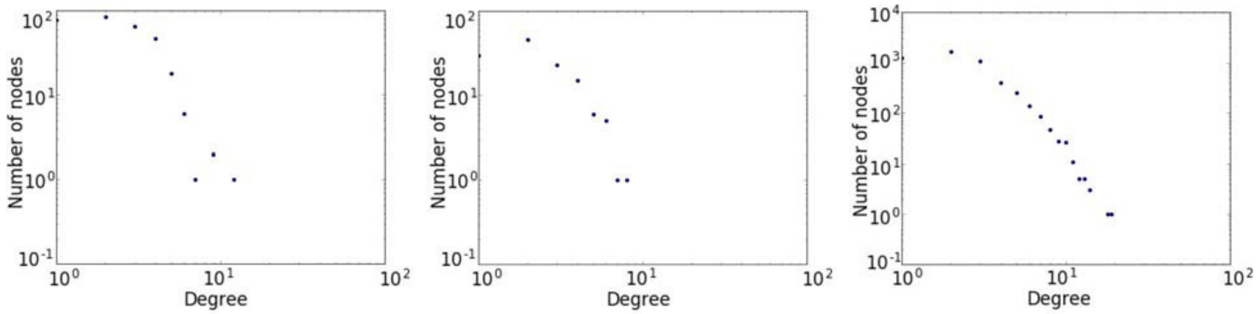
vi) If the new node degree is 2: first select a node within the cluster to be connected to the new node with the probability of proportional to the node degree. And then select a node within the cluster with the probability inversely proportional to the distance between the cluster center and each node in the cluster, and connect it with the new node;

vii) If the new node degree is 3: first select a node within the cluster to be connected to the new node with the probability of proportional to the node degree. And then select a node within the cluster with the probability inversely proportional to the distance between the cluster center and each node in the cluster, and connect it with the new node. And finally a random node in the other cluster is selected to be connected with the new node with the probability inverse proportional to the distance between the center that the new node belongs to and any other center.

4. Simulation Results

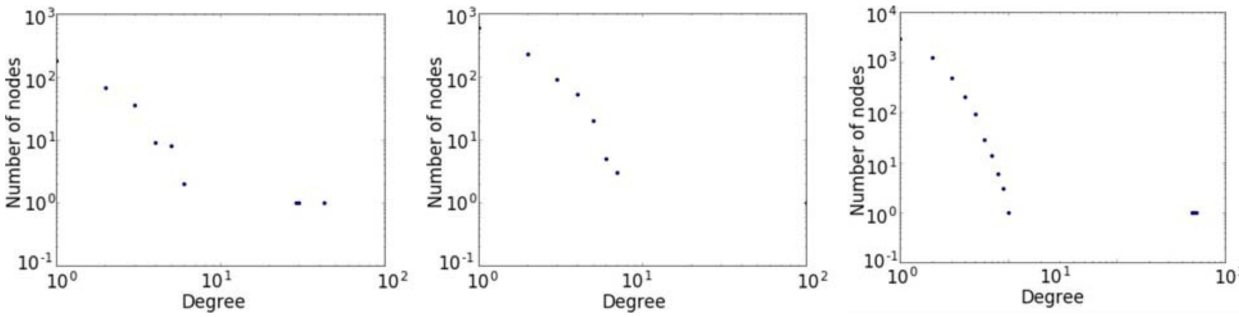
In order to verify the validity of our model (GLC), we compare our model with the power grid local-world evolving (LWE) network model and three real power grids (MC302, NEC127, USPower) in terms of the degree distribution, clustering coefficient and average distance. These three criteria are the main characteristics to describe the topological feature of a complex network and can be used to determine if a network is "small-world" and/or "scale-free". USPower means US western power grid which has 4941 nodes and 6594 edges. NEC127 stands for Northeast China power grid (NEC127) which contains 127 nodes and 163 edges. MC302 means Middle China power grid which contains 302 nodes and 396 edges.

Figure 1 shows the degree distributions of three real-world power grids. Figure 2 shows the degree distributions of the LWE models with 300, 1000 and 5000 nodes respectively. Figure 3 shows of the degree distributions of our GLC models based on 20 clusters with 100, 1000 and 5000 nodes respectively. According to Fig. 1, Fig. 2 and Fig. 3, we can see that the LWE models cannot well simulate the degree distributions of real-world power grids, but our models can simulate the degree distribution of China's power grids



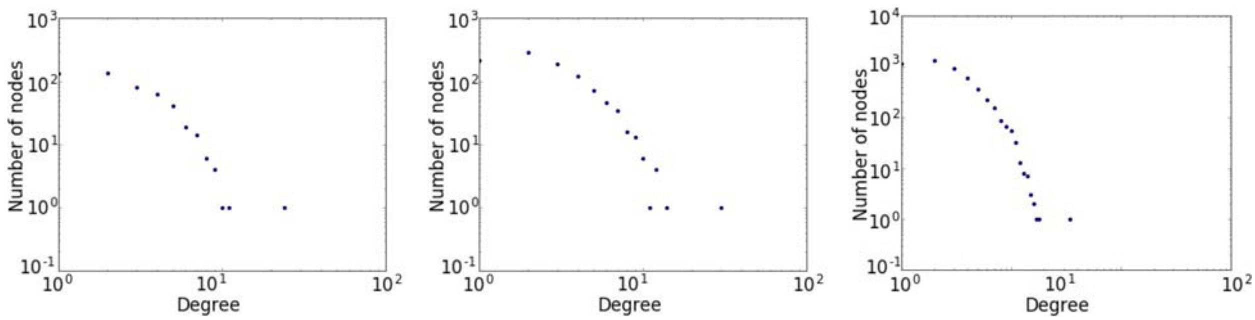
(a) NEC127 (b) MC302 (c) USPower

Fig. 1 The degree distributions of three real-world power grids.



(a) 300 nodes (b) 1000 nodes (c) 5000 nodes

Fig. 2 The degree distributions of LWE models with different numbers of nodes.



(a) 100 nodes (b) 1000 nodes (c) 5000 nodes

Fig. 3 The degree distributions of our models with different numbers of nodes.

Table 1 The average distances and clustering coefficients of real-world power grids and local-world evolving models with different nodes.

Network	LWE100	LWE200	LWE500	LWE1000	LWE2000	LWE5000	MC302	NEC127	USPower
Clustering Coefficient	0.002	0.0004	0.0003	0.0001	0.00002	0.000006	0.124	0.054	0.080
Average distance	4.362	4.940	5.616	5.881	6.345	6.514	12.908	7.112	18.989

Table 2 The average distances and clustering coefficients of real-world power grids and our evolving models with different nodes.

Network	GLC20_100	GLC20_200	GLC20_500	GLC20_1000	GLC20_2000	GLC20_5000	MC302	NEC127	USPower
Clustering Coefficient	0.165	0.120	0.066	0.042	0.028	0.012	0.124	0.054	0.080
Average distance	4.001	4.867	5.944	6.259	7.005	7.669	12.908	7.112	18.989

when the number of nodes is small. When the number of nodes exceeds 800, our model can simulate the USA western power grid's degree distribution.

Table 1 compares the average distance and clustering coefficients between real power grids with the LWE evolving models with different numbers of nodes. It can be seen

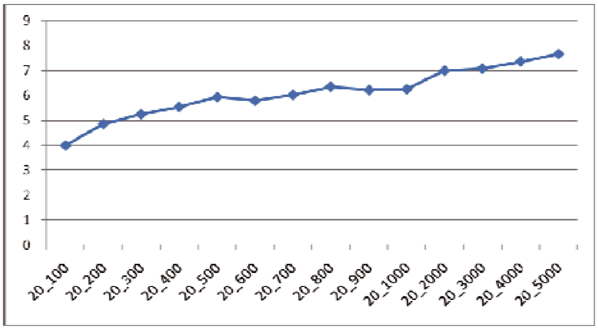


Fig. 4 The average distance changes with the increase of the number of nodes for our evolving models

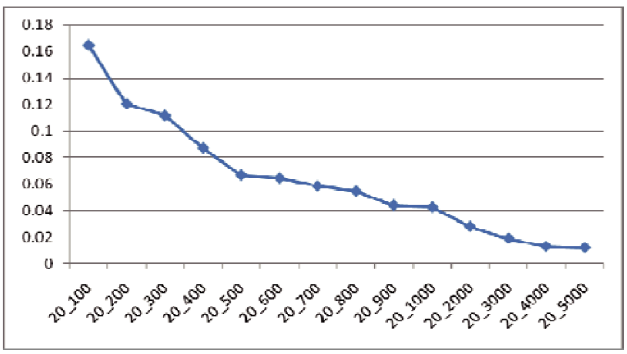


Fig. 5 The clustering coefficient changes with the increase of the number of nodes for our evolving models

from this table that the clustering coefficient of LWE models are not in line with that of the real world power grids. Table 2 compares the average distance and clustering coefficients between real power grids with our GLC evolving models with different numbers of nodes. GLC20_100 in the table means that the number of clusters is 20 and the number of nodes is 100. It can be seen from this table that the properties of our models are similar to that of the real world power grids. Figure 4 shows how the average distance changes with the increase of the number of nodes for our evolving models. Figure 5 shows how the clustering coefficient changes with the increase of the number of nodes for our evolving models. It can be seen from Fig. 4 that the average distance of the model increases slightly with the increase of the number of nodes under the same number of clusters. It can be seen from Fig. 5 that under the same number of clusters, the clustering coefficient of our model decreases to be stable with the increase of the number of nodes. On the whole, we can see that our model is more realistic than the local-world evolving model in terms of degree distribution, average distance and clustering coefficient.

5. Conclusions

This Letter presents a new evolving model for power grids. This model takes into account the geographical locations and degree values of nodes during the evolving process. Experimental results demonstrate the effectiveness of the proposed model in terms of degree distribution, average distance and clustering coefficient. Compared with the local-world evolving model, our model is more in line with the real-world power grids.

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