Electric Power Components and Systems

ISSN: 1532-5008 (Print) 1532-5016 (Online) Journal homepage: http://www.tandfonline.com/loi/uemp20

Investigation on Impacts of Alternative Generation Siting in Power Grids from the View of Complex Network Theory

Yue Xiang, Yilu Liu, Junyong Liu, Feifei Bai, Yong Liu & Cheng Huang

Electric Power Components and Systems, 44(7):820–831, 2015

ISSN: 1532-5008 print / 1532-5016 online
DOI: 10.1080/15325008.2015.1137995

Investigation on Impacts of Alternative Generation Siting in Power Grids from the View of Complex Network Theory

Yue Xiang,[1,2] Yilu Liu,[2,3] Junyong Liu,[1] Feifei Bai,[2,4] Yong Liu,[2] and Cheng Huang[5]
[1]School of Electrical Engineering and Information, Sichuan University, Chengdu, China
[2]Department of Electrical and Computer Science, University of Tennessee, Knoxville, Tennessee, USA
[3]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[4]School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China
[5]College of Electronics and Information Engineering, Sichuan University, Chengdu, China

CONTENTS

Abstract—In this article, the impacts of alternative generation integration in a power grid are discussed from the view of complex network theory. Using the improved complex network index, the structural performance of the system could be assessed in planning. Also, the distribution of load and generation are also considered in the modeling. Compared with the existing planning method, the proposed method can not only solve alternative generation units siting issues but also locate the corresponding conventional generation to be curtailed or replaced. Furthermore, as more information is obtained, *e.g.*, related policy or cost parameters, a multi-objective comprehensive decision model is designed, the weight coefficient of which is determined by the two-tuple linguistic decision method. The proposed indices and models can effectively realize fast location and help improve the structural performance of the system with appropriate alternative generation integration. The models and methods are tested and verified by test cases.

Keywords: alternative generation, siting, complex network theory, two-tuple linguistic decision
Received 25 December 2014; accepted 14 December 2015
Address correspondence to Mr. Yue Xiang, School of Electrical Engineering and Information, Sichuan University, No. 24 South Section 1, Yihuan Road, Chengdu 610065, China. E-mail: exxyye@gmail.com
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uemp.

1. INTRODUCTION

The past two decades witnessed a massive expansion of clean and green energy in power systems, which has greatly changed the energy structure. Compared with conventional fossil generation, they are environmentally friendly and more flexible, making the introduction of alternative generation (AG) technology more important [1]. AG technology indicates a supply of clean generation resources offering partial replacement of fossil energy when technically feasible, economically rational, and acceptable both environmentally and socially [2, 3]. AG resources include not only renewable energy, such as wind, solar, biomass energy, hydropower, ocean energy, etc., but also non-renewable energy, such as geothermal energy, nuclear energy, hydrogen energy, and so on, existing in the form of bulk generation (BG) [4-7] and distributed generation (DG) [8] in

NOMENCLATURE

$B(l)$	= flow betweenness of line l
$B_e(n)$	= electrical betweenness of bus n
b_{ij}	= susceptance of line i-j
$B_{ij}(l)$	= flow betweenness item of line l corresponding to generation–load pair i-j
d_{ij}	= distance between bus i and bus j
E	= importance-rank consistency division matrix
g_{ij}	= conductance of line i-j
GS	= generation bus set
$I_{ij}(k,n)$	= current produced on line k-n after unit power injection being added in generation–load bus pair i-j
LIS	= line set
LS	= load bus set
N	= total number of buses
N_D	= number of load buses
N_G	= number of generation buses
$P(l)$	= power flow of line l in initial operation mode
P_{Gi}	= generation capacity at bus i
P_{Lj}	= power demand at bus j
$P^{max}(l)$	= maximum allowable power flow of line l
$P_{ij}^{\max}$	= maximum network power of the generation–load bus pair i-j
$PTDF_{ij}(l)$	= power transmission distribution factor for line l corresponding to generation–load bus pair i-j
R	= risk index
S_i	= net power injection at bus i
SE_i	= power loss–voltage sensitivity of bus i
V_i	= voltage magnitude at bus i
w_{ij}	= weight coefficient between generation bus i and load bus j
W_k	= number of the shortest paths between load bus k and the particular generation bus
$W_{k(i)}$	= number of times bus i is passed by shortest path between load bus k and particular generation bus
Z_{ij}	= element in the ith row and jth column of the bus impedance matrix
ε_{ij}	= efficiency indicator between bus i and j

different scales of power grids. One of the challenges is to investigate the siting of AG units and their impacts on power grids. To deal with that, many methods have been proposed [9]. Cost modeling is a common approach in planning [10–12] that determines the siting and sizing problems together. Other methods use different indices [13–18], such as voltage regulation, environmental factors, power loss related, maximum DG capacity, and so on, to assess the performance of the system after the new unit is installed. Although there are several studies covering the integration of DG and BG, few have addressed how to directly replace or curtail conventional energy accordingly.

Since the power grid can be viewed as a complex network, it is beneficial to study how alternative energy affects the whole power grid in the perspective of holism, *i.e.*, system theory. In previous research, complex network theory was mainly used to assess the vulnerability of the system. The structural characteristics of the power grid, *i.e.*, node degree, critical path length, and clustering coefficient, were described in [19] based on the complex network theory. In [20], a weighted betweenness vulnerability index was designed that could identify lines essential to optimize power grid performance based on their location.

Since the structural vulnerability reflects the inherent responsiveness of the power grid, AG integration from different locations (buses) could be regarded as a "power injection attack." Thus, it is essential to identify the appropriate installation location for AG units that will improve system performance rather than putting potential threats based on complex network indices.

In this article, a complex network method (framework) is proposed to help achieve the siting of the AG units, as well as to locate corresponding conventional generation (CG) curtailment or replacement, just from the view of physical features of the power grid, without detailed cost information. The main contributions of the article are presented as follows. Improved network efficiency and betweenness indices are presented. Based on that, a simple but practical betweenness-based framework for AG siting is designed. In addition, considering the utility coefficient and degree of consumer support, a comprehensive multi-objective model is built, and the two-tuple linguistic method is used to assign the weights, which gives a wider horizon to guide the siting problem.

This article is organized as follows. Section 2 discusses the power injection model of AG and various indices. Section 3 proposes the framework for AG siting based on the improved indices, and an improved model is also presented. Section 4 presents the test cases, and finally, conclusions are provided in Section 5.

2. INDICES AND MODELS

The power injection from AG and the power curtailment from CG would impact the performance of the power system dramatically. From the view of a complex network, several performance indices can be proposed and used in the comprehensive assessment, which can be used as the theoretical basis for AG siting. In this section, some basic concepts and indices are proposed based on the complex network theory, such as improved network efficiency and betweenness for the cumulated effects of the buses, which are integrated with the physical features of the power grid.

2.1. Power Injection Model

According to the positive or negative quantity of net power injection, buses in the power grid are divided into three categories: generation buses (positive power injection), load buses (negative power injection), and connection buses. Generally, the main function of AG units is to adjust the power generation structure and relieve load burdens in its local area. However, integration at different buses can affect the performance differently, *e.g.*, the structural vulnerability of the system. In the alternative mechanism, AG is used to replace some CG outputs, so the AG integration does not significantly change the total generation capacity of the system.

2.2. Network Efficiency Index (NEI)

In complex network theory, average distance (efficiency) is an index used to describe the basic network efficiency of the whole network [21]:

$$E = \frac{1}{N(N-1)} \sum\nolimits_{i \neq j \in \Omega} \varepsilon_{ij} \tag{1}$$

or

$$E = \frac{1}{N(N-1)} \sum\nolimits_{i \neq j \in \Omega} \frac{1}{d_{ij}}, \tag{2}$$

where Ω is the node set of the network. The index reflects the interaction degree of each vertex in a graph. Smaller d_{ij} in the index indicates that the network structure is better for information communication. Therefore, an analogy can be made in the network efficiency analysis of the power grid. For example, efficiency ε_{ij} of a power grid could be defined as the inverse of the "shortest distance" based on the weight of transmission lines [22, 23].

The power grid transmits power from the generation bus to the load bus, so a shorter transmission distance can contribute to higher transmission efficiency according to Eq. (1). To describe the electrical connection information between two buses, the electrical distance is introduced and utilized if the topology of the power grid is clear. It can be formulated as Eq. (3) based on the combination of elements in the system's bus impedance matrix and the circuit theory [23]:

$$Z^e_{ij} = (Z_{ii} - Z_{ij}) - (Z_{ij} - Z_{jj}), \tag{3}$$

where Z^e_{ij} is the equivalent impedance between bus i and j, the value of which equals the voltage difference between bus i and j if one unit current injects into the two-port network formed by the generation–load bus pair. According to Eq. (3), Z^e_{ij} is determined by the bus connection relationship and line impedances, which reflects the structural information of the power grid. A shorter electrical distance leads to higher transmission efficiency between the generation–load bus pair. Thus, an improved NEI for the power grid is formulated as

$$NEI_j = \frac{1}{P_{Lj} N_G} \sum\nolimits_{i \in GS} \frac{P_{Gi}}{e^{\left|Z^e_{ij}\right|}} \quad j \in LS, \tag{4}$$

$$NEI = \frac{1}{N_D} \sum\nolimits_{j \in LS} NEI_j. \tag{5}$$

The NEI is used to analyze the network efficiency of the system. Larger NEI values mean higher power supply efficiency. Equation (4) is from the bus level view, while Eq. (5) is an index to analyze network efficiency on the system level. Based on the electrical distance of generation–load bus pairs, the NEI indicates the power transmission ability from the topology view.

2.3. Betweenness Index

The NEI can indicate the whole network transmission performance. However, it cannot easily identify the influence of a certain bus or line in the power grid or the generation–load bus pairs to locate the AG. Thus, betweenness is introduced as another index in the complex network theory to measure the importance of the buses in the complex network from a topological point of view. It has been proven that the performance of a power grid would be greatly weakened after removing several buses with large betweenness [24]. In a power grid, the importance of a bus or line can be measured by the bus or line betweenness. Taking the power grid with a generation unit at bus g for an example, the basic bus betweenness b_i can be defined as the number of times that bus i is passed by the shortest paths between the generation bus and the load buses, and the formulation is as follows:

$$b_i = \sum\nolimits_{k \in LS} \frac{W_{k(i)}}{W_k}, \tag{6}$$

$$W_k \leftarrow \text{Min } Z_{k \to g}, \tag{7}$$

where $Z_{k \to g}$ is the sum of impedance from load bus k to a certain generation bus g, and the smaller the value of $Z_{k \to g}$ is, the shorter the path will be.

Although there are several mathematical expressions of betweenness indices, some were built with pure topology concepts that ignored the real physical properties and constraints. Some other indices are much more realistic to a real power grid, such as the electrical distance index. In reality, the power flow may not always follow the "shortest path" in the power grid. Therefore, integrated with the information of power flow distribution and generation–load bus pair, two betweenness indices are presented.

2.3.1. Electrical Betweenness (EB).

EB is formulated with a power flow cumulative sum of generation–load bus pairs to reflect the influence (importance) of a certain bus or line [25]. It can be used to assess the usage degree of a certain bus occupied by the power transmission between different lines, which can be formulated as

$$B_e(n) = \sum\nolimits_{i \in GS, j \in LS} w_{ij} \beta_{ij}^e(n), \tag{8}$$

$$\beta_{ij}^e(n) = \begin{cases} \frac{1}{2} \sum_{k \in K} |I_{ij}(k, n)| & n \neq i, j \\ 1 & n = i, j \end{cases}, \tag{9}$$

where the bus in set K is directly connected with bus n. w_{ij} reflects weight of the generation–load bus pair, and it can be formulated as several formats, such as $w_{ij} = \min\{S_i, S_j\}$, which indicates the available transmission power between generation bus i and load bus j.

3.2.2. Flow Betweenness (FB).

Each line in the power grid transmits the power from different generation–load bus pairs and is possibly passed through multiple times, in which the total times of a certain line could be used to reflect its importance level in the operation mode of the power grid. Considering the power transmission limit of each line, integrated with topology and operation information, the max-flow min-cut theorem [26] is introduced to determine the maximum network power between each generation–load bus pair. Based on the definition in [27], with the accumulative effect of all generation–load bus pairs, the improved FB indices (including the line index and bus index) are given as follows:

$$B(l) = \sum\nolimits_{i \in GS, j \in LS} w_{ij} \beta_{ij}(l) \quad \forall l \in LIS, \tag{10}$$

$$\beta_{ij}(l) = \frac{P_{ij}^{\max} \times PTDF_{ij}(l)}{P^{\max}(l) - P(l)}, \tag{11}$$

$$P_{ij}^{\max} = \min\left\{\frac{P^{\max}(l) - P(l)}{PTDF_{ij}(l)}\right\}, \tag{12}$$

where $P_{ij}^{\max}$ is the maximum network power of the generation–load bus pair *i*-*j*. The largest FB value of all the lines can be regarded as the FB performance of the system. For each line, each FB item $B_{ij}(l)$ corresponding to generation–load pair *i*-*j* can be calculated as

$$B_{ij}(l) = w_{ij} \beta_{ij}(l). \tag{13}$$

Thus, the equivalent FB of load bus j can be obtained:

$$B_j = \sum\nolimits_{i \in GS} \sum\nolimits_{l \in LIS} B_{ij}(l). \tag{14}$$

2.4. Risk Index

Since the impact of AG integration can be investigated based on the proposed complex network indices, the performance before and after installing AG at different buses would be assessed and compared. Then a risk index can be used to evaluate the effectiveness:

$$R = (B_s - B_{s0})/B_{s0} \times 100\%, \tag{15}$$

where B_s is the system performance index quantity with AG integration, while B_{s0} indicates that without AG integration.

3. STRATEGIES FOR ALTERNATIVE GENERATION SITING

Based on the indices proposed in the previous section, the impacts of power injection or curtailment can be assessed with the NEI and the improved betweenness index. Compared with the NEI, the improved betweenness index integrates the power flow and network constraints, representing the features of the power grid more realistically. Thus, based on the proposed betweenness index, a framework for AG siting and CG replacement or curtailment is proposed in this section. The method from the view of complex network theory can be used to assess the structural performance of the system based on the power injection information. Furthermore, if the information about the energy types, bus location distribution, price, and policy is known or given, a comprehensive decision model is proposed, integrated with the improved complex network index, to study deeply the AG siting from multi-performance views.

3.1. Betweenness-based Framework for Siting

As introduced in Section 1, the siting of AG can be determined from the view of structure vulnerability through various complex network indices. The NEI is designed from the whole grid view, which is hard to locate quickly the appropriate integration location or the replacement location without enumeration. Therefore, it is only used for siting plans analysis and comparison in this article. Betweenness can provide a feasible way to identify the important lines or buses. Whether EB, FB, or other indices are selected mainly depends on the certain objectives and constraints. Taking FB as an example, the appropriate load buses for siting can be selected from high FB pairs according to the given amount of AG units to be installed. The complex network index mainly focuses on the structure of the

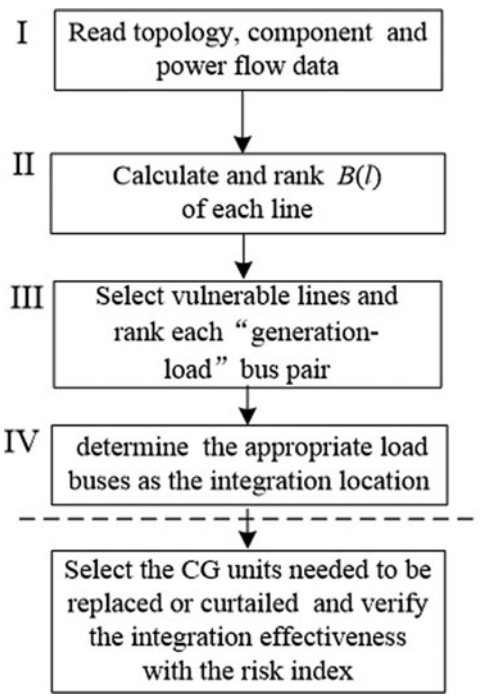

FIGURE 1. Betweenness-based framework for siting.

network. Thus, only the structure data of the power grid, the capacity information of the AG units, and the power flow data in the typical operation mode are needed to lead to the final result. Selecting the appropriate buses can greatly decrease the vulnerability risk of the system. An AG siting framework based on the proposed betweenness index is given in Figure 1. The framework can also be extended with other line or bus betweenness indices except FB.

After Stage IV, the appropriate siting (locations) of AG integration can be obtained. The corresponding CG units will be replaced or curtailed when the AG units work. In terms of selecting the CG units for which power outputs need to be reduced, there are mainly two replacement strategies: ([1]) average mechanism, *i.e.*, all generation buses are selected to be curtailed on average, and ([2]) pair mechanism, *i.e.*, one AG integration corresponds to the most related CG unit replacement or curtailment based on the generation–load bus pair and the electrical distance, and the second AG-CG pair would be arranged if the AG capacity is larger than that of the CG in the first pair.

3.2. Improved Comprehensive Model Based on Multi-indices

According to the proposed complex network indices, the "optimal" location of the alternative energy can be obtained from the viewpoint of the power system structure vulnerability. In real planning, more factors may be involved besides the structure

Mood	Negative effect	Almost no benefit	A little benefit	High benefit
Value	1	2	3	4

TABLE 1. Mood operator and the utility coefficient quantity

index, for example, the public awareness of the environment in AG integration, such as the type of nuclear energy. So a comprehensive assessment is needed if more factors are considered and the related information is obtained. In the assessment, if the generation resources, such as wind or solar density, are not enough in a certain area (corresponding to an equivalent load bus), the load bus cannot be selected as the candidate location for AG siting. On the other hand, AG is not limited to wind or solar generation. Others, such as the environmentally friendly combined heat and power (CHP) units or emerging nuclear DG, may also be utilized and planned in the power grid. In this article, three factors are considered in the comprehensive model:

$$F = \alpha F_1 + \beta F_2 + \gamma F_3, \tag{16}$$

where F_i represents the ith objectives; α, β, and γ are coefficients; and $\alpha + \beta + \gamma = 1$.

F_1 is the structure importance index, reflecting the importance degree of the candidate buses and is expressed by the betweenness index. The higher the value of F_1 is, the greater the bus's impact on the structure vulnerability of the power grid will be.

F_2 is the utility coefficient and indicates the unit utility (land acquisition cost, environmental effect, etc.) for the energy resource and cost recycle degree in different siting candidates, which can be obtained from surveys. For simplicity, mood operators can be used to quantify, as shown in Table 1.

F_3 is the customers' support degree and describes customers' attitudes toward AG integration in some buses. For example, if the type of AG is nuclear generation, although safe when planned, some customers may be anxious and resist its integration, and the conditions vary in different areas. Here five levels are given with different mood operators to describe the support degree in a certain area (bus), as shown in Table 2.

The units of the three objectives are different, so a simple normalization method as described in Eq. (17) can be utilized

Mood	Strong opposition	Opposition	No opinion	Support	Strong support
Value	1	2	3	4	5

TABLE 2. Mood operator and customers' support quantity

to replace F_i in Eq. (16) by its normalized values:

$$\bar{F}_i = \frac{F_i - F_i^{\min}}{F_i^{\max} - F_i^{\min}}. \tag{17}$$

The final comprehensive results of each candidate bus can be obtained from F_i ($i = 1, 2, 3$), all of which are leading in the same direction toward the maximum solution to select the important locations. So the appropriate buses can be selected by the rank of F from the largest value to the next. The replacement CG units or curtailed quantity can then be obtained correspondingly based on the strategy proposed in Section 3.1.

3.3. Weight Coefficients Decision

Weight coefficients reflect the importance of the objectives. Due to the mood operators in the comprehensive model, the two-tuple linguistic decision method [28–30] is used to determine the weight coefficients; the main steps follow.

Regarding the set of m indices ($F = \{f_1, f_2, ..., f_m\}$), the importance of each index is described by 0, 0.5, and 1; that is to say, if f_k is greater than f_l, then $e_{kl} = 1$ and $e_{lk} = 0$; if f_k and f_l share the same importance, then $e_{kl} = e_{lk} = 0.5$; if f_l is greater than f_k, then $e_{kl} = 0$, $e_{lk} = 1$, and $e_{kk} = e_{ll} = 0.5$. According to the rough comparison between different objects, the importance-rank consistency division matrix E is established as $E = (e_{kl})_{m\times m}$, calculating all the elements in each row of matrix E whereby the rank points out the importance of the indices.

After that, let the most important index compare with other indices, and the mood operator, fuzzy scale, and the corresponding relation between the relative membership degrees can be applied based on Table 3. [28, 30]. The fuzzy scale quantity indicates the linguistic degree of the mood operator, while the membership degree reflects the corresponding weight coefficient. The next is to obtain the non-normalized weight coefficients of the indices to get the normalized ones.

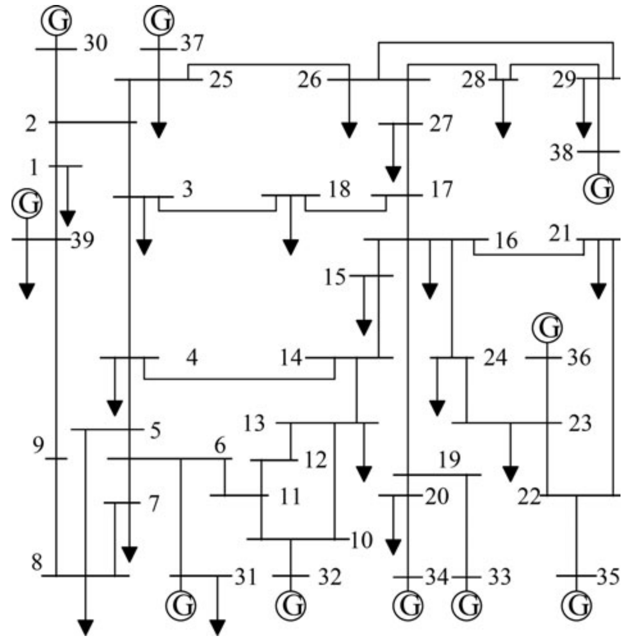

FIGURE 2. Ten-generator 39-bus system.

Then, they can be used in Eq. (16) and contribute to obtain the final siting plan based on the rank of the comprehensive quantity for each one.

4. CASE STUDY

A 10-generator 39-bus system [31] that includes 21 load buses and 46 lines is used in the case study, as shown in Figure 2. First, the network efficiency has been analyzed and assessed for the AG siting issues in different scenarios. Then the siting problem is studied and tested based on the betweenness-based framework and the comprehensive decision model, respectively.

Mood operator	Fuzzy scale quantity	Membership degree	Mood operator	Fuzzy scale quantity	Membership degree
The same	0.5	1	Fully	0.8	0.25
	0.525	0.905		0.825	0.212
Sort of	0.55	0.818	Very	0.85	0.176
	0.575	0.739		0.875	0.143
A little	0.6	0.667	Highly	0.9	0.111
	0.625	0.6		0.925	0.081
Relatively	0.65	0.538	Extremely	0.95	0.053
	0.675	0.481		0.975	0.026
Obviously	0.7	0.429	Beyond comparison	1	0

TABLE 3. Relationship of mood operator, fuzzy scale, and membership degree

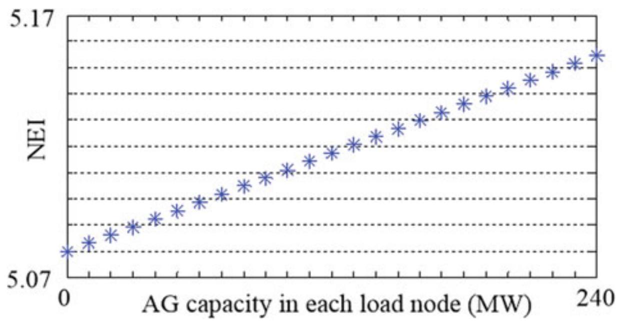

FIGURE 3. NEI variation trend with different AG capacity integration.

4.1. Network Efficiency Analysis

Considering the impact of AG integration on different buses, two scenarios, *i.e.*, integrating at all load buses or just one load bus, are considered based on different power injection strategies and locations. Meanwhile, an assumption is made: Since all load buses are regarded as potential integration points, the increased power generated by AG units would be equivalent by decreasing the capacity of CG units on average with the designed replacement strategy ([1]) in Section 3.1.

4.1.1. Scenario 1.

Let an AG unit be installed into every candidate load bus at the same time from 0 to 240 MW with a 10-MW step, while the new generation capacity is equivalent by decreasing the corresponding capacity of CG units on average. The NEI result can be seen in Figure 3.

As shown in Figure 3, the power injection of AG can effectively improve the NEI level. It also indicates that the NEI value increases as the capacity of AG integration grows. Based on Eq. (4), the NEI_j variation of each load bus can be obtained, part of which is shown in Figure 4. A smaller NEI_j indicates that bus j needs more local power supply according to the generation and load conditions. It should be noted that ranking the result of the buses in this way is different than those based on "degree" [21], which is also a structure index in complex network theory. The definition of "degree" is the number of connections or lines of the bus that are adjacent to other buses. The bus with a higher degree indicates it is important in the relationship of connection but does not reflect its transmission efficiency since it ignores the generation–load transmission path features of the power grid.

4.1.2. Scenario 2.

Letting an AG unit integrate into a load bus at one time, from 0 to 5000 MW with a 100-MW step, the NEIs of the system are shown in Figure 5.

As shown in Figure 5, the AG unit integration at bus 20, 28, or 29 decreases the NEI level of the whole system, which indicates that it is not wise to install an AG unit into those buses according to the system-level NEI results. However, integration at bus 8, 7, or 4 could be given a priority to improve network efficiency for the positive gradient.

It is worth noting that NEI_{20} is small, which means bus 20 needs more power injection theoretically. However, Figure 5 shows that single AG unit integration at bus 20 decreases the NEI level of the system instead of improving it. The reason is that the NEI mainly focuses on the performance of the overall system. The AG unit integrated at bus 20 could indeed improve the performance of bus 20 in the local area, but it does not improve the network transmission efficiency of the overall system. Therefore, the NEI could give the overall information of the whole network based on network efficiency, but the pure NEI does not always work efficiently for only considering the capacity of generation and load distribution. This is mainly why it is necessary to investigate the impact of AG siting based on other complex network indices, such as betweenness from different aspects with more power grid information.

4.2. AG Siting Based on the Proposed Complex Network Index

FB is used with the betweenness-based framework in this case to show how to locate the appropriate integration locations (buses) for AG units and the replacement or curtailment locations (buses) for CG units, as well as the impacts.

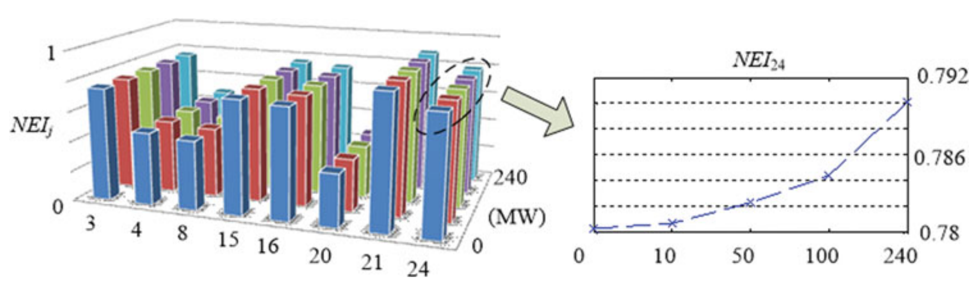

FIGURE 4. NEI_j variation trend with different AG capacities integrated at load buses 3, 4, 8, 15, 16, 20, 21, and 24.

Line	"Generation, load" bus pair	FB of the line	Line	"Generation, load" bus pair	FB of the line	Line	"Generation, load" bus pair	FB of the line
2-3	37, 8	5.16	6-11	32, 8	5.22	16-19	38, 20	6.8
2-3	37, 4	5	6-11	31, 4	5	16-19	31, 20	6.68
2-3	38, 4	3.65	6-11	36, 8	4.32	16-19	35, 20	6.5
2-3	37, 16	3.29	6-11	32, 4	4.31	16-19	32, 20	5.6
2-3	37, 3	3.22	6-11	38, 8	3.9	16-19	36, 20	5.4
2-3	37, 15	3.2	6-11	31, 16	3.29	16-19	37, 20	5.22
2-3	38, 3	3.19	6-11	31, 3	3.22	16-19	33, 8	5.08
2-3	37, 24	3.09	6-11	31, 15	3.2	16-19	34, 4	5
2-3	38, 8	2.91	6-11	35, 8	3.17	16-19	33, 4	5
2-3	37, 21	2.74	6-11	31, 24	3.09	16-19	34, 16	3.29

TABLE 4. Partial pair results of lines 2-3, 6-11, and 16-19

Based on the bus classification method in Section 2.1, there are 9 generation buses and 20 load buses in the test system. According to the power flow distribution in the typical operation mode, the FB of lines can be obtained, as shown in Figure 6. Here it is labeled as Case I (base case). Lines 2-3, 6-11, and 16-19 are the most vulnerable lines, and the FB of the system is 151.65. Considering three AG units integration, the generation–load bus pair items are calculated and shown in Table 4 (select partial results that FB of the line is >3). According to the proposed framework of Figure 1, buses 8, 20, and 4 are then determined as the integration locations.

Replacement strategy (^{2}) for CG is implemented in the case, and the critical reduced power of CG units can be seen in Table 5 (assuming that the integration power does not exceed the load demand at the nodes, known as Case II). Note that if the power demand in the integration bus is larger than the generation power of the "shortest distance" generation bus, the second CG would be arranged. Taking the replacement plan of AG integrating at bus 20, for example, the replacement plan is given as follows: 508-MW CG capacity at bus 34 would be replaced for its shortest electrical distance between bus 20 and bus 34, as well as the pair impact information presented in Table 4, while the remaining 172-MW CG capacity would be decreased at bus 33.

FB of the system after the three AG units integration (with penetration ratio of 27.2%) is 94.08, and the value is the same as that of line 16-17, while line 2-3 is 39.28 in Case II. So $R =$ –37.96%. This shows that AG integration greatly decreases the operational risk of the system from the FB perspective, and the transmission conditions of lines could be effectively relieved by appropriate AG placement according to the comparison of the power flow distribution in Case I and Case II, which is shown in Figure 7.

The impact and risk of the AG capacity are simply discussed as follows. To avoid power curtailment in multiple CG units, generation–load bus pairs 32-8, 34-20, and 30-4 are selected to simulate with the step 6.5, 5.08, and 2.5 (MW) for the power output change and run 100 times (until each CG unit power limit stops at bus 32, 34, and 30). Thus, the risk index based on FB is shown in Figure 8.

As seen in Figure 8, inflection point A indicates the change of the most vulnerable lines with a specific penetration level of AG, as well as the FB value of the system. It can be seen from the simulation result that the risk trend of the system decreases

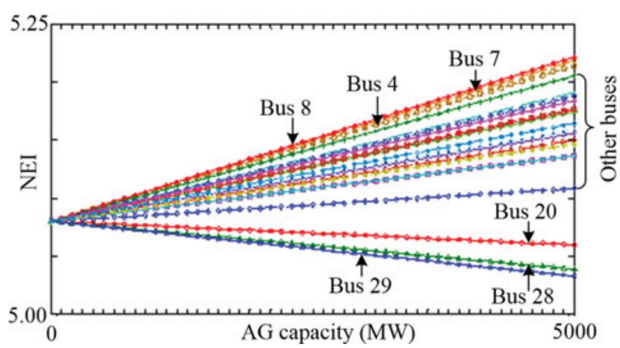

FIGURE 5. NEI variation trend with different AG capacities integrated at different load buses.

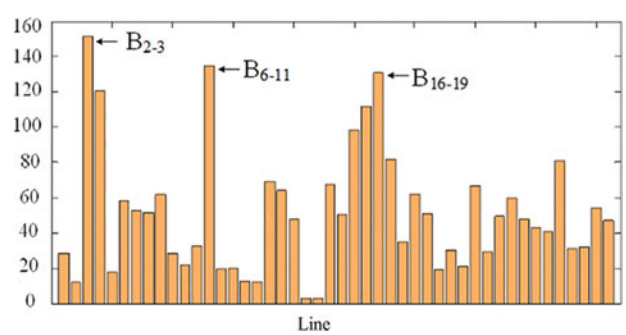

FIGURE 6. FB of each line (the sequence of the lines is the same as that in the data file of [31]).

AG integration bus	Replace or curtailment plan
Bus 8 (522 MW)	Bus 32 (–522 MW)
Bus 20 (680 MW)	Bus 34 (–508 MW); bus 33 (–172 MW)
Bus 4 (500 MW)	Bus 32 (–128 MW); bus 30 (–250 MW); bus 37 (–122 MW)

TABLE 5. Power output (MW) of corresponding CG units reduced by AG units

Note: The total capacity of the CG units at buses 30, 32, 33, 34, and 37 are 250, 650, 632, 508, and 540 MW, respectively.

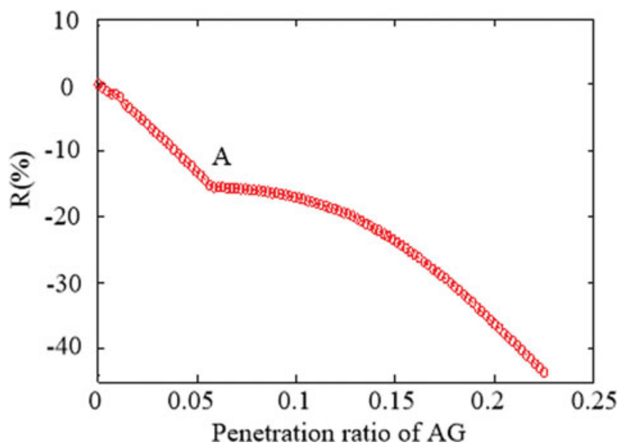

FIGURE 8. Risk index results of the system with the AG capacity increase.

when the penetration of AG increases, which shows that appropriate AG placement is good for improving performance of the power system. However, it does not mean that more AG integration is better. So in a large-scale power system, the sizing of AG units needs to be determined based on risk analysis after siting.

The complex network index, *e.g.*, the improved betweenness index and its framework, provides a way to improve the structural performance of the system and help optimize the power distribution structure to realize AG siting. It owns several significant advantages in some aspects compared with other index methods for siting. Sensitivity is a common method in determining DG siting, for example, the power loss–voltage sensitivity index in [13],

$$SE_i = \sum_{j=1, j\notin i}^{N} V_j(g_{ij} cos\theta_{ij} + b_{ij} sin\theta_{ij}), \qquad (18)$$

is designed from the view of reducing power loss. It is obtained by transforming the polar coordinates based Newton power flow equation and letting the mathematical expression of power loss differentiate bus voltage. So the index of each bus can be derived based on the basic power flow calculation. After all *SE*s of buses are obtained and ranked, those with voltage magnitudes less than the reference value while SE_i is negative are selected. That kind of bus has the potential for voltage increase and power loss reduction. In this way, the optimal location for DG can be selected.

Using the index in Eq. (18) to help locate AG, all *SE* and voltage profiles can be seen in Figure 9. As shown in Figure 9, there are 25 buses for which the *SE* quantities are negative. According to the rules mentioned, the appropriate integration bus should satisfy two conditions including SE_i being negative and having enough growth space for the voltage magnitude. If the reference voltage is set as 1.0, then buses 8, 7, and 20 could be in the candidate set. It is noted that the generation buses are not regarded as the candidate locations for AG units. If enhancing the reference value a little, then buses 4, 5, and 12 can also be included. Considering three AG unit integration as the test case, buses 8, 7, and 20 could be selected as the optimal plan for AG units if referring to the voltage magnitude of 1.0.

Compared with the proposed complex network method result, the selection of buses 8 and 20 indicates that the integration of AG in those two buses could improve the performance of the power system, not only in structure optimization but also in power loss reduction. The selected bus 7 by the method in [13] can help relieve the power loss burden, but the improvement impact on the system structural performance is not better than that by integration at bus 4 (larger load demand at bus 4). So bus 7 is not included in the final plan using the

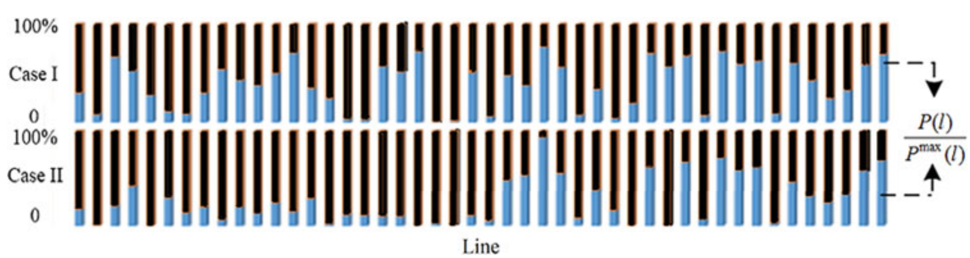

FIGURE 7. Power flow distribution of each line in Cases I and II (the sequence of the lines is the same as that in the data file of [31]).

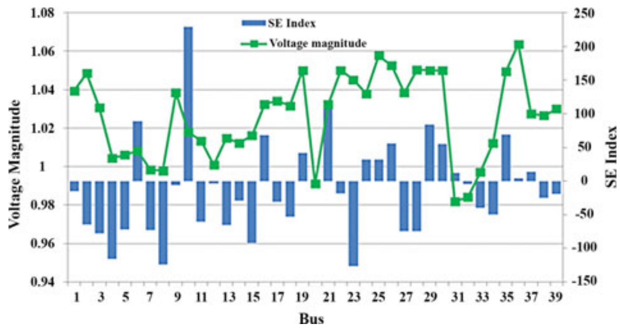

FIGURE 9. *SE* index and voltage magnitude simulation result by the method in [13].

method in this article. Moreover, it can be seen from Figure 9 that the power loss–voltage sensitivity of bus 4 ranks in front, which indicates that the result from the proposed method can also have a power-related performance. That is to say, although the method herein is based on structure assessment, the distribution of load and generation are considered in modeling, as well as the network constraints, so the proposed method could optimize the power distribution, power loss, and voltage profile.

4.3. Extended Improvements Based on the Comprehensive Model

In this case, as more information is obtained, the proposed comprehensive decision model is tested for an AG siting problem considering more factors than just structure importance, such as the betweenness index in Section 4.2. Assuming all load buses have the energy resource of AG, *e.g.*, enough wind speed for wind power, solar intensity of solar power, etc., FB of the bus can then be calculated based on Eq. (14), together with the given utility coefficients and customers' support degree, as listed in Table 6.

As shown in Table 6, the FB of buses 8, 4, 16, 3, 15, and 24 are the largest. Thus, these buses should be ranked at the top of the list for appropriate AG siting if the structure vulnerability of the power grid is focused. Compared with the case result in Section 4.2, bus 20 is excluded. This is because in Section 4.2, FB of the line is used to determine the "severe" line and find the most effective bus to be installed with AG to relieve the pressure, and bus 20 ranks in front for the line index, so it is selected in that case. However, in this case, FB of the bus is utilizated and indicates the FB capability of a certain bus from the viewpoint of the whole system, which leads to the difference.

Considering the utility coefficient and customers' support degree, F_1 reflects the structure importance of the power grid and is regarded as the most important factor. So it is assumed that F_1 is more important than F_2, which is the utility coefficient, and F_2 is more important than F_3. Thus, the importance-rank consistency division matrix can be formed as follows:

$$E = \begin{bmatrix} 0.5 & 1 & 1 \\ 0 & 0.5 & 1 \\ 0 & 0 & 0.5 \end{bmatrix}.$$

This matrix satisfies the importance of scale consistency. The importance of different indices (objectives) is verified by the sum of each row $2.5 > 1.5 > 0.5$, *i.e.*, $F_1 > F_2 > F_3$. Then, in the following rank comparison, it is between "a little" and "relatively" comparing F_1 and F_2, and it is between "relatively" and "obviously" comparing F_1 and F_3. So the non-normalized weight coefficients are [1 0.6 0.481] and the normalized weight coefficients are [0.48 0.29 0.23].

The final comprehensive value of the candidate buses based on Eqs. (16) and (17) can be obtained. With a larger comprehensive value, the performance of AG siting at the corresponding bus for the power grid would be better. So, as shown in Figure 10, buses 8, 4, and 15 are selected if three AG units are

Bus number	FB of the bus	Utility coefficient	Customers' support degree	Bus number	FB of the bus	Utility coefficient	Customers' support degree
1	1.95	2	3	20	5.15	1	1
3	6.44	3	3	21	4.75	4	3
4	10	3	2	23	4.95	3	1
7	4.68	4	3	24	6.17	3	2
8	10.44	3	4	25	4.48	3	1
9	0.13	3	4	26	2.78	3	2
12	0.15	2	3	27	5.62	3	3
15	6.4	4	3	28	3.15	4	3
16	6.58	2	3	29	5.67	3	1
18	3.16	1	3	39	2.08	2	1

TABLE 6. Data for comprehensive assessment

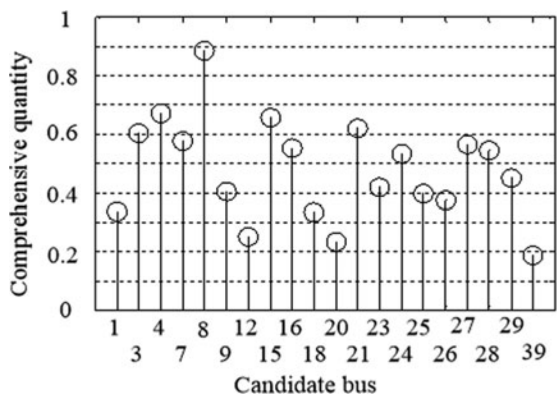

FIGURE 10. Comprehensive quantity of the candidate buses.

going to be installed. The result is based on the comprehensive assessment of the three objectives. Thus, although buses 16 and 3 have larger FB than that of bus 15, they are not selected because the final comprehensive quantity based on the three objectives is not high. The replacement locations of CG units can be also determined on account of generation–load bus pair and electrical distance analysis if necessary.

It can be seen from the test case in Section 4.3 that if more information, including policy, human support, cost, and others, is obtained, then based on the proposed complex network index, the comprehensive decision model can be used to get more realistic and significant results.

5. CONCLUSION

This article has proposed different improved complex network indices for investigating the impact of AG integration and its siting problem in the power grid. Then a simple but practical betweenness-based framework is designed for AG siting from the view of structure vulnerability. Integrated with the improved complex network index, the structural performance of the system can be assessed in planning. Compared with the existing methods, the proposed can not only solve AG unit siting issues but also locate the corresponding CG to be curtailed or replaced. As more information is obtained, *e.g.*, policy or cost parameters, the AG siting can be further determined based on the multi-objective comprehensive decision model. The two-tuple linguistic decision method is also utilized to assign the weight coeffiecents, as verified in the test case. In-depth analysis of the sizing, together with the siting problem, will be studied in the future work.

REFERENCES

[1] Ding, D., *Development and Security of Modern Power Grid*. Beijing, China: Tsinghua University, Chaps. 1–3, 2012.

[2] Su, S., "Research on the development of substitute energy of low carbon energy in Xinjiang on the basis of saving energy and reducing emission,"*Ecol. Econ.*, Vol. 3, pp. 68–74, March 2011.

[3] Som, T., and Chakraborty, N., "Studies on economic feasibility of an autonomous power delivery system utilizing alternative hybrid distributed energy resources," *IEEE Trans. Power Syst.*, Vol. 29, No. 1, pp. 172–181, 2013.

[4] Smil, V., "A skeptic looks at alternative energy," *IEEE Spect.*, Vol. 49, No. 7, pp. 46–52, 2012.

[5] Tuohy, A., Kamath, H., and Rogers, L., "Evaluation of storage for bulk system integration of variable generation," *IEEE Power and Energy Society General Meeting*, San Diego, CA, 22–26 July 2012.

[6] da Rosa, M. A., Heleno, M., Miranda, V., Matos, M., and Ferreira, R., "Reliability impact on bulk generation system considering high penetration of electric vehicles," *IEEE Trondheim Power Technology*, pp. 1–6, Trondheim, Norway, 19–23 June 2011.

[7] Bassiouny, E., El-Ela, A., and Othman, S., "Adequacy assessment of bulk electric power systems incorporating wind energy," *IEEE GCC Conference and Exhibition*, Dubai, UAE, pp. 279–282, 19–22 February 2011.

[8] Guerrero, J. M., Blaabjerg, F., Zhelev, T., Hemmes, K., Monmasson, E., Jemei, S., Comecha, M., Granadino, R., and Frau, J., "Distributed generation: Toward a new energy paradigm," *IEEE Indus. Electr. Mag.*, Vol. 4, No. 1, pp. 52–64, 2010.

[9] Georgilakis, P., and Hatziargyrious, N., "Optimal distribution generation placement in power distribution networks: Models, methods and future research," *IEEE Trans. Power Syst.*, Vol. 28, No. 3, pp. 3420–3428, 2013.

[10] Evangelopoulos, V., and Georgilakis, P., "Optimal distributed generation placement under uncertainties based on point estimate method embedded genetic algorithm," *IET Gener. Transm. Dist.*, Vol. 8, No. 3, pp. 389–400, 2014.

[11] Jahromi, M., Ehsan, M., and Meyabadi, A., "A dynamic fuzzy interactive approach for DG expansion planning," *Int. J. Electr. Power Energy Syst.*, Vol. 43, pp. 1094–1105, 2012.

[12] Liu, Z., Wen, F., and Ledwich, G., "Optimal siting and sizing of distributed generators in distribution systems considering uncertainties," *IEEE Trans. Power Del.*, Vol. 26, No. 4, pp. 2541–2551, 2011.

[13] Yang, C., Zhou, B., Lin, H., Wang, D., Ran, Y., and Zhan, C., "A method of distributed generators' optimization allocation," *Electr. Measur. Instrumentat.*, Vol. 52, No. 8, pp. 109–114, 2015.

[14] Zheng, Z., Ai, Q., Gu, C., and Jiang, C., "Multi-objective allocation of distributed generation considering environmental factor," *Proc. CSEE*, Vol. 29, No. 13, pp. 23–28, 2009.

[15] Al Kaabi, S., Zeineldin, H., and Khadkikar, V., "Planning active distribution networks considering multi-DG configurations," *IEEE Trans. Power Syst.*, Vol. 29, No. 2, pp. 785–793, 2014.

[16] Gelli, G., Ghiani, E., Mocci, S., and Pilo, F., "A multiobjective evolutionary algorithm for the sizing and siting of distributed generation," *IEEE Trans. Power Syst.*, Vol. 20, No. 2, pp. 750–757, 2005.

[17] Xiang, Y., Liu, J., Liu, Y., Zhang, J., and Yang, J., "A search strategy for optimal configuration of distributed generation con-

sidering centroid mapping and path analysis," *Power Syst. Tech.*, Vol. 36, No. 6, pp. 133–140, 2012.
[18] Gozel, T., and Hocaoglu, M. H., "An analytical method for the sizing and siting of distributed generators in radial systems," *Electr. Power Energy Syst.*, Vol. 79, No. 6, pp. 912–918, 2009.
[19] Sun, K., "Complex networks theory: A new method of research in power grid," *2005 IEEE/PES T&D Conference & Exhibition: Asia and Pacific*, pp. 1–6, Dalian, China, 15–17 August 2005.
[20] Chen, X., Sun, K., Cao, Y., and Wang, S., "Identification of vulnerable lines in power grid based on complex network theory," IEEE PES General Meeting, Tampa, FL, pp. 1–6, 2007.
[21] Wang, X., Li, X., and Chen, G., *Complex Network Theory and Its Application*. Beijing, China: Tsinghua University Press, Chap. 1, 2006.
[22] Bompard, E., Wu, D., and Xue, F., "Structure vulnerability of power systems: A topological approach," *Electr. Power Syst. Res.*, Vol. 81, pp. 1334–1340, 2011.
[23] Xiang, Y., Bai, F., and Liu, Y., "Network efficiency analysis for power grid with distributed generation based on complex network theory," CURENT's 2014 Site Visit & Indusrial Conference, Knoxville, TN, pp. 1–5, 12–16 May 2014.
[24] Wei, Z., and Liu, J., "Research on the electric power grid vulnerability under the directed-weighted topological model based on complex network theory," International Conference on Mechanic Automation and Control Engineering (MACE), Wuhan, China, pp. 3927–3930, 26–28 June 2010.
[25] Xu, L., Wang, X., and Wang, X., "Electric betweenness and its application in vulnerable line identification in power system," *Proc. CSEE*, Vol. 30, No. 1, pp. 33–39, 2010.
[26] Wang, G., Wang, Y., and Ran, J., *Graph Theory: Algorithm, Theorem, Implementation, Application*. Beijing, China: Peking University Press, Chap. 6, 2011.
[27] Li, M., Xu, L., Gong, H., Song, Z., Ding, L., and Liu, J., "Study on critical lines identification," 2013 International Conference on MEC, Shengyang, China, pp. 3132–3135, 20–22 December 2013.
[28] Lei, J., Xie, J., and Gan, D., "Optimization of distributed energy system and benefit analysis of energy saving and emission reduction," *Auto. Elect. Power Syst.*, Vol. 33, no 23, pp. 29–36, 2009.
[29] Zhang, Y., Zhang, Y., and Kuang, X., "Approach for multiple group decision-making based on two-tuple linguistic considering weight," *J. WUT (Info. Math. Eng.)*, Vol. 30, No. 6, pp. 928–931, 2008.
[30] Chen, S., *Fuzzy Decision Theory and Application*, Dalian, China: Dalian University of Technology Press, Chap. 2, 1994.
[31] Zimmerman, D., Murillo-Snchez, C., and Gan, D., "39-bus system," http://www.pserc.cornell.edu/matpower.

BIOGRAPHIES

Yue Xiang received his B.S. from Sichuan University, Chengdu, China, in 2010, where he is currently pursuing his Ph.D. From 2013 to 2014, he was a joint Ph.D. student at the University of Tennessee, Knoxville, TN, USA. His main research interests are power system planning and optimal operation, renewable energy integration, electric vehicles, and smart grids.

Yilu Liu received her Ph.D. from Ohio State University, Columbus, OH, USA, in 1989. She is currently Governor Chair Professor at University of Tennessee, Knoxville, and Oak Ridge National Laboratory, prior to which she was a professor at Virginia Tech. She led the effort to create the North American power grid monitoring network (FNET) at Virginia Tech, which is now operated at University of Tennessee, Knoxville, and Oak Ridge National Laboratory as FNET/GridEye. Her current research interests include power system wide-area monitoring and control, renewable energy integration, and information technology (IT) applications.

Junyong Liu received his Ph.D. from Brunel University, UK, in 1998. He is currently a professor in the School of Electrical Engineering and Information, Sichuan University, China. His main research areas of interest are power system planning, operation, stability, and computer applications.

Feifei Bai received the B.S. and Ph.D. from Southwest Jiaotong University, China, in 2010 and 2016, respectively. She was a joint Ph.D. Student at the University of Tennessee, Knoxville, USA, from September 2012 to December 2014. Her main research interests are small signal stability analysis and wide-area damping control, wide-area monitoring and analysis.

Yong Liu received his Ph.D. in electrical engineering (power system direction) from the University of Tennessee, Knoxville, in 2013. He received his M.S. and B. S. in electrical engineering from Shandong University, China, in 2007 and 2010, respectively. He is currently a research assistant professor in the DOE/NSF-cofunded engineering research center CURENT and Department of Electrical Engineering and Computer Science at the University of Tennessee, Knoxville. His research interests are wide-area power system measurement, power system dynamic analysis and renewable energy integration.

Cheng Huang received his B.S. and M.S. from Sichuan University, China, in 2010 and 2013, respectively, where he is currently pursuing his Ph.D. His main research interests are information system security and computer applications.