Structural and Hierarchical Partitioning of Virtual Microgrids in Power Distribution Network

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***Abstract*—Nowadays, the infrastructure and technologies in conventional distribution networks (CDNs) limits its further development to smart distribution networks (SDNs). One way to overcome this is to develop CDNs using interconnected virtual microgrids (VMs), however there is no consensus for an explicit definition of VMs. Therefore, in this paper, a comprehensive discussion on VMs is conducted, and a general framework for developing VMs is proposed. The core issue for developing VMs is to identify boundaries of VMs, and most of the suggested methods are based on analyzing operating states. In this paper, a different partitioning method which is based on the analysis of structural characteristics is proposed. The electrical coupling strength (ECS) is defined as a composite weight coefficient for the analysis of electrical connection, and the electrical modularity is used to assess the quality of the partition so as to identify boundaries of VMs. This partitioning method is applied to the IEEE 33-bus distribution network and the PG&E 69-bus distribution network, and it can quickly evaluate the partitioning quality and effectively identify the boundaries of VMs.**

***Index Terms*—Boundaries, electrical coupling strength (ECS), electrical modularity, virtual microgrids (VMs).**

I. INTRODUCTION

NOWADAYS, distribution networks are facing lots of challenges, such as incremental load demands, limited expansion space, environmental issues, aging infrastructure and so on [1], [2]. In order to overcome these challenges, it is necessary to plan and upgrade conventional distribution networks (CDNs) to smart distribution networks (SDNs). In general terms, SDN should contain diverse variety of distributed generations (DGs) and related devices with intelligent technologies, which may make the operation of SDN more complicated. It should be an intelligent and modernizing grid which is possible to accommodate bi-directional power flow and communication [3], [4]. Because most topology of CDNs are radial, and CDNs are designed not only to remain unidirectional but also to efficiently and economically deliver electrical power to customers [5], [6], so the infrastructure and technologies of CDNs restricts the adoption of SDNs. It is necessary to do more investigation so as to draw up a realistic upgrading plan for CDNs [5].

To fully explore the advantages of SDNs, CDNs should be upgraded with more flexible, resilient and free operation. Microgrids is one of the most popular concepts for the conversion from CDNs to SDNs, and a comprehensive literature review for microgrids planning is carried out in [7]. However, microgrids have limited energy handling capability [8], [9], and it is very hard, if not impossible, to completely reconstruct new microgrids in existing distribution networks. Therefore, virtual microgrids (VMs) have drawn much attention these days as they can provide a new way to upgrade CDNs, and it is based on partitioning the CDN into a group of areas which will be constructed to microgrids eventually [9], [10]. Until now, there is no commonly accepted definition for VMs, so this paper will summarize the features of VMs according to the current research, and a number of existing methods for partitioning VMs will also be discussed in the following section.

Power network partitioning has been widely studied with different methods. An optimal and distributed partitioning strategy based on spectral clustering is proposed in [11]. It focuses on reducing the convergence time while guarantees the solution quality for a given power system, and the optimal partitioning is used to solve the AC optimal power flow without considering the geographical topology of the power system. A hierarchical spectral clustering is presented in [12]. It provides a dendrogram from which all partitioning results for different cluster numbers can be seen clearly. Either power flow or line admittances can be used as weight indexes. In [13], a multi-attribute partitioning method for the electrical network is

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presented. The electrical distance is taken as an important factor, and the K-Means algorithm is used as a fundamental tool in this method. Rather than considering the topology of the power grid, an optimal partitioning method taking the energy policy and ownership as operational constraints is presented in [14]. Whether it is based on state or structure information, these partitioning methods are effective for special purposes, and the future resource allocation for DGs is not considered. What is more, these papers focus on transmission networks rather than distribution networks, so these methods are not dedicated to VMs.

Recently, complex network theory has drawn much attention for analyzing the networked system. In [15], a divisive method for community detection is proposed but it may be invalid for larger networks. In order to solve this problem, a hierarchical agglomeration algorithm is presented in [16]. A genetic algorithm is proposed in [17], it is used to identify the groups in which nodes have dense connections but sparse connections between groups. The optimal number of modules can be determined automatically by optimizing two objective functions. In order to obtain a good balance between the accuracy and complexity, a community detection method based on the edge antitriangle centrality is proposed in [18]. The method for community detection in complex networks is also applied to power networks. In [19], an alternative method for detecting communities is proposed. This novel method is based on defining a new similarity index, and it can be used to detect communities and explore the effect of bridging nodes on the cascading failure in power grids. To solve the overvoltage caused by the penetration of photovoltaic in distribution networks, a community detection algorithm based on the improved modularity for zonal voltage control is proposed in [20]. It is found that power networks have similar network structure with other complex networks [19]–[21], so community detection methods in complex networks have great potential to be applied to VM detection in distribution networks.

According to the features of VMs to be further discussed in Section II, some partitioning methods [22]–[27] are proposed to determine the boundaries of VMs, however, until now, there is no widely accepted standard approaches for partitioning and operation of VMs. Based on the partitioning idea in the complex network, in this paper, a structural and hierarchical partitioning method is proposed. By using this kind of hierarchical partitioning method, we can detect not only the boundaries for VMs but also dynamic boundaries which can improve the power stability of the partitioned distribution network. Main contributions of this paper include:

- Discussing features and functions of VMs, and proposing a developing framework for VMs.
- Proposing a structural partitioning approach to determine boundaries of VMs, and comparing the results with other partitioning results based on the analysis of operating states.
- Defining the electrical coupling strength (ECS) as a composite weight coefficient to describe the electrical connection from the structural point of view.
- Proposing the electrical modularity to estimate the quality of the partition.

This paper consists of five sections, and it is organized as follows. Features of VMs is summarized and the developing framework for VMs is explained in Section Ⅱ. In Section Ⅲ, the definition of ECS and the reasons for such definition are discussed. The implementation steps of the partitioning method based on the electrical modularity are explained in section Ⅳ. In section Ⅴ, the proposed partitioning method is applied to the IEEE 33-bus distribution network and the PG&E 69-bus distribution network, and the partitioning results demonstrate the feasibility of this method. Finally, the research work is summarized in section Ⅵ.

II. VIRTUAL MICROGRIDS

According to the IEEE Standard 1547.4 [28], the reliability and operation of distribution networks can be improved by dividing the distribution network into multiple “island systems”. These island systems have similar characteristics as microgrids, such as high penetration of DGs, various operating modes [29], [30], and they also have the ability of self-adequacy, self-sufficiency and self-healing [24], [31]–[34]. On the one hand, for each island system, it should be self-adequate, which refers to the power generation and consumption should keep balanced [31], [32]. On the other hand, for the whole distribution network, self-sufficient refers to minimize the transferred power between island systems, and the imbalance between the generation and load [24]. Self-healing is the capability of autonomous restoration after faults or disturbances [31], [33], [34]. However, island systems also have some special features which is different from microgrids, such as these “island systems” are virtual systems, and they are developed from the existing CDNs. Hence, in this paper, we use virtual microgrids (VMs) to represent this kind of island systems. The use of the concept for VMs have been recognized in some papers. In [24], [25], [33], [34], VMs with virtually boundaries is constructed based on CDNs, and different operating states are considered. Microgrids with virtually dynamic boundaries are proposed in [26] to improve the self-adequate ability and make the operating mode more flexible.

Although several methods are proposed to construct VMs, there is little discussion about the concept and characteristics of VMs. Based on previous research and our understanding, we propose the definition of VMs as follows: “Virtual microgrids are virtually island systems based on the structure of CDNs, they have the similar control strategies and operating modes as microgrids and can adapt to the future requirements of SDNs”. The characteristics of VMs are summarized as

1) They are developed from CDNs;
2) They have characteristics of microgrids;
3) They have flexible structure based on virtual boundaries.

According to these characteristics, an upgrading plan for transforming CDNs into distribution networks with VMs is proposed as shown in Fig.1, and it can be divided into three phases. Phase 1 is to partition the CDNs, which refers to identifying boundaries for VMs considering the structural characteristics. Based on the interconnected structure of VMs obtained in phase 1, phase 2 is to optimize the resource allocation of DGs for each VM considering the power balance and the cost. Based on the partitioned network with resource allocation in phase 1 and phase 2, phase 3 is to further optimize the control and coordination strategies for the upgraded distribution network in order to ensure the stable operation of the system. Various arising functions, such as DG resource allocation, power transactions, and load balancing within the VMs, should be realized by a new intermediate role, referred to as the 'VM operator (VMO)", which is similar to the role of "EV aggregator" discussed in [35]. In the following sections, we mainly focus on the first phase which is the most important and fundamental step in the whole upgrading plan.

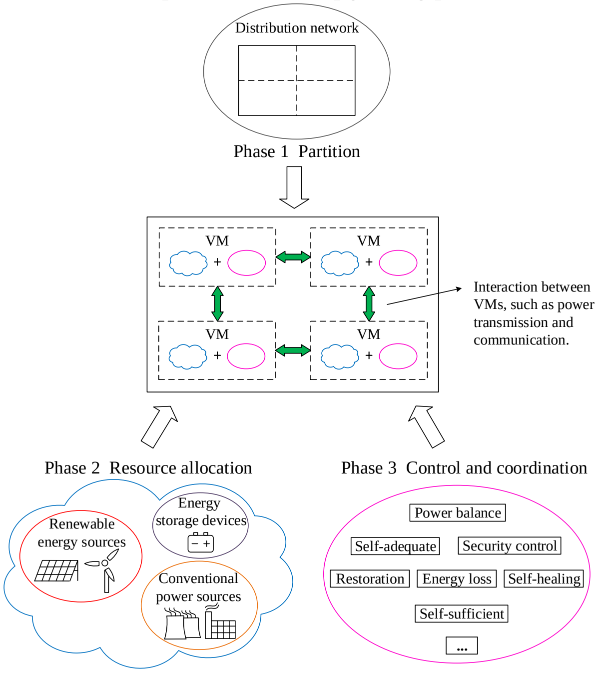


Fig.1. The upgrading plan for CDNs.

Several partitioning methods for upgrading CDNs to distribution networks with multiple VMs have been proposed. An optimal construction for VMs is proposed in [25], this construction is based on minimizing the power imbalance by considering the probabilistic nature of DGs, distributed energy storage resources (DGRs), and distributed reactive sources (DRSs). Besides these factors, the reliability and supply-security is also taken into consideration so as to optimize the construction of the VM in [24]. Using the non-dominated genetic algorithm-Ⅱ, a two-step partitioning method is proposed in [27]. Firstly, energy storage devices are used to determine the boundaries of VMs, and then the operation quality is tested by considering several technical indices, such as adequacy, efficiency, voltage and reliability. A two-stage multi-objective partitioning method is proposed in [22]. The optimal detection of VMs is based on analyzing the loss sensitivity factor firstly, and then optimizing the size and location of DGs by the Pareto-based non-dominated sorting genetic algorithm II. In [23], a method to develop autonomous microgrids based on particle swarm optimization and genetic algorithm is proposed. In this method, the siting and sizing of DGs are determined firstly, then the virtual boundaries of microgrids are identified by the analysis of power flow. In order to improve the self-adequacy of the distribution network, the dynamic boundary for VMs is used as the control variable in [26]. In this paradigm, the size and location of DGs are given, and dynamic boundaries of VMs are determined as the transmission lines with the lightest power flow according to different scenarios.

The main function of the conventional distribution network is to distribute the power to customers, therefore, for most of the existing distribution networks, there is no resource allocation for DGs. Although there are many partitioning methods which are already proposed for constructing VMs [22]–[27], in these models, the resource allocation for DGs is assumed to be given, and these methods are based on analyzing the operating states. In fact, besides resource allocation, another important factor which determines the operating states is the network structure. In addition, according to the characteristics of VMs, each VM should be considered as self-sufficient system in the island mode. Therefore, VMs should also have some features from the structural point of view, which refers to dense electrical connection inside their own system while relatively sparse electrical connection between VMs. This feature can also meet the goal for power transmission, which refers to transmit the maximum power with least losses. What is more, for the conventional distribution network, the network structure is already formed, and it is unlikely to be changed much, but the resource allocation for DGs should be an evolutionary process. Hence, it should be more reasonable to partition the VMs based on the analysis of inherent characteristics of the network structure, and it is more feasible for upgrading the CDNs in which the resource allocation for DGs is not performed yet. Therefore, rather than analyzing the operating states based on given resource allocation, in this paper, we use the network structural characteristics to identify the boundary of VMs in the partitioning phase. We define the ECS to describe the structural characteristics and identify boundaries for VMs. In future research of phase 2, we will further optimize the resource allocation of DGs based on the partitioned network.

III. ELECTRICAL COUPLING STRENGTH

As the partition based on structural characteristics is more reasonable and meaningful, it is necessary to find a suitable way to describe the structural characteristics and electrical connection of the distribution network in terms of the following three problems.

- *In the complex network, the adjacent matrix is used to describe the characteristics of connection. But for distribution network, what quantities should be considered for the definition of weight index?*
- *If the number of quantities for weight index are more than one, how to define the composite weight index?*

- *To incorporate the characteristics of the electrical network where power flows through different routes between two buses, how to describe and define the equivalent weight index?*

Now, we will discuss and solve these problems one by one.

- *For distribution network, what quantities should be considered for the definition of weight index?*

From the structural point of view, in general, adjacent matrix is commonly used to represent the undirected and unweighted network.

$$A_{vw} = \begin{cases} 1 & \text{there is an edge between vertex v and w} \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

Although distribution networks can be seen as a kind of complex networks, this simple representation is not suitable as the power flowing on transmission lines is different, so distribution networks should be regarded as weighted networks rather than unweighted networks. Many papers use the electrical distance to analyze the problems in distribution networks [13], [36]–[38], and a popular definition for electrical distance is based on the impedance [13], [38], but the electrical characteristics of the distribution network should not be measured only by the electrical distance. Taking the water pipe line as an example, the efficiency for water supply relies not only on the length of the pipe but also on the cross sectional area of the pipe. Similarly, for the distribution network, both the electrical distance and transmission capacity should be important quantities to define the weight index. The smaller the electrical distance is, the less voltage drop and power losses are. On the other hand, the larger the transmission capacity is, the more power can be transmitted. Therefore, the definition of the weight index should be based on these two quantities, i.e. electrical distance and transmission capacity, to realize the goal to transmit the maximum power with least losses as discussed before.

- *If the number of quantities for weight index are more than one, how to define the composite weight index?*

So far, most of the weight index in complex networks usually consider one quantity, for example the interpersonal relationship in social networks, the energy between predators and preys in food chain networks [39]. However, for the partition of distribution networks, two quantities should be taken into account at the same time.

The net-ability is used to spot important elements in power grids and its definition is on the basis of taking two quantities into consideration [40], which is similar to our case. The net-ability is defined as

$$A(\mathrm{Y}) = \frac{1}{N_G N_D} \sum_{g\in G} \sum_{d\in D} \frac{C_g^d}{Z_g^d} \qquad (2)$$

where N_G and N_D are the number of generation buses and load buses. C_g^d is the transmission capacity and Z_g^d is the equivalent impedance (which is similar to the electrical distance defined in this paper).

Although the inversely proportional relationship between the transmission capacity and electrical distance can be used to describe the ECS, the scale difference between these two quantities may result in the value of ECS being only sensitive to C^d_g or Z^d_g. Therefore, in this paper, we redefine these two quantities by normalizing their values based on the average,

$$\bar{C}_{vw} = \frac{C_{vw}}{\bar{C}} \qquad v,w \in \mathrm{B} \qquad (3)$$

$$\bar{Y}_{vw} = \frac{Y_{vw}}{\bar{Y}} = \frac{1/Z_{vw}}{\bar{Y}} \qquad v,w \in \mathrm{B} \qquad (4)$$

where C_{vw} is the transmission capacity between bus v and bus w. Z_{vw} is the electrical distance between bus v and bus w, and Y_{vw} is the reciprocal of Z_{vw}. $\bar{C}$ and $\bar{Y}$ are the average values of the total transmission capacity and total electrical distance in the same network. B refers to all the buses in the network.

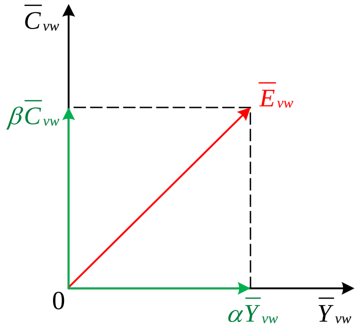


Fig.2. The relationship for different values describing composite weight index.

In order to obtain different partitioning results according to different purposes and improve the flexibility for the upgrading plan, we can further make the weight proportions of the two quantities changeable, thus, the composite weight index is defined as

$$\bar{E}_{vw} = \left|\alpha \bar{Y}_{vw} + j\beta \bar{C}_{vw}\right| \qquad v,w \in \mathrm{B} \qquad (5)$$

where α and β are proportion coefficients, and $\alpha + \beta = 1$. The relationship for different values in this equation can be clearly seen in Fig.2, which is similar to the relationship of impedance, resistance and reactance.

- *To incorporate the characteristics of the electrical network where power flows through different routes between two buses, how to describe and define the equivalent weight index?*

In the complex network, sometimes, it is necessary to analyze the weighted network, but only directly connected lines are considered [21], [39]. It is different from distribution networks due to the specific electrical characteristics. For the distribution network, the power flows not only on directly connected transmission lines but also on indirectly connected transmission lines. Taking the network shown in Fig.3 as an example, the numbers on transmission lines are impedance values. Assuming the transmission capacity for all lines are identical, if we want to inject certain amount of power from bus 2 and withdraw it from bus 4, the power will not only flow on the directly connected transmission line $l_{2\text{-}4}$ but also on the indirectly connected lines $l_{2\text{-}3}$ and $l_{3\text{-}4}$. If we consider the impact from $l_{2\text{-}3}$

and $l_{3\text{-}4}$, it can be easily seen that the parallel impedance between bus 2 and bus 4 ($\frac{0.6*(0.2+0.4)}{0.6+(0.2+0.4)}=0.3$) is smaller than the impedance directly connecting bus 2 and bus 4 (0.6), so the value of ECS between bus 2 and bus 4 is bigger than that just considering directly connecting line $l_{2\text{-}4}$. It has a great impact on the evaluation of electrical connection between these two buses. Therefore, when we calculate the composite weight index between any two buses, all possible lines for power transmission should be considered, so we consider the equivalent values of transmission capacity C_{vw} and electrical distance Z_{vw} in (3) and (4). The equivalent transmission capacity and the equivalent electrical distance between bus v and bus w are defined as [40]

$$C_{vw}=\min\left(\frac{P_{l\max}}{\left|F^{l}_{vw}\right|}\right),\qquad v,w\in \mathrm{B},\ l\in \mathrm{L} \tag{6}$$

$$Z_{vw}=Z^{'}_{vv}-2Z^{'}_{vw}+Z^{'}_{ww},\qquad v,w\in \mathrm{B} \tag{7}$$

where P_{lmax} is the maximum power limit of the transmission line *l*. *F* is called the Power Transfer Distribution Factor (PTDF), and it is used to describe the power flow change on all transmission lines in the power system when the input power from specific buses changes. Therefore, F^{l}_{vw} means the power flow change on transmission line *l* when a unit power is injected to bus v and withdraws from bus w. $Z^{'}_{vv}$ ($Z^{'}_{ww}$) is the vth (wth) row and vth (wth) column of the impedance matrix, and $Z^{'}_{vw}$ is the vth row and wth column of the impedance matrix.

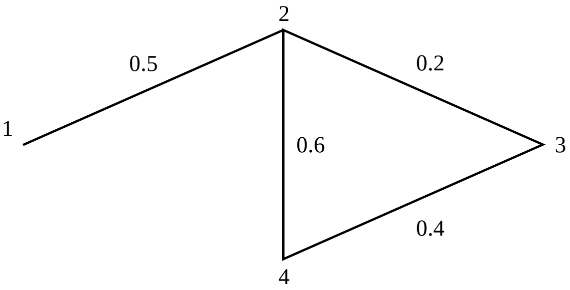


Fig.3. A simple distribution network.

Based on the discussion above, we define the ECS matrix to describe the electrical connection from the structural point of view, and the element in the ECS matrix is expressed as

$$A^{E}_{vw}=\begin{cases}\overline{E}_{vw} & \text{there is a transmission line between bus v and w}\\ 0 & \text{otherwise}\end{cases} \tag{8}$$

IV. PARTITIONING BASED ON ELECTRICAL MODULARITY

In the complex network, a community is defined as the nodes within the group have stronger interactions and more likely to be connected than the other nodes in the network [41], [42]. As discussed before, we want to divide CDN into several VMs within which the buses have stronger electrical connection from the structural perspective. It can be found that VMs have similar structural characteristics with the community. Since there are a number of methods for community detection in the complex network, and the Newman Fast Algorithm based on modularity [43] is popular and widely used for different networks, in this paper, we further develop this method by proposing the electrical modularity which is more suitable for distribution networks.

A. Electrical Modularity

For the community detection in complex networks, Newman propose to use the modularity to judge the quality of the partition [21]. If the modularity is bigger, it means the nodes which are in the same community are densely connected with each other, while the nodes which are in different communities have sparse connection with each other. Therefore, the bigger the modularity is, the better the partition is, and the modularity is defines as [39], [43]

$$Q=\frac{1}{2m}\sum_{vw}\left[A_{vw}-\frac{k_{v}k_{w}}{2m}\right]\delta(C_{v},C_{w}) \tag{9}$$

where A_{vw} is defined in (1). k_v (k_w) is the degree of node v (w), and it is the number of edges connecting to node v (w). $m=\frac{1}{2}\sum_{vw}A_{vw}$ is the total number of edges in the network. $\delta(a,b)$ is the Kronecker delta, and C_v (C_w) represents the community to which node v (w) belongs. If node v and node w are in the same community, $\delta(\mathrm{C}_v,\mathrm{C}_w)=1$. Otherwise, $\delta(\mathrm{C}_v,\mathrm{C}_w)=0$.

However, this modularity index can only be applied to unweighted networks, and it is unsuitable for partitioning weighted distribution networks. In [39], Newman proposes the algorithm for weighted network, but it is not suitable for describing the electrical characteristics as discussed in section Ⅲ . Therefore, according to the definition of ECS and modularity, we propose the electrical modularity which can be used to judge the partitioning quality for CDNs, and it is expressed as

$$Q_{e}=\sum_{v,w\in B}\left[\frac{A^{E}_{vw}}{2M}-\frac{A^{E}_{v}}{2M}\cdot\frac{A^{E}_{w}}{2M}\right]\delta(C_{v},C_{w}) \tag{10}$$

$$A^{E}_{v}=\sum_{i\in B}A^{E}_{vi} \tag{11}$$

$$M=\frac{1}{2}\sum\nolimits_{vw}A^{E}_{vw} \tag{12}$$

where A^{E}_{v} is defined as the ECS degree of bus v, and it is equal to the sum of ECS connecting to bus v. Similarly, A^{E}_{w} is the ECS degree of bus w. *M* is the sum of ECS in the whole distribution network.

The meaning of electrical modularity can be explained as: For the given network G, if we randomly take one unit of ECS from it, the probability of this unit of ECS connecting between bus v and bus w can be explained by considering the following two events:

a. One side of the unit of ECS is connected with bus v.
b. The other side of this unit of ECS is connected with bus w.

The probability for event a should be $\frac{A^{E}_{v}}{2M}$. As in the given network G, the ECS $A_{vw}{}^{E}$ between bus v and bus w is already known, so event b is not independent from event a. When event a is true, the probability for event b should be $\frac{A_{vw}^E}{A_v^E}$. Therefore, the probability for the selected unit of ECS connecting bus v and bus w is equal to $\frac{A_v^E}{2M}\cdot\frac{A_{vw}^E}{A_v^E}=\frac{A_{vw}^E}{2M}$.

Similarly, image there is a benchmark network R. In this network, the number of buses, the ECS degree and the total ECS are exactly the same with those in G, however, the distribution of ECS is random. If we randomly take one unit of ECS from this network, the probability of event a is also equal to $\frac{A_v^E}{2M}$. However, as the distribution of ECS is random, event b and event a are independent, so the probability of event b should be $\frac{A_w^E}{2M}$. Therefore, the probability for the selected unit of ECS connecting bus v and bus w is $\frac{A_v^E}{2M}\cdot\frac{A_w^E}{2M}$.

Consequently, according to the definition in (10), the electrical modularity is based on calculating the probability difference of the randomly selected unit of ECS between the network G and R. The stronger the electrical connection between nodes is, the higher the probability in the given network G is compared to the corresponding probability in the benchmark network R (the bigger the probability difference Q_e is). Therefore, the optimal partitioning can be determined by seeking the partitioning results with the maximum Q_e. In the following section, we will discuss how to group the buses in detail.

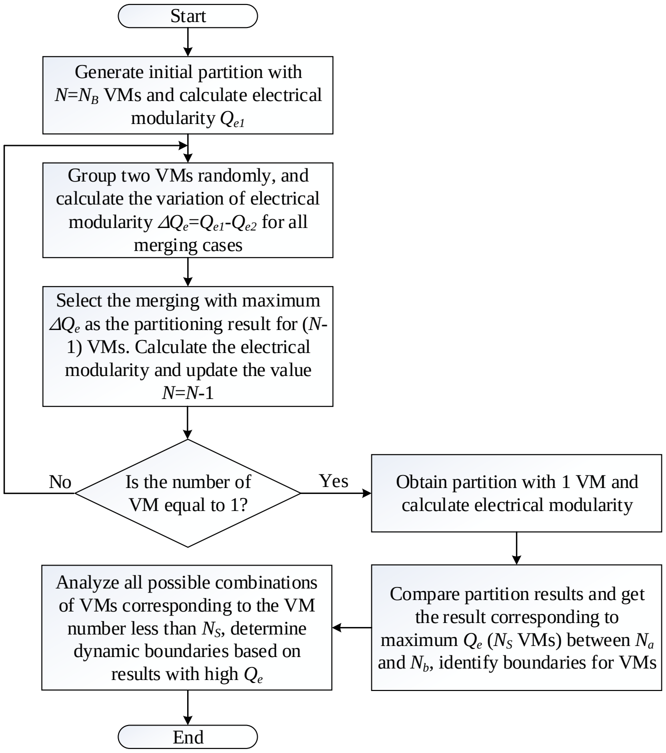


Fig.4. The partitioning process based on electrical modularity.

B. Hierarchical Partitioning for boundary detection

As we discussed in section A, although Newman Fast Algorithm is popular, it is not suitable for partitioning distribution networks considering the electrical characteristics, so we developed (9) to (10). According to the basic partitioning method proposed in [21],we develop the partitioning process by replacing the modularity Q by the electrical modularity Q_e, and the overall partitioning process is shown in Fig.4. In the updated algorithm, we add one step (the last step) to determine dynamic boundaries in order to maintain self-sufficiency, detailed characteristics for dynamic boundaries are discussed in [26]. According to the practical engineering conditions and constraints, we assume the possible acceptable range of VM number is between N_a and N_b ($1<N_a<N_b<N_B$), N is a variable number being the VM number in each step, and N_B is the bus number of the distribution network. Q_e is calculated based on (10).

V. CASE STUDY

In this section, the hierarchical partitioning method based on electrical modularity is applied to the IEEE 33-bus distribution network [35] and the PG&E 69-bus distribution network [36] in MATLAB based on the Octave toolbox [44]. Here, the weight proportions for electrical distance and transmission capacity (α and β) are equal to 0.5, and the calculation of the electrical distance is on the basis of reactance but ignore the resistance as the resistance is much less than reactance for transmission lines. For each distribution network, we assume that the power limit of all transmission lines is the same, which is common for the real distribution network.

A. IEEE 33-bus distribution network

Before applying the partitioning method to the IEEE 33-bus distribution network, we should calculate ECS firstly by using (8). After that, we calculate the electrical modularity for all possible numbers of VMs as shown in Fig.5. From Fig.5, it can be seen that the electrical modularity reaches to its maximum value (0.71) when the number of VMs is equal to 7. It is regarded as the best partition result, and this result is used to determine boundaries for VMs as shown in Fig. 6 (a).

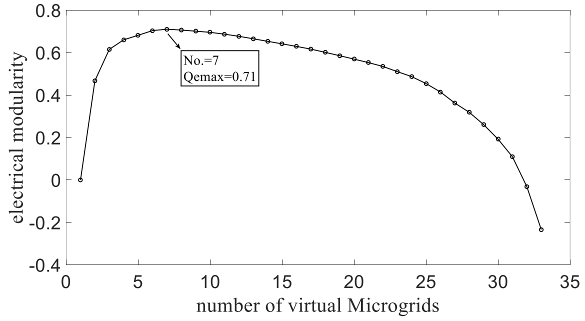
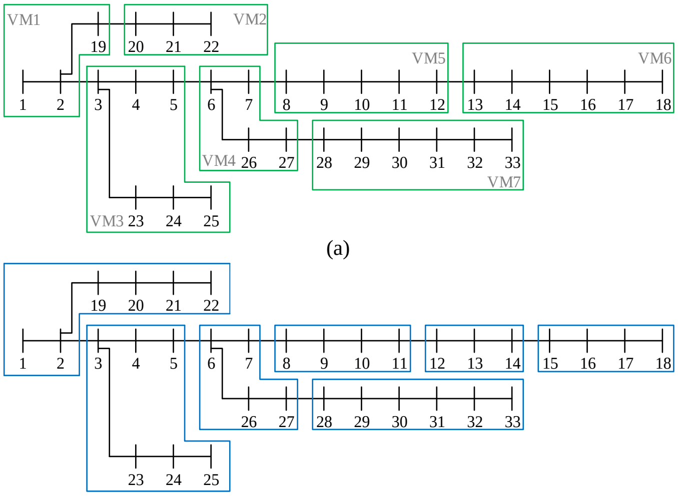


Fig.5 The value of electrical modularity with different numbers of VMs in IEEE 33-bus distribution network.

Comparing the partitioning result based on the hierarchical partitioning method in this paper with that using the partitioning method in [27], several boundary differences for VMs can be seen clearly. As discussed before, we hope the power transmission happens on the transmission lines with strong electrical connection in order to reduce losses and improve efficiency. Because the maximum power limit of transmission lines is same, so the electrical connection is mainly determined by reactance, and transmission lines with big reactance should be determined as boundaries. Taking $l_{19\text{-}20}$ which is the boundary between VM1 and VM2 as an example, the reactance of this line (0.0112) is the largest compared to all the other lines in VM1 and VM2, and it is also the line with minimum ECS, so $l_{19\text{-}20}$ is reasonable to be identified as the boundary between VM1 and VM2, but $l_{19\text{-}20}$ is not determined as the boundary in Fig.6 (b). Then we will analyze the other boundary difference between VM5 and VM6. $l_{12\text{-}13}$ is the boundary in Fig.6 (a) while $l_{11\text{-}12}$ and $l_{14\text{-}15}$ are boundaries in Fig.6 (b). Comparing the reactance value of these three lines, the reactance of $l_{12\text{-}13}$ (0.0095) is obviously bigger than $l_{11\text{-}12}$ (0.0010) and $l_{14\text{-}15}$ (0.0043), and the ECS of $l_{12\text{-}13}$ is the smallest (0.9053). Finally, we will compare the quality of the partition result by analyzing the value of electrical modularity. After calculation, the electrical modularity for Fig.6 (a) is 0.71 while the electrical modularity for Fig.6 (b) is 0.625, so it can be concluded that the partitioning result based on hierarchical partitioning method seems to be more reasonable from the structural point of view.

TABLE Ⅰ
DATA FOR IEEE 33-BUS DISTRIBUTION NETWORK

From Bus	To Bus	Reactance (p.u.)	ECS
1	2	0.0004	18.2797
2	19	0.0013	5.5918
19	20	0.0112	0.8146
20	21	0.0040	1.8893
21	22	0.0077	1.0558
8	9	0.0061	1.2796
9	10	0.0061	1.2796
10	11	0.0005	13.4188
11	12	0.0010	7.0582
12	13	0.0095	0.9053
13	14	0.0059	1.3209
14	15	0.0043	1.7309
15	16	0.0045	1.6756
16	17	0.0142	0.7117
17	18	0.0047	1.5987



(a)

(b)

Fig.6. Partitioning results for IEEE 33-bus distribution network. (a) Boundaries for VMs based on the hierarchical partitioning method (Q_e=0.71); (b) Boundaries for VMs based on the partitioning method in [27] (Q_e=0.625).

B. PG&E 69-bus distribution network

TABLE Ⅱ presents the value of electrical modularity with different number of VMs for PG&E 69-bus distribution network. Comparing to the electrical modularity shown in Fig.5, it can be seen that the curve in Fig.7 is slighter and most of the electrical modularity in Fig.7 is bigger especially for the number of VMs varies from 4 to 57. Therefore, by using this kind of hierarchical method, we may find which network has a stronger community structure more easily.

TABLE Ⅱ
THE ELECTRICAL MODULARITY FOR PG&E 69-BUS DISTRIBUTION NETWORK

No. of VMs	Q_e	No. of VMs	Q_e	No. of VMs	Q_e
1	0	24	0.7903	47	0.7535
2	0.4807	25	0.7894	48	0.7506
3	0.6426	26	0.7886	49	0.7460
4	0.7263	27	0.7876	50	0.7428
5	0.7504	28	0.7866	51	0.7396
6	0.7728	29	0.7854	52	0.7362
7	0.7908	30	0.7841	53	0.7329
8	0.7953	31	0.7829	54	0.7287
9	**0.7976**	32	0.7816	55	0.7225
10	0.7989	33	0.7803	56	0.7157
11	**0.7991**	34	0.7789	57	0.7020
12	0.7989	35	0.7774	58	0.6883
13	0.7986	36	0.7759	59	0.6702
14	0.7981	37	0.7743	60	0.6567
15	0.7974	38	0.7727	61	0.6255
16	0.7967	39	0.7711	62	0.5908
17	0.7959	40	0.7694	63	0.5117
18	0.7952	41	0.7676	64	0.3848
19	0.7944	42	0.7659	65	0.2788
20	0.7936	43	0.7637	66	0.1729
21	0.7928	44	0.7614	67	0.0274
22	0.7920	45	0.7589	68	-0.0952
23	0.7911	46	0.7563	69	-0.2406

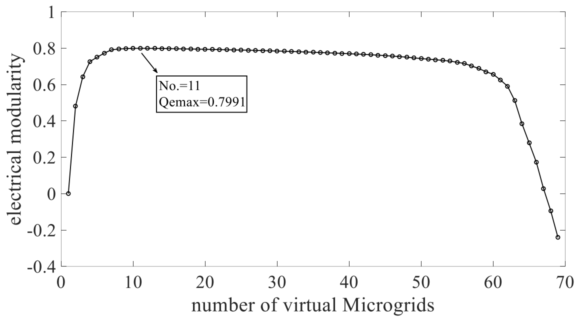


Fig.7. The value of electrical modularity with different numbers of VMs in PG&E 69-bus distribution network.

We select the partitioning result with the maximum electrical modularity (0.7991) to determine the boundaries for this distribution network, and this result is compared with the partition result based on operating states in [25]. Green lines in Fig.8 (a) are boundaries of VMs based on structural analysis while blue lines in Fig.8 (b) are boundaries of VMs based on operating states. Because there are lots of differences between these two results, so we will only take some parts of the network as the example to analyze the boundary difference. In VM9 and VM10, it can be easily found from TABLE Ⅲ that the reactance of $l_{63\text{-}64}$ (0.0531) is the biggest and the ECS is the smallest comparing to all the other lines, so it is reasonable to select $l_{63\text{-}}$

$_{64}$ as the boundary for this area as shown in Fig.8 (a). Since the reactance on $l_{62\text{-}63}$ (0.0001) is the smallest in this area, it seems unsuitable to select this line as the boundary in Fig.8 (b). What is more, in general, as the electrical modularity in Fig.8 (a) is 0.7991, which is larger than that in Fig.8 (b) (the electrical modularity is 0.7102), so the partitioning result in Fig.8 (a) is more reasonable for this distribution network.

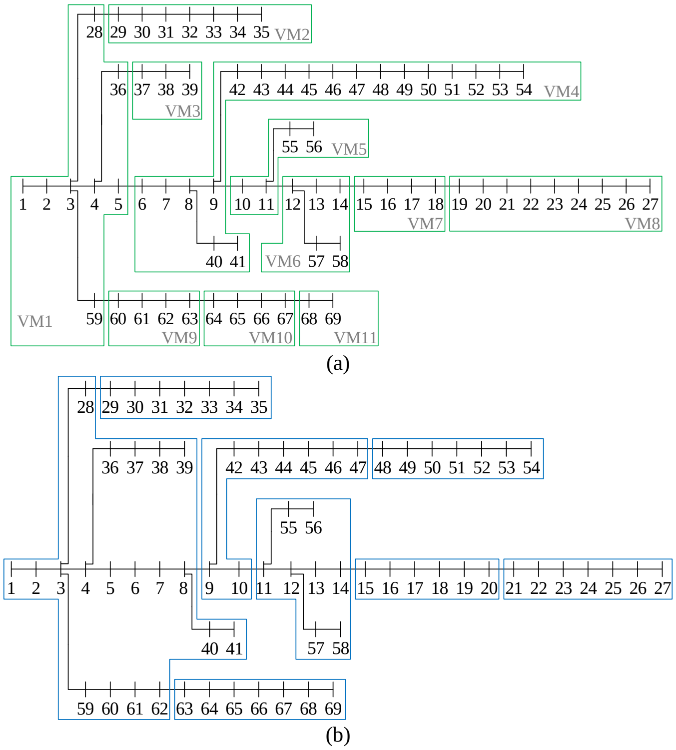


Fig.8. Partitioning results for PG&E 69-bus distribution network. (a) Boundaries for VMs based on hierarchical partitioning method (Q_e=0.7991); (b) Boundaries for VMs based on operating states in [25] (Q_e=0.7102).

TABLE III
DATA FOR PG&E 69-BUS DISTRIBUTION NETWORK

From Bus	To Bus	Reactance (p.u.)	ECS
12	13	0.0212	0.6011
12	57	0.0152	0.6822
57	58	0.0001	70.9044
13	14	0.0215	0.5984
14	15	0.0218	0.5961
15	16	0.0041	1.8155
16	17	0.0077	1.0439
17	18	0.0001	70.9044
60	61	0.0077	1.0491
61	62	0.0022	3.2345
62	63	0.0001	54.0234
63	64	0.0531	0.5175
64	65	0.0226	0.5900
65	66	0.0030	2.4254
66	67	0.0007	9.7925

Based on the partitioned network in Fig.8 (a), we will further analyze the possible combinations of VMs to determine the dynamic boundaries, and the electrical modularity for the combination results are also shown in TABLE Ⅱ, which refers to the data when the number of VMs is smaller than 11. If we determine the dynamic boundaries according to the rule in which the electrical modularity should be bigger than 0.7, it can be seen that there are seven possible schemes (when the number of VMs is equal to 4 to 10). Here, we select the partitioning result with 9 VMs as an example to explain the dynamic boundaries as shown in Fig.9 (a). The difference between Fig.8 (a) and Fig.9 (a) is that VM1 and VM3, VM9 and VM10 can be combined separately, and operate as two new VMs under some special conditions. One possible operating scheme with dynamic boundaries in [26] is also shown in Fig.9 (b).

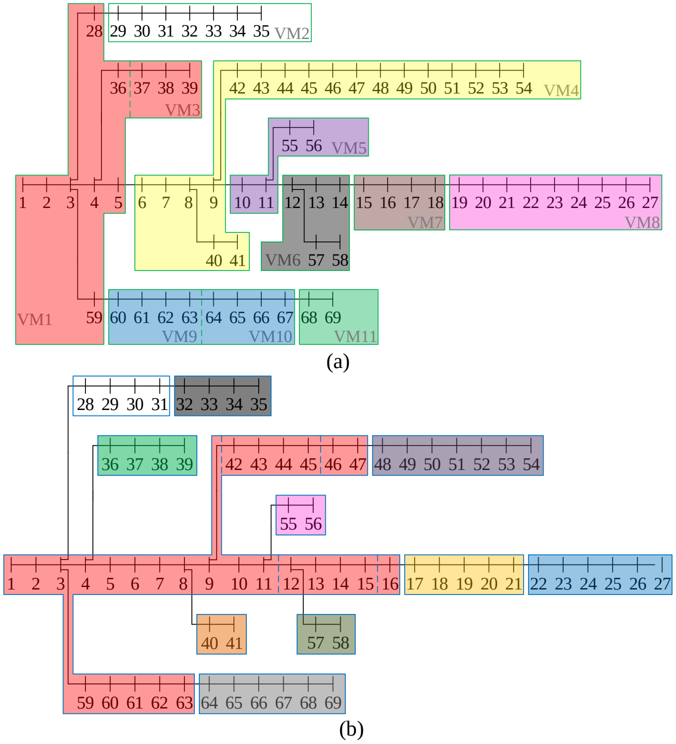


Fig.9. Possible dynamic boundaries for PG&E 69-bus distribution network. (a) Dynamic boundaries based on hierarchical partitioning method (Q_e=0.7976); (b) Dynamic boundaries based on operating states in [25] (Q_e=0.5026).

In Fig.9 (b), the determination of dynamic boundaries is based on the transmission lines with the lightest power flow in different operating states, and the resource allocation for DGs in this network is given, but the resource allocation of this network may not be in accord with the electrical connection in the structure, and the location of dynamic boundaries may not fit the natural characteristics of the structure. This can be verified by the comparison of electrical modularity. Generally, the electrical modularity in Fig.9 (b) (0.5026) is much lower than that in Fig.9 (a) (0.7976). Hence, it seems to be more reasonable to design the resource allocation of DGs after structural analysis. What is more, as discussed before, the resource allocation of DGs for real distribution network is not determined and performed yet, so it may be unreasonable to analyze the network based on assumed conditions. In Fig.9 (b), we can found that there are many VMs contain very little number of buses, especially for bus 16, there is only one bus in this VM if bus 16 is not combined with other VMs. It is not reasonable for the operation in the real case. On the contrary, if the partition is based on the structural analysis in this paper, these problems can be solved. Therefore, the identification scheme in this paper seems to be a good choice for the application to the real power grids, and more optional schemes for the determination of dynamic boundaries can be provided, so the operating modes of the upgraded distribution network are more various and flexible.

VI. CONCLUSION

Nowadays, constructing VMs is a feasible way to enhance the operating condition of CDNs as it can provide flexible operating modes and ensure the stability of the power supply. Therefore, in this paper, the characteristics for VMs are summarized and an upgrading plan for constructing VMs is proposed. As the boundary identification for VMs is a fundamental and important step in this plan, this paper proposes a hierarchical partitioning method, and this method is based on ECS which is defined as a composite weighted factor for the analysis of electrical connection. Then the electrical modularity based on ECS is proposed and it is used to evaluate the quality of the partitioning result. Through analyzing the results for two real distribution networks, it can be concluded that the ECS can describe the structural characteristics of distribution networks very well, and the partitioning method based on electrical modularity can provide better choices to determine the boundaries for VMs. As it is a kind of hierarchical partitioning method, it can not only identify the boundaries of VMs but also provide more choices for dynamic boundaries. It is reasonable and feasible to apply this method to the real power grids.

Future work will focus on completing the other phases in the upgrading plan. Based on the partitioned distribution network obtained, the resource allocation for DGs should be redesigned with the purpose of balancing the generation and load in each VM, reducing transmission losses and minimize the investment cost. Then based on the partitioned network with the optimized resource allocation, we will try to further optimize the control and coordination for the upgraded distribution network.

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