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# Adaptive Dynamic Grid Partitioning for Reactive-Power/ Voltage Control Based on Secondary Voltage Control

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**Abstract**. Reactive power voltage partition control is an important part of AVC secondary voltage control. Aiming at the current status of secondary voltage control, based on the voltage/reactive sensitivity and modularity function, an adaptive dynamic partitioning method is proposed, which changes with the operating conditions of the grid. With each reactive power source partition center, the load nodes are mapped to the corresponding reactive power sources according to the voltage/reactive sensitivity, and the regional merging automatically forms the optimal partition by using the modularity function as a measure. Finally, the proposed method is verified by the IEEE-39 system.

## 1. Introduction

Reactive voltage control is an important means to ensure the safe and stable operation of the power system. For large-scale power grids, due to the differences between the parameters of the branches and the different access points of the reactive power source, the reactive voltage problem has obvious areas characteristic. At present, the layered voltage control scheme proposed by the French Electric Power Company (EDF) has been widely used [1]. Among them, the large-scale power grid is decomposed into several loosely coupled partitions, which decomposes the whole network voltage control problem into sub-problems of independent voltage control in several partitions, which is the main content of the secondary voltage control [2].

Partition control is based on the local characteristics of reactive voltage. Because of the electrical connection of the entire power grid, reactive voltage coupling between regions is present, so the effect of secondary voltage control depends on the degree of electrical coupling between regions. EDF adopts the fixed partition mode of offline tuning, that is, the “hard partition” mode. With the expansion of power system scale and the change of operation mode, the reactive voltage sensitivity between nodes changes in real time with the change of operating conditions, and the coupling between regions the degree changes, and the fixed partition mode is difficult to meet the needs of development. Therefore, the domestic adopted a layered voltage control mode based on “soft partitioning”. The area division is completed online in the main station system. According to the current grid structure characteristics, the grid is divided into loosely coupled areas, load nodes and power supplies. The area to which the node belongs is not static, but is completed online by the online soft partition module according to the current topology and operation mode [3]. At present, the partitioning problem can be reduced to a typical clustering problem. Many clustering algorithms [4-7] have been applied to the division of reactive voltage regions, but the number of partitions needs to be given in advance regardless of the clustering algorithm, or give a parameter threshold to determine the number of partitions, it is difficult to achieve real-time dynamic partition without human intervention.

In this paper, a new grid adaptive dynamic reactive voltage partition method is proposed. From the regional controllability, the reactive power source node is used as the center of each partition, and the load node is mapped to the load node voltage/reactive sensitivity according to the control node. Each reactive source forms an initial partition. Then, the modularity function is used as a measure to automatically determine the number of partitions for regional merging to form an optimal partition. Finally, the proposed method is verified by the IEEE-39 system.

## 2. Grid Partition Theory

### *2.1. Partitioning Principle*

The grid reactive voltage partition needs to meet the following requirements:

1) Ensure strong electrical coupling between the internal nodes of each partition, and weakly couple the electrical coupling between the partitions to reduce the mutual influence of reactive voltage control between the regions;

2) Ensure the reactive power balance in each zone and leave a certain reactive reserve to realize the rational distribution of reactive resources;

3) Each node in the same partition maintains connectivity, that is, each node in the same partition is directly or indirectly connected, and does not need to be connected through nodes in other partitions;

4) There are no isolated nodes, that is, there are at least two nodes in the partition, and each partition cannot have duplicate nodes.

### *2.2. Full-scale Voltage / Reactive Sensitivity*

When studying the voltage partition problem, the nodes in the power grid can be basically divided into two categories: load node and control node. The load node generally appears as a PQ node in the power flow equation, and the control node is a reactive power source node capable of providing reactive power support. In this paper, the generator node is used to replace the general reactive power source node, and an automatic excitation regulator (AVR) is installed. The generator node is generally represented as a PV node in the power flow equation.

The voltage/Reactive sensitivity of each PQ node in the system can be obtained from the inverse of the Jacobian matrix in the power flow calculation. Based on the AC flow equation, the nonlinear power flow equation is linearized at the steady state solution to obtain a matrix expression:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P}{\partial \theta} & \dfrac{\partial P}{\partial U} \\ \dfrac{\partial Q}{\partial \theta} & \dfrac{\partial Q}{\partial U} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix} = J \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix} \tag{1}$$

Where: $\Delta P$ and $\Delta Q$ are respectively injected into the active and reactive power deviation matrix; $\Delta\theta$ and $\Delta U$ are respectively the node voltage phase angle and amplitude variation matrix; $J$ is the Jacobian matrix. Inverting equation (1):

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = S \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} S_{P\theta} & S_{Q\theta} \\ S_{PU} & S_{QU} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{2}$$

Where: the sensitivity factors $S_{PU}$ and $S_{QU}$ are the unit injection active and reactive power voltage amplitude changes respectively; the $S_{P\theta}$ and $S_{Q\theta}$ are the unit injection active and reactive power voltage phase angle changes respectively. From equation (2), The relationship between the distribution node voltage variation $\Delta U$ and the active and reactive power variation sequences $\Delta P$ and $\Delta Q$ can be expressed as:

$$\Delta U = S_{PU}\Delta P + S_{QU}\Delta Q \tag{3}$$

In the formula: $\Delta P=[\Delta P_1, \Delta P_2, \ldots, \Delta P_N]^T$, $\Delta Q=[\Delta Q_1, \Delta Q_2, \ldots, \Delta Q_N]^T$.

In addition to the influence of the active/reactive power variation, the node $i$ voltage is also affected by the injection of other nodes $\Delta P_j$ and $\Delta Q_j$ , which is expressed as:

$$U_i = U_i^0 + \sum_{j=1}^{N} S_{PU,ij}\Delta P_j + \sum_{j=1}^{N} S_{QU,ij}\Delta Q_j \tag{4}$$

Where: $U_i^0$ is the steady-state voltage of node $i$; $S_{PU,ij}$ and $S_{QU,ij}$ are elements of $S_{PU}$ and $S_{QU}$, respectively. The sensitivity factors $S_{PU}$ and $S_{QU}$ reflect the magnitude of the effect of active/reactive power on the node voltage, respectively.

The PV node contains the control of the voltage, and the PV node needs to be dimensioned into the sensitivity matrix. In reference [8], the concept of reactive power control space is proposed, and the influence of reactive power failure on the voltage of each node is considered. Based on this idea, the literature [9] further constructs a node including the system except the balance node. Voltage/reactive full-dimensional sensitivity matrix.

For n-node systems, nodes 1~m are PQ nodes, and nodes m+1~n-1 are PV nodes. According to the linearized power flow equation, the system PQ node voltage/reactive sensitivity can be expressed as:

$$\Delta U / \Delta Q = S_{QU} = X_{m\times m} \tag{5}$$

Each reactive source node is solved one by one in a "successive recursive" manner, and its corresponding physical meaning is the voltage response of other nodes in the case of only regulating the reactive power source node reactive. When solving the sensitivity of a reactive source node A, set node A as the PQ node, which is called the observation power supply, and the other reactive power source nodes are still PV nodes (if a reactive source node has insufficient reactive reserve, it is set to The PQ node) can obtain an augmented voltage/reactive sensitivity matrix $X'$.

$$X' = \begin{bmatrix} x_{11} & \cdots & x_{1m} & x_{1(m+1)} \\ \vdots & \ddots & \vdots & \vdots \\ x_{m1} & \cdots & x_{mm} & x_{m(m+1)} \\ x_{(m+1)1} & \cdots & x_{(m+1)m} & x_{(m+1)(m+1)} \end{bmatrix} \tag{6}$$

The first $m$ elements in the last column of matrix $X'$ represent the voltage/reactive sensitivity of the observed power supply to other PQ nodes of the system; the first $m$ elements in the last row indicate the voltage/reactive sensitivity of other PQ nodes to the observed power supply; the last element of the matrix To observe the voltage/reactive sensitivity of the power supply node itself; the other elements of $X'$ are substantially equal to the $X$ matrix. Before solving the sensitivity of the next reactive source node B, set A back to the PV node and B to the PQ node, so that each power node is successively listed as the power of the observation point, and the above process is repeated to obtain the full-width augmentation sensitivity matrix *S*., as in the formula (7), wherein *Y* is a diagonal matrix of *n*-*m*-1 order. Before and after the observation power is changed from the PV node to the PQ node, the system power flow changes little, and the power supply corresponding to the *X'* array in the upper left corner of the m-th order is fixed to be equal to the X array.

$$S=\begin{bmatrix} X_{m\times m} & M_{m\times(n-m-1)} \\ N_{(n-m-1)\times m} & Y_{(n-m-1)\times(n-m-1)} \end{bmatrix} \tag{7}$$

The full-dimensional sensitivity matrix contains the information of the load node and the power node, which can directly integrate the power node into the dynamic partitioning process of the system. Compared with the existing AVC secondary voltage control partition algorithm, only the load node is partitioned, and the power node is added to the geographic node. The practice in similar partitions is more reasonable.

### 2.3. *Modularity Function*

The community structure is an important attribute of a complex network. It is a set of nodes in the network with similarities between each other and less similarity with other nodes. The complex network consists of several communities [10, 11]. Girvan and Newman et al. proposed the concept of modular *Q* function, which was extended to the weighted network to measure the structural characteristics of complex networks and determine the optimal number of partitions [12-13], as described below:

$$Q=\frac{1}{2m}\sum_i\sum_j\left(A_{ij}-\frac{k_ik_j}{2m}\right)\delta\left(c_i,c_j\right) \tag{8}$$

$$k_i=\sum_j A_{ij} \tag{9}$$

$$m=(\sum_i\sum_j A_{ij})/2 \tag{10}$$

In the formula: $A_{ij}$ is the weight of the sides connecting node *i* and node *j*, $A_{ij}$=1 when node *i* and node *j* are directly connected, $A_{ij}$=0 when they are disconnected; $k_i$ represents the weight sum of all the sides connected to node *i*; *m* represents the weight sum of all the sides in the network; and $\delta(i,j)$=1 if node *i* and node *j* are in the same partition; otherwise $\delta(i,j)$=0.

According to the definition of module degree, the value of module *Q* is strictly less than 1. In a complex network, the modularity is positive if the sum of the weights of the internal links is greater than the sum of the weights of the random internal links. In practical applications, the higher the modularity, the closer the community inside, the more sparse the outside, the more reasonable the community structure of the network. Therefore, the optimal network partition can be determined by searching for the maximum modularity in all connections. As a kind of artificial complex network, power system has the characteristics of community structure, which can be studied by the theory of community structure.

In this paper, in order to accurately describe the coupling coefficient between nodes, the weights of sides between nodes are mainly determined by the sensitivity of voltage and reactive power:

$$A_{ij}=\frac{S_{QU,ij}+S_{QU,ji}}{2} \tag{11}$$

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Sensitivity between different nodes is related to the impedance between nodes, and the impedance between nodes is directly related to the geographical attributes between nodes. The sensitivity of voltage and reactive power between two nodes directly connected is higher, and the sensitivity between nodes not directly connected is lower. Therefore, the voltage sensitivity can be used as a partition evaluation index to ensure the connectivity and electrical coupling between nodes in a certain extent.

## 3. Partition Method

The partitioning method proposed in this paper is mainly divided into two parts: the first part is the initial partitioning; the second part is the merging of partitions.

1) Starting from the controllability of the reactive power source, the initial partition is carried out. Firstly, n-m-1 reactive power node is regarded as n-m-1 independent partition, and *m* load nodes are mapped to the reactive power node which is most sensitive to voltage/reactive power respectively, and the balanced node is added to the partition which is close to its geographical location. In this way, all nodes of the whole network are divided into n-m-1 regions, and each region contains reactive power nodes to ensure the controllability of the region.

2) The modularity function of the initial partition is calculated. Then, the modularity function is calculated by two sets of combinations of initial partitions. If the modularity function value of the original partition is higher than that before the combination, the combination scheme with the maximum modularity function value is selected to merge. Repeat the above process until the modularity function reaches its maximum to stop the merging of partitions, at which point the partition is the best partition.

Most of the existing partitioning methods, which take modularity function as evaluation index, adopt hierarchical clustering. Each time, the two nodes with the largest modularity are merged to determine the optimal network partition. With the expansion of power grid scale, this global search method has higher time complexity and space complexity. In this paper, the initial partitions based on voltage/reactive power sensitivity can reduce the complexity of partition calculation to a certain extent and improve the efficiency of partition. Modularity index is used to merge partitions to ensure the strong electrical coupling of nodes within the partition and the weak electrical coupling of nodes between the partitions. The number of partitions can be automatically determined according to the current operating state of the system.

## 4. Example Calculation and Analysis

In this paper, IEEE 39 node system is used for simulation analysis. 1-29 nodes are load nodes (PQ nodes), 30-31 nodes and 33-39 nodes are control nodes (PV nodes), and 32 node is balance node. Table 1 is the result of the initial partition.

**Table 1.** Initial partition results based on reactive voltage sensitivity.

| Partition number | Power node | Load node | Modularity function value |
|---|---|---|---|
| 1 | 30 | 2 | 0.257254 |
| 2 | 31,32 | 4,5,6,7,10,11,12,13,14,15 | |
| 3 | 33 | 19 | |
| 4 | 34 | 20 | |
| 5 | 35 | 16,21,22,24 | |
| 6 | 36 | 23 | |
| 7 | 37 | 25 | |
| 8 | 38 | 3,17,18,26,27,28,29 | |
| 9 | 39 | 1,8,9 | |

From the results of the initial partition in Table 1, it can be seen that the connectivity between the power nodes and the load nodes in each partition meets the requirements. Table 2~5 is the result of each region merging. Figure 2 shows the trend of the modularity function value with the number of partitions.

**Table 2.** The first result of partition merge.

| Partition number | Power node | Load node | Modularity function value |
|---|---|---|---|
| 1 | 30 | 2 | 0.266779 |
| 2 | 31,32 | 4,5,6,7,10,11,12,13,14,15 | |
| 3 | 33 | 19 | |
| 4 | 34 | 20 | |
| 5 | 35,36 | 16,21,22,23,24 | |
| 6 | 37 | 25 | |
| 7 | 38 | 3,17,18,26,27,28,29 | |
| 8 | 39 | 1,8,9 | |

**Table 3.** The second result of partition merge.

| Partition number | Power node | Load node | Modularity function value |
|---|---|---|---|
| 1 | 30 | 2 | 0.271503 |
| 2 | 31,32 | 4,5,6,7,10,11,12,13,14,15 | |
| 3 | 33,34 | 19,20 | |
| 4 | 35,36 | 16,21,22,23,24 | |
| 5 | 37 | 25 | |
| 6 | 38 | 3,17,18,26,27,28,29 | |
| 7 | 39 | 1,8,9 | |

**Table 4.** The Third result of partition merge.

| Partition number | Power node | Load node | Modularity function value |
|---|---|---|---|
| 1 | 30,37 | 2,25 | 0.274983 |
| 2 | 31,32 | 4,5,6,7,10,11,12,13,14,15 | |
| 3 | 33,34 | 19,20 | |
| 4 | 35,36 | 16,21,22,23,24 | |
| 5 | 38 | 3,17,18,26,27,28,29 | |
| 6 | 39 | 1,8,9 | |

**Table 5.** The Forth result of partition merge.

| Partition number | Power node | Load node | Modularity function value |
|---|---|---|---|
| 1 | 30,37 | 2,25 | 0.27424 |
| 2 | 31,32,39 | 1,4,5,6,7,8,9,10,11,12,13,14,15 | |
| 3 | 33,34 | 19,20 | |
| 4 | 35,36 | 16,21,22,23,24 | |
| 5 | 38 | 3,17,18,26,27,28,29 | |

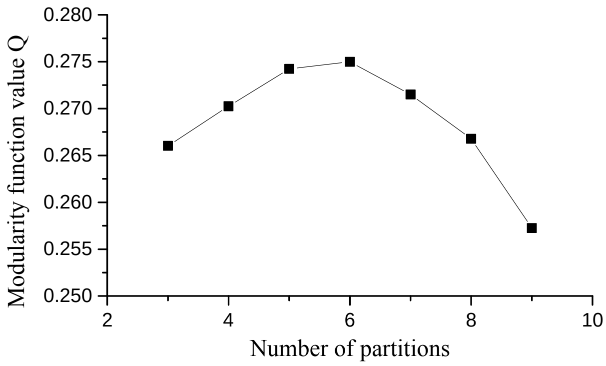


**Figure 1.** The trend of the modularity function value with the number of partitions.

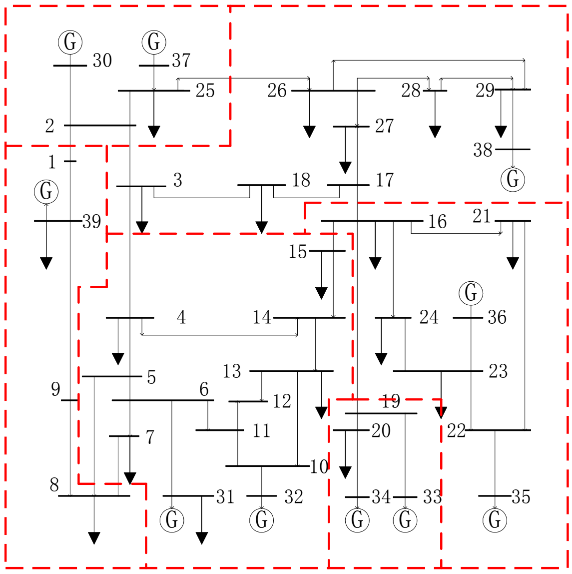

**Figure 2.** The optimal partition diagram.

As shown in Figure 1, the modularity function value increases first and then decreases as the number of partitions decreases. When the number of partitions is merged from 6 to 5, the modularity function value decreases. The optimal partition number is 6, and the partition scheme in Table 4 is the best partition scheme. The optimal partition diagram is shown in Figure 2.

## 5. Conclusion

Aiming at the problem that the existing reactive power and voltage partition schemes need to determine the number of partitions in advance, an adaptive dynamic partition scheme without manual intervention is proposed, which can automatically update the partitions according to the current operating conditions of the grid. In this paper, the partition scheme is proposed under the condition of sufficient reactive power capacity, but the actual reactive power reserve is constantly changing with the operating conditions. On this basis, considering the dynamic partition method to meet the constraints of regional reactive power reserve will be the main direction of future research.

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## References

[1] G Pan, X Wang, X Peng, et al, Research on reactive power zoning and selection of leading nodes based on community structure theory [J]. Power system protection and control, 2013, 41(22): 32-37.

[2] L Yu, Y Sun, R Xu, et al. Improved particle swarm optimization algorithm and its application in power grid reactive power partition [J]. Power system automation, 2017, 41 (03): 89-95.

[3] H Sun, Q Guo, B Zhang. Automatic Voltage Control of Power System [M]. Beijing: Science Press, 2018, 60-62.

[4] Y Cheng, N Hang. Zoning method of reactive power and voltage control based on power grid central point identification [J]. Power automation equipment. 2015, 35 (08): 45-52.

[5] W Bao, T Zhu, C Zhao, et al. Three stage two level voltage control partitioning method based on cluster analysis [J]. Power system automation, 2016, 40 (05): 127-132.

[6] Y Xu, W Jiang, X Cheng. Reactive power voltage partitioning and dominant node selection based on spectral clustering [J]. Power system protection and control, 2016, 44 (15): 73-78.

[7] Y Kang, H Li, W Zheng, et al. Voltage controlled zoning based on energy sensitivity matrix and fuzzy clustering analysis [J]. Power system protection and control, 2011, 39 (12): 69-73.

[8] Q Guo, H Sun, B Zhang, et al. Reactive power and voltage partitioning based on reactive power source control space clustering analysis [J]. Power system automation, 2005, 29 (10): 36-40.

[9] L Qiao, J Lu, H Huang, et al. Power system voltage control zoning method with wind farms [J]. Power grid technology, 2010, 34 (10): 163-168.

[10] L Yu, Y Sun, R Xu, et al. Improved particle swarm optimization algorithm and its application in Power Grid Reactive Power Division [J]. Power system automation, 2017, 41 (03): 89-95.

[11] M Ding, X Liu, R Bi, et al. High performance distributed power generation cluster division method based on comprehensive performance index [J]. Power system automation, 2018, 42 (15): 1-7.

[12] G Pan, X Wang, X Peng, et al. Research on Reactive Power Zoning and Leading Node Selection Method Based on Community Structure Theory [J]. Protection and Control of Power System, 2013, 41 (22): 32-37.

[13] G Wei, M Li, W Lu, et al. Multistage voltage control zoning method for charging and discharging storage stations and integrated grids [J]. Proceedings of the Chinese Academy of Electrical Engineering, 2015, 35 (15): 3823-3831.