An Improved Network Partition Method of Voltage Control Considering Coordinated Active and Reactive Power Sources

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Abstract. In order to coordinate distributed generarions and reactive power compensation equipment to improve the voltage level, this paper proposes an improved network partition method of voltage control considering coordinated active and reactive power sources. According to the basic theory of the Newton-Raphson method, the sensitivity expression of the node voltage *vs* the node active power, the node voltage *vs* the node reactive power are deduced from the modified power flow equations. Two kinds of sensitivity matrices are calculated by the perturbation power flow calculation. The calculation process and steps are introduced respectively. Based on these two sensitivity matrices, a kind of comprehensive sensitivity matrix is synthesized. The electrical distance matrix is calculated to complete mapping the load nodes ino the corresponding voltage control region with the help of mapping algorithm. The validity of the proposed method is verified with the simulation results of IEEE 33 nodes.

1. Introduction

In recent years, distributed generarions (DGs) in the distribution network has increased rapidly. The traditional distribution network will gradually evolve into an active distribution network (ADN) with a large number of adjustable and controllable active/reactive power resources. Its operation and management will also encounter many challenges. Especially voltage fluctuation can not be ignored. It is an important research topics of how to coordinate DGs and reactive power compensation equipment to improve the voltage level.

Based on the sensitivity of a small system, it proposed a new method to coordinate the DG active power and reactive power compensation device to adjust the voltage more effectively [1]. The influence of DG output on the voltage of the whole network is analyzed Based on the single-phase power flow model [2]. Existing research that the active distribution network DG output and compensation equipment switching will have great impact on the power grid voltage level, regulation mode, the trend of the distribution. [3][4] Reference [5] proposed a novel overvoltage preventive control method which three phase models are used to overcome the overvoltage problems with high penetration photovoltaic (PV)generation In the active distribution network.

Based on the above analysis, this paper completes the following work: according to the basic theory of the Newton-Raphson method, the sensitivity expression of the node voltage vs the node active power, the node voltage vs the node reactive power are deduced from the modified equations of

power flow. Two kinds of sensitivity matrices are calculated by the perturbation power flow, which are synthesized and the electrical distance matrix is calculated. The partitioning of the network is done by mapping algorithm. The validity of the proposed method is verified with the simulation results of IEEE 33 nodes.

2. Sensitivity Matrix of Active and ReactivePower Source Partition

Active and reactive power is decoupled for the transmission network, reactive power and node voltage have a strong correlation. Node reactive power is very important to maintain the node voltage level in the sub-region. While the distribution network is non-decoupled for active and reactive power. Both the node injection active power and reactive power can affect the node voltage, especially in the line resistance parameters and reactance parameters of the almost identical value of the low-voltage network. The effect of the voltage regulation is not obvious and limited only by reactive power adjustment or by active regulation.

In order to ensure every partition region has the adequate and reasonable control power sources, the method proposed in this paper uses the electrical distance to describe the relationship between the node voltage and the node injection power source.

A sensitivity matrix is expressed with the reactive power injection of source node between the voltage of other reactive power nodes. For a certain power grid, the correction equations of Newton-Raphson method can be formulated as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{1}$$

In the equations (1) , ΔP , ΔQ are the node injection increment of active and reactive power; $\Delta \theta$, ΔV are the increments of node voltage amplitude and phase angle; H , N , J and L are the sub-arrays of the Jacobian matrix, respectively. For a normal operation mode, H , N , J and L can be obtained according to a certain power flow calculation results.

To determine the sensitivity of the relationship between node active power and node voltage, we can make $\Delta Q = 0$. The linearized equations (1) can be simplified as

$$\Delta V = \left[N - H J^{-1} L \right]^{-1} \Delta P = S_{VP} \Delta P \tag{2}$$

In the equation (2), the coefficient matrix S_{VP} is the sensitivity matrix between node injection active power and node voltage.

To determine the sensitivity of the relationship between node active power and node voltage, we can make $\Delta P = 0$. The linearized equations (1) can be simplified as

$$\Delta V = \left[L - J H^{-1} N \right]^{-1} \Delta Q = S_{VQ} \Delta Q \tag{3}$$

In the equation (3), the coefficient matrix S_{VQ} is the sensitivity matrix between node injection reactive power and node voltage.

Sensitivity matrix S_{VP} and S_{VQ} show the corresponding electrical distance from two different aspects. According to these two sensitivity matrices, the whole network can be partitioned into several voltage control regions.

For a typical power system operation mode, the results of power flow calculation is the basis for the network partition. Different from the previous scenes, this paper considers the active and reactive coordination to complete the voltage control region partition. Sensitivity matrix S_{VP} and S_{VQ} will be calculated and adapted to improve the previous partition method.

3. Calculation and Analysis of Comprehensive Sensitivity

For a certain network, suppose the number of load node is L, the number of active power sources is N_p, the number of reactive power sources is N_q, the number of reactive power source partitions is M, he number of reactive power sources belonging to the ith volatge control partition is N_{qi} ($i \in M$). The comprehensive sensitivity between M and load node l is calculated as follows.

3.1. Comprehensive Sensitivity Calculation of reactive power

The whole process can be divided into the following steps:

- Input the data necessary for the calculation of the power flow, including: branch information (line parameters R_L, X_L, B_L; transformer parameters R_T, X_T, K; network topology, etc); node information (generator parameters (as needed) P_G, Q_G, V_G, θ_G; distributed generation parameters (as needed) P_{DG}, Q_{DG}, V_{DG}, θ_{DG}; load power data P_D, Q_D; reactive power compensation data Q_C, etc).
- Make the original power flow calculation, obtain the original results.
- Based on the Newton-Raphson method, set the node type before carrying out the power flow calculation. When making the reactive power sensitivity calculation: for the reactive power injection node $i \in M$ which takes part in the primary voltage control, it's node type is set to PV node, otherwise it is set to PQ node. While those reactive source nodes $i \notin M$ are set to PQ nodes [6].
- Let a small perturbation with load reactive power of node l ($l \in L$), including the junction nodes which have no load power. The node type should be reverted back to the its original type, i.e. set the small perturbation to zero, while the comprehensive sensitivity computation is completed.
- Make the reactive perturbation power flow calculation, obtain the perturbation results.
- Base on these two power flow results, the comprehensive sensitivity of reactive power is defined as

$$S_{VPi}^k = \frac{\sum_{k \in M} \Delta Q_k}{\Delta V_i} \qquad (i \in L) \tag{4}$$

- By using the above steps, the comprehensive sensitivity can be calculated while partitioning all the active and reactive power source.

3.2. Comprehensive Sensitivity Calculation of active power

The whole process can be divided into the following steps:

- When making the active power sensitivity calculation: based on the Newton-Raphson method, all the node type are set as the original type.
- Let a small increasement with active power of generator node g ($g \in N_p$). The node power should be reverted back to the its original value, i.e. set the small perturbation to zero, while the comprehensive sensitivity computation is completed.
- Make the active perturbation power flow calculation, obtain the actinve perturbation results.
- Base on the original results and the actinve perturbation results, the comprehensive sensitivity of active power is defined as

$$S_{VPi}^k = \frac{\sum_{k \in M} \Delta V_k}{\Delta P_i} \qquad (i \in L) \tag{5}$$

3.3. Comprehensive Sensitivity Calculation of reactive power and active power

- According to the comprehensive sensitivity Sensitivity matrix $\boldsymbol{S}_{VP}$ and $\boldsymbol{S}_{VQ}$, a comprehensive sensitivity matrix between the and load node and the active/reactive power source partitions is established[8] as equation (5).

$$\boldsymbol{S}_{region} = \boldsymbol{S}_{VQ} + \boldsymbol{S}_{VP} = \begin{bmatrix} S_{VQ1}^1 & S_{VQ1}^2 & L & S_{VQ1}^M \\ S_{VQ2}^1 & S_{VQ2}^2 & L & S_{VQ2}^M \\ L & L & L & L \\ S_{VQL}^1 & S_{VQL}^2 & L & S_{VQL}^M \end{bmatrix} \tag{6}$$

3.4. Analysis of the comprehensive sensitivity

The method proposed in this paper establishes the comprehensive sensitivity matrix between load nodes and voltage control region from the angle of the normal power system operation mode. Comprehensive sensitivity of active and reactive power in equation (5) reflects the comprehensive power response characteristic of the active/reactive power source partition with load nodes.

The sensitivity value is positive generally. The greater its value of S_{region}, indicating that the accused in the case of the same perturbation, the partition Gj reactive response output is greater than the other partition, it is clear that the node i should be partitioned into this sub-region. Therefore, the definition of a comprehensive sensitivity shows the comprehensive control effect power in the cluster for a controlled load nodes. The analysis results are apparently close to the actual power system operation.

The partition method proposed in this paper impoves the previous algorithm proposed by [6], the main difference lies in the comprehensive sensitivity which is formulated from the perspective of the reactive power and active power coordination. Reference [6] only adapted the scomprehensive sensitivity based on reactive power. So this method proposed in this paper is more universal and versatile, especially suitable for distribution network partition occasions.

4. Mapping the Load Node into the Partition

On the basis of comprehensive sensitivity matrix in formula (6), the electrical distance [7] between two node i and j is shown as follows.

$$\lambda_{ij} = -\lg\left|S_{ij}\right| \tag{7}$$

The whole matrix D, representing the electrical distance, can be formulated between the load node and voltage control partition on the basis of formula (7). The dimension of matrix D is $L \times M$, where L is the number of load nodes, M is the number of number of partitions. A row of a matrix D represents the proportion of the load node to each partition. The whole matrix D can be defined as

$$\boldsymbol{D} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & L & \lambda_{1M} \\ \lambda_{21} & \lambda_{22} & L & \lambda_{2M} \\ L & L & L & L \\ \lambda_{L1} & \lambda_{L2} & L & \lambda_{LM} \end{bmatrix} \tag{8}$$

Accordiong to the electrical distance matrix D, this paper adapts the mapping partitioning algorithm in [8] adapted "minimum electrical distance" principle to partition the load node into the nearest voltage control partition. This mapping algorithm can reflect the comprehensive control effects of all active and reactive sources to load node. But if two minimum electrical distance" belonging to a certain load node are almost the same value, this load node will be mapped into the corresponding control partitions. Such case will be shown in Section 5.

5. Simulation case

In order to verify the validity and correctness of the above-mentioned partitioning method, the IEEE33 node testing system is used whose wiring diagram is shown in Figure 1. The testing system has 33 nodes, 37 branches, 5 contact switches (indicated by dashed lines). The initial contact switch is off, so the line number of normal operation is 32. The system has the rated voltage of 12.66kV, the total network load of 3.715MW + j2.300MVar, where node 1 for the power node.

The original system has only one power node (that node 1) supplying power to the whole network. In this paper some appropriate changes is made on the original network in order to achieve power grid partition. Three distributed generations are added as the active and reactive power source.
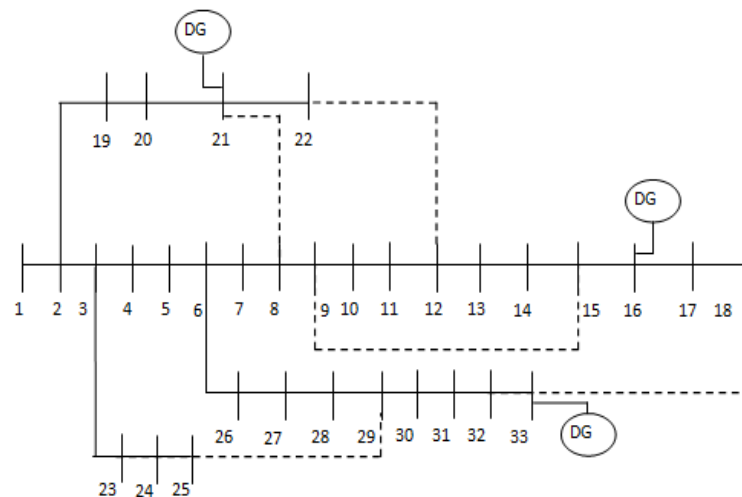
Figure 1. IEEE33 node system with distributed generations

5.1. Simulation Case 1

In this case, three DGs has the enough reactive outputs. The maximum reactive power of the node 16 is 200kvar micro-gas turbine power generation system. The reactive power of node 21 nodes is 400kvar PV power generation system. A doubly fed wind power generation system connecting to node 33 f the reactive capacity of 900kvar.
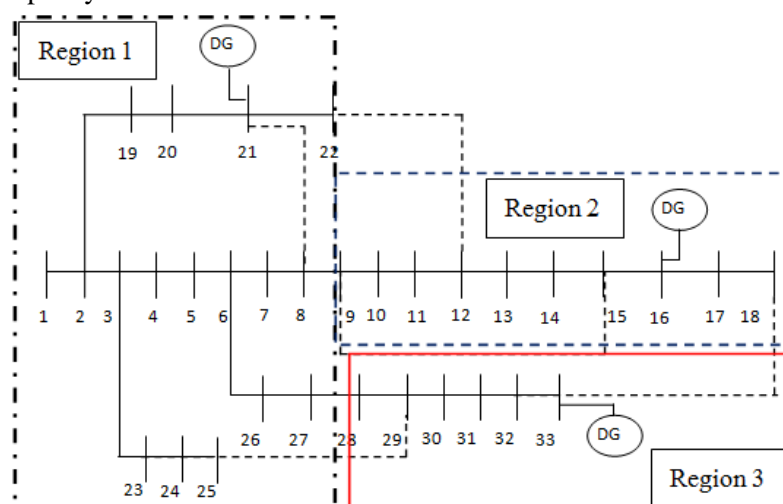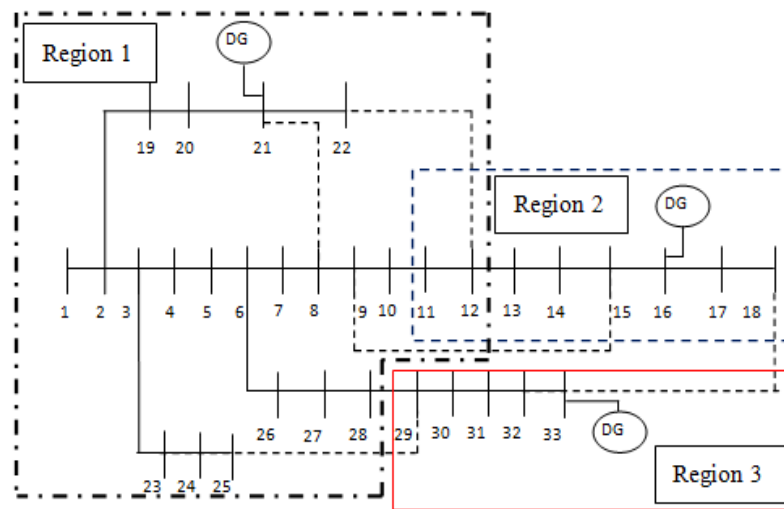

Figure 2. Partition results with enough Var output ability of the three distributed generations

As can be seen from the Figure 2, the four power sources are divided into three voltage control partitions of the entire network. Node 1 and node 21 belong to the same partition. Node 16 nodes and

node 33 are distributed in different areas. This partition results ensure that the voltage fluctuations in the region, there are appropriate control methods to ensure that the system voltage level.

5.2. Simulation Case 2

In this case, two DGs has the enough reactive outputs. The maximum reactive power of node 21 nodes is 400kvar PV power generation system. A doubly fed wind power generation system connecting to node 33 f the reactive capacity of 900kvar. As for the node 16, for some reason, its reactive power does not reach the specified value. Its maximum reactive output is only 150kvar. In thess hypothetical scenario the grid partition may have different results which is shown in Figure 3.

Figure 3. Partition results with different Var output ability of the three distributed generations

Compare Figure 2 and Figure 3, different settings of the reactive power source and active sources have a great impact on the system voltage control partitions. Part of the nodes belonging to the district has changed, these nodes are the node 9, 10, 11 and 12. And specially, the node 11 and node 12 belong to the two different partitions. It means if such a node voltage changes, a certain separate control method cannot improve the voltage level to normal standard. Comprehensive control method must be adapted at the same time to complete the voltage restoring goals.

6. Conclusions

In this paper we proposed an improved network partition method. According to the basic theory of the Newton-Raphson method, the sensitivity expression of the node voltage vs the node active power, the node voltage vs the node reactive power are deduced from the modified equations. Two kinds of sensitivity matrices are calculated by the perturbation power flow, which are synthesized and the electrical distance matrix is calculated. The partitioning of the network is done by mapping algorithm. The validity of the proposed method is verified with the simulation results of IEEE 33 nodes.

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