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A calculation method of electrical distance considering operation mode

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Abstract. An electrical distance calculation method considering operation mode is proposed. Based on line impedance, Phase-angle difference between buses is taken into account to characterize strength of electrical connections. Derivation of electrical distance considering operation mode is introduced. Comparing with traditional impedance electrical distance calculation method, rationality of this method was verified. Electrical distance of IEEE 39 example system is calculated. To explain effect of operating mode on the electrical distance, electrical zone division of power system under different operation modes are compared.

1. Introduction

With development of power system, grid structure and operation modes of the system have become more complex and power system analysis becomes more difficult. Power system analysis of large grids can be avoided by simplifying the grid based on electrical distances. Electrical distance is widely used in various researches of the power system.

Electrical distance is widely used in amounts of studies of power system. Definition of electrical distance is not unified currently. It can be mainly divided into following three categories: sensitivity method [1, 2, 3], impedance method [4], phase-angle method [5]. Influence of components on parameters in power grid is measured by sensitivity. Sensitivity is inversely proportional to electrical distance. That is to say, as sensitivity is larger, node coupling relation is stronger and electrical distance is shorter. However, this method lacks clear physical significance. Proportional relationship of voltage and current between nodes is expressed as impedance. But influence of transmission power on degree of electrical coupling under specific operation mode cannot be reflected by impedance method. Phase-angle represents real-time power transmission capability between nodes, but system's network structure cannot be reflected. The impedance between lines cannot be considered.

Based on logarithmic voltage sensitivity which is used to calculate electrical distance between buses, a dual-stage partitioning method for reactive power and voltage for large power grid is proposed, which can quantitative assess partition results [6]. In order to adapt to random variability of power grid operation mode caused by wind power access, node electrical distance expectation matrix is considered as partition basis [7]. Line impedance is used to determine electrical distance in impedance electrical distance method [8]. By calculating contact impedance between two nodes, degree of electrical connection between nodes is measured by impedance value. The smaller impedance value is, the closer electrical distance between two nodes becomes [9, 10]. Considering impedance electrical distance and parameters of generator unit, coherent generator groups is identified [11]. Electrical distance between access point of generator control system and receiving-end grid is an



important factor affecting effect of trip generators. Phase-angle method is used to quantify electrical distance with phase-angle difference between nodes [12].

An electrical distance calculation method considering operation mode is proposed. Based on line impedance, transmission power of line is taken into account to characterize strength of node's electrical connections. Comparing with traditional impedance electrical distance calculation method, rationality of this method is verified. In order to reflect influence of operation modes on electrical distance, electrical zoning of power system under different operation modes is displayed.

This paper is organized as follows. In section II, definition of electrical distance between nodes is introduced along with derivation process. In section III, electrical distance calculation method is compared with traditional impedance electrical distance. Influence of operation mode on electrical distance is analyzed. In section IV, electrical distance between IEEE39 node systems is calculated. Based on electrical distance, example system is partitioned. In section V, conclusions is drawn.

2. Definition Of Electrical Distance Considering Operation Mode

2.1. Definition of equivalent admittance considering operation mode

At a certain load level, operation mode of power system is an economic decision for generating distribution. Power flow distribution is affected by grid structure and load level of the system. According to Newton-Raphson method, neglected influence of reactive power, system power flow equation can be expressed as equation (1).

$$[\Delta P] = [H][\Delta \theta] \quad (1)$$

where n is number of system nodes. Dimension of H matrix is n . and the matrix is a symmetric sparse matrix. The value of H_{ij} is in equation (2).

$$H_{ij} = \frac{\partial \Delta P_i}{\partial \theta_j} = -V_i V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (2)$$

Considering electrical distance from perspective of power transmission, effect of phase angle is more important than the voltage. Assuming that voltage of the system is constant, all are rated voltages. And in transmission network, resistance on line can be ignored only when reactance is considered, that is equation (3).

$$H_{ij} \approx B_{ij} \cos \theta_{ij} = y_{ij}^m \quad (3)$$

where, equivalent admittance y_{ij}^m between bus i and j is defined as H_{ij} . When admittance between lines is larger and phase angle difference is smaller, equivalent admittance between nodes is smaller.

2.2. Definition of electrical distance based on equivalent admittance

System admittance matrix Y^m is calculated based on equivalent admittance. According to grid structure of the system, when bus i and bus j are not directly connected, $y_{ij}^m = 0$. Diagonal elements value of Y^m is in equation (4). The non-diagonal elements value of Y^m is in equation (5).

$$Y_{ii}^m = \sum_{j>i} y_{ij}^m \quad (4)$$

$$Y_{ij}^m = -y_{ij}^m \quad (5)$$

Impedance matrix Z^m is the inverse of Y^m . as shown in equation (6).

$$Z^m = (Y^m)^{-1} = \begin{bmatrix} Z_{11}^m & Z_{1j}^m & \cdots & Z_{1n}^m \\ Z_{21}^m & Z_{22}^m & \cdots & Z_{2n}^m \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1}^m & Z_{n2}^m & \cdots & Z_{nn}^m \end{bmatrix} \quad (6)$$

Considering the grid as a two-terminal network. Electrical distance between bus i and bus j is network equivalent impedance from bus i and bus j , that is equation (7).

$$D_{ij}^m = Z_{ii}^m + Z_{jj}^m - 2Z_{ij}^m \quad (7)$$

3. Physical Significance of Electrical Distance Considering Operation Mode

3.1. Comparison with traditional impedance electrical distance

Difference between traditional impedance electrical distance definition and electrical distance definition in this paper is definition of admittance y_{ij} [13]. Definition of traditional electrical distance uses actual admittance of line to calculate admittance matrix. This electrical distance is indicated by D^Z .

For a simple two-machine power system, as shown in Fig.1. In this figure, Gen_2 is set to a balancing machine with terminal voltage unchanged and zero phase angle. Admittance on the line is B_{12} , and $B_{12} = B_{21}$. Electrical distance calculated by two calculation methods are shown as follow.

$$D_{12}^Z = D_{21}^Z = \frac{1}{B_{12}} \quad (8)$$

$$D_{12}^m = D_{21}^m = \frac{1}{B_{12} \cos \theta_{12}} \quad (9)$$

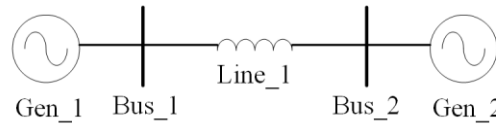


Figure 1. Two-machine power system.

From equation (8) and equation (9), it can be concluded that $D_{ij} = D_{ji} > 0$. Electrical distance calculation method in this paper guarantees non-negativity and symmetry of electrical distance. Comparing with traditional method of impedance electrical distance calculation, phase angle difference between nodes that can characterize the operating mode of the system is taken into account in definition of electrical distance.

3.2. The Relationship between Electrical Distance and Static Stability

For one machine infinite bus system, it is assumed that electromotive force E of generator is constant. Bus1 is a balanced node. In this case, active power transmitted on the line is Equation (10). Power angle characteristics of the generator are shown in Fig.3.

$$\begin{cases} P_e = EU_0 B_{12} \sin \theta \\ \frac{\partial P_e}{\partial \theta} = EU_0 B_{12} \cos \theta \end{cases} \quad (10)$$

where P_e , B_{12} , θ are output electrical power of generators, reactance on power transmission path, and phase difference between generator electromotive force (E) and voltage of infinite power bus (U_0) respectively.

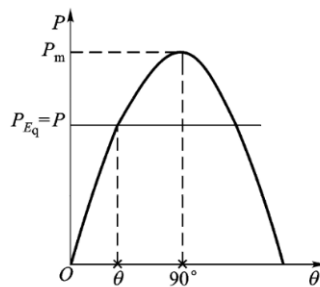


Figure 2. Power angle characteristics.

From static stability characteristics of power system, it can be concluded that maximum point of power angle swing curves is critical point of steady state stability, and derivative of P_e to θ is equal to 0 at this point. If critical point moves towards to left side, $B\cos\theta$ will become bigger and then increase of margin of system transmission power is greater. Similarly, when H_{ij} is bigger, increase of margin of system transmission power is greater. The smaller susceptance between node i and j, the bigger phase difference is, and the smaller absolute value of H_{ij} is. On the contrary, when H_{ij} becomes bigger, electrical connection will be closer. It is similar to relation between admittance matrix and electrical connection.

4. Case Study

New England is located in the northeastern part of the United States, including 6 states. New England 39 buses system is a simplified power system for the region. The western bus39, bus1 and bus9 are the western equivalent area. South of bus4 and bus14 are the southern equivalent region. East of bus16 and bus15 is the eastern coastal equivalent area. The rest are northern equivalent area. In such a network, it can be seen as a community with strong electrical connections. Therefore, electrical connections between communities are loose. Dividing network into communities is called community discovery. Analysis and discovery of community structure in network is similar to process of system electrical partition. Principle of community discovery is used to design an electrical partitioning algorithm in this paper.

4.1. Calculation of electrical distance considering operation mode

Electrical distance considering operation mode of 39 buses system is calculated, as shown in the table below.

Table 1. Electrical distance of 39 buses system.

$i=38$	$j=28$	$j=29$	$j=18$	$j=32$
D^z	0.0160	0.029	0.124	0.129
D^m	0.0161	0.030	0.1241	0.130

In two or three column of the table1, two points nearest to the bus38 are shown. In two and three column of the table, two points far away from the bus38 are shown. Comparing with the system's geographic wiring diagram, value of electrical distance is reasonable.

When phase angle difference between two terminals of the line changes, electrical distance considering operation mode is calculated. When phase angle between bus28 and bus29 gradually becomes from 5° to 30° , electrical distance increases from 0.0132 to 0.0296. When phase angle changes a little, electrical distance changes very small. It is shown that when operation mode changes drastically, change of electrical distance is obvious.

4.2. Electrical zone division based on electrical distance considering operation mode

Using Python language to implement Fast unfolding algorithm, electrical zone division of 39 buses system is realized. There are two operation modes.

1. Initial operation mode.
2. Total network load is increased by 30%.

Electrical zone division under initial operation mode. The geographic wiring layout of the system is shown below, which shows electrical zone division under operation mode 1.

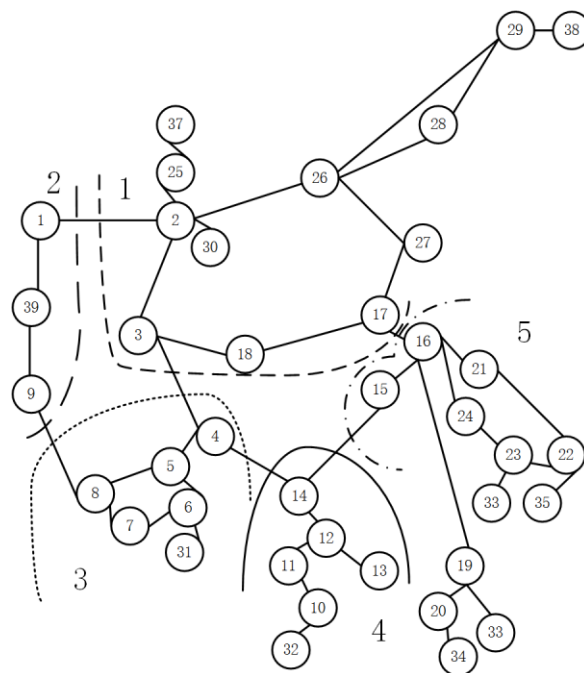


Figure 3. Electrical zone division under operation mode 1.

In Fig.3, electrical zone corresponds to the geographical area. Electrical zone 1 corresponds to the northern equivalent region of the example. Electrical zone 2 corresponds to the western equivalent region. Electrical zone 3 has a lot of loads. And electrical zone 4 has a lot of power generation. Electrical zone 3 and 4 have a lot of power transmission, so it is divided into two zones. Electrical zone 5 corresponds to the eastern equivalent region of an example.

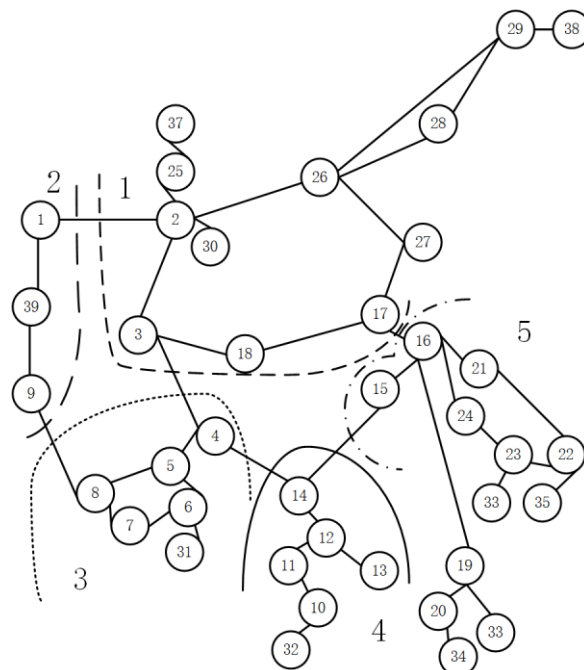


Figure 4. Electrical zone division under operation mode 2.

When total network load is increased by 30%. The number of zone change from five to six. It shows that when operation mode changes drastically, electrical zone division change accordingly.

5. Conclusion

An electrical distance calculation method considering the operation mode is put forward in this paper. Line impedance and phase angle difference are considered to measure electrical connection between buses. Comparing to traditional electrical distance calculation methods, physical significance is clearer. Simulation shows that the change of operation mode is reflected, and this electrical distance can be used as the basis of electrical zoning. Electrical zone corresponds to the geographical area.

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