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Implementation of three-phase transformer model in radial load-flow analysis

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Abstract This paper presents an efficient approach for developing three-phase transformer admittance matrices in the radial power-flow analysis. The proposed transformer model overcomes the singularity problem of the nodal admittance submatrices of ungrounded transformer configurations. This has been achieved by applying symmetrical components modeling. The classical (6×6) transformer nodal admittance matrix written in phase components is converted to sequence components instead of the (3×3) admittance submatrices. In this model, the phase shifts accompanied with special transformer connections are included in the radial power-flow solution process without any convergence problems. The final model of the transformer is represented by a generalized power-flow equation written in phase components. The developed equation is applicable for all transformer connections. The transformer model is integrated into the radial power-flow and tested using the IEEE radial feeders. The results have shown that the developed transformer model is very efficient and the radial power-flow has robust convergence characteristics.

1. Introduction

Distribution systems are characterized with both system and load unbalance. This is due to unequal mutual coupling among line phases, existence of a mixture single-phase, two-phase, three-phase systems, and unbalanced loads. Distribution systems are also distinguished with high R/X ratio of transmission lines and network radial structure [1]. Due to these features, classical balanced power-flow methods such as Newton–Raphson, Gauss–Seidel, and fast-decoupled are not applicable for distribution system analysis [2,3].

Consequently, many power-flow methods have been intended particularly for solving radial distribution systems such as the backward/forward method and its variants [4–10]. The backward/forward method has low memory requirements and robust convergence characteristics. It is easy to implement and takes the full advantage of the radial structure of distribution systems. In addition, many power system models are integrated straightforward in the radial power-flow algorithm including [4–11].

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Three-phase transformers are one of the most important power system elements which have given a special attention for appropriate implementation in load-flow analysis. This is due to variety of connections and zero-sequence current blocking in some connections which affects the accuracy of the final power-flow solution. For example, the assumption of complex power load models, PQ loads, zero sequence components may drive power-flow method to converge to inaccurate solutions [12–14]. In addition, some transformer configuration such as open delta and center-tap transformers requires special modeling requirements [15,16]. Consequently, many transformer models have been proposed in the literature to account for different features of transformer connections. Basically, three-phase transformers can be developed using phase coordinates or symmetrical components [17].

Kirchhoff's voltage and current laws are introduced for each transformer connection for radial load-flow analysis [18,19]. This technique requires a set of separate equations for each transformer connection to be implemented inside the load-flow solution process. In [20,21], the zero-sequence component is separated from the transformer submatrices to avoid the singularity problem. The separation of the zero sequence in this method is a tedious process due to derivation the model using the (3×3) nodal admittance submatrices in phase components. In this approach, it is difficult to represent the transformer by a generalized equation and a special treatment is required for implementing the transformer admittance matrices in the radial power flow method. Another phase-coordinates approach also has been developed based equivalent π line model to account for inter-phase coupling [22]. Current injections are also proposed to avoid the singularity of the transformer admittance matrices and improve convergence characteristics in bus admittance load flow analysis [23,24]. Finally, the neutral grounding have been included in the transformer admittance matrix written in phase coordinates in [25].

In [26], three-phase transformer models have been developed based on sequence components and integrated in the in the forward/backward method. However, classical sequence components representation lacks the efficiency to model transformer probably. This is mainly due phase-shifts associated with some transformer connection [17]. The aim of this paper is to develop a generalized transformer model for radial power-flow analysis using improved sequence components transformer models [27,28]. In the proposed model, the phase shifts accompanied with some transformer connections are included in the solution process without any convergence problems. The final transformer model is expressed in the radial power-flow solution by a generalized power-flow equation written in phase components. A set of submatrices corresponding to different connections are created. According to the transformer connections, the developed submatrices are substituted in the generalized power-flow equation of the transformer.

The proposed model is incorporated in the forward/backward sweep method and all various connections are tested using the IEEE radial test feeders. The obtained results illustrate that the proposed transformer model is reliable and has good convergence characteristics. The paper is organized as follows: Section 2 introduces the radial power-flow technique. In Section 3, the proposed three-phase transformer model is introduced. The results are presented in Section 6 and the conclusions are drawn in Section 7.

2. Radial power-flow analysis

The radial power flow technique is based on the fact that the voltage at the root node is known and the current at the lateral is zero [1]. Consequently, an iterative process is developed for solving the power-flow problem. For a line segment l connected between nodes i, j, the iterative solution includes the following main steps [8–11]:

2.1. Nodal current calculations

The load currents are initially calculated by assuming initial voltages at all nodes. The injected currents due to loads at node i are expressed as follows:

$$\mathbf{I_i^{abc}} = \left[\left(\frac{S_i^a}{V_i^a}\right)^* \quad \left(\frac{S_i^b}{V_i^b}\right)^* \quad \left(\frac{S_i^c}{V_i^c}\right)^* \right]^t \tag{1}$$

where $\mathbf{I_i^{abc}}$ is the current injections for each phase a, b, c at node i. S_i^a the scheduled power injections for each phase a, b, c at node 'i'. V_i^c is the phase voltages at node i.

2.2. Backward sweep

The total current at the source node can be calculated based on the fact that the line currents are known at the laterals of the feeder. Hence, the current flows in a line segment l is calculated as follows:

$$\mathbf{J}_l^{abc} = -\mathbf{I}_j^{abc} + \sum_{\mathbf{m}\in\mathbf{M}} \mathbf{J}_m^{abc} \tag{2}$$

where $\mathbf{J}_l^{\mathbf{abc}}$ is the current flows into the line section l; M the set of line sections connected downstream to node j.

In the case of using power summation instead of current summation, the injected powers at node l are calculated as follows:

$$\mathbf{S}_l^{abc} = \left[V_j^a (J_l^a)^* \quad V_j^b (J_l^b)^* \quad V_j^c (J_l^c)^* \right]^t \tag{3}$$

where

$$\mathbf{V}_j^{abc} = \mathbf{V}_i^{abc} + \mathbf{Z}_l^{abc}\mathbf{J}_l^{abc} \tag{4}$$

2.3. Forward sweep

After calculating the branch currents/powers in the previous step, the receiving end voltages are calculated using based on the knowledge of the voltage at the root node. In the current summation method, the line current of each line segment are updated using the entering powers as follows:

$$\mathbf{J_l^{abc}} = \left[\left(\frac{S_l^a}{V_j^a}\right)^* \left(\frac{S_l^b}{V_j^b}\right)^* \left(\frac{S_l^c}{V_j^c}\right)^* \right]^t \tag{5}$$

Then, the voltages at the receiving end of line segment are calculated by:

$$\mathbf{V_i^{abc}} = \mathbf{V_j^{abc}} - \mathbf{Z_l^{abc}}\ \mathbf{J_l^{abc}} \tag{6}$$

After the above three steps are executed every iteration, the power mismatches at each node for all the three phases are calculated as follows: