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ORIGINAL ARTICLE

Analysis of simultaneous unbalanced short circuit and open conductor faults in power systems with untransposed lines and six-phase sections

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Abstract The paper introduces a generalized method for analysis of multiple, simultaneous short circuit, open circuit, and open circuit falling conductor faults in mixed three-phase and six-phase power systems with untransposed lines. The method is systematic and suitable for all types of faults, any number of simultaneous faults, and any number of phases. Calculation of all network unbalanced voltages and currents during faults is done in one straightforward step. Coupling among sequence networks in untransposed transmission lines is accounted for. Coupling between the three-sequence networks of the three-phase part and the six-sequence networks of six-phase part is also derived. The method is applied also for transient stability study of mixed three-phase and six-phase power systems during any type of faults. Detailed derivation of the governing equations in each part is presented. Simulation results on the IEEE 300-bus system and the IEEE 30-bus system are given to validate the proposed method.

1. Introduction

Analyzing abnormal conditions in power systems, such as short circuit, and open conductor faults, is important for protection system design and transient stability assessment. Fault analysis is well studied in the literature but only few publications have discussed the analysis of complex simultaneous faults such as multiple faults at different busses, open circuit at multiple branches, complex and unusual phase combination involved in the fault (more than one type of fault at the same bus), cross-country faults, faults in mixed three-phase/higher-order-phase networks, effect of transformers phase shift, and untransposed transmission networks. Multiple simultaneous faults can occur in natural catastrophes, stormy weather and intended attacks.

In [1–5], fault analysis is done in phase coordinates using the three-phase bus admittance matrix. Individual Faults in unbalanced distribution systems are analyzed using three-phase bus impedance matrix in [6,7]. When forming the bus impedance matrix Z_{bus} in phase coordinates for unbalanced multi-phase power systems, each single-phase is considered a bus. So, in three-phase case for example, the size of Z_{bus} will be $3N{*}3N$; where N is the number of three-phase buses. The size will also increase for higher order phases. Accommodating multiple faults at multiple locations in the network in bus

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impedance matrix constitutes a large computational burden. In [8], fault points can be added in modular form but this requires inversion of large augmented matrix containing full admittance matrix is required. Also, this method is suitable for shunt faults only.

Reduced bus impedance matrix in the form of thevenin impedances and thevenin voltages to represent the other parts of the network requires the full Z_{bus} prefault full matrix and the reduction itself is dependent on fault locations.

On the other hand, in symmetrical component reference frame, sequence bus admittance matrices are constants and only the connection between them is altered in the sequence networks according to the fault type. But handling multiple faults is a complex task and in some cases the sequence admittance matrices become coupled. It is well known that untransposed transmission lines can only be decoupled into sequence networks using shunt compensating current sources at the beginning and end of the lines [9,10]. These injected currents introduces coupling between sequence networks and this complicates to a great extent the short circuit analysis in symmetrical components coordinates. Most of commercial short circuit packages have neglected this effect. In [11,12], simultaneous short circuit faults at two different buses have been analyzed using two-port network theory.

The use of six-phase or higher-order-phase transmission lines aims to transmit more power in the same right-of-way and without increasing the voltage level. Only few publications have concerned with fault analyses in six-phase networks such as [13–16] where only basic types of six-phase single faults have been discussed using circuit combinations of the 6-sequence networks.

In this paper, a proposed method of fault analysis in symmetrical components coordinates is presented for networks with mixed three-phase and six-phase parts. The method can accommodate any number of short circuit and open conductor faults at the same time at any number of buses and branches with any phase combination. The addition of fault points/lines is done in modular form in a systematic way and only selected part of admittance matrix is used in the augmented matrix. Untransposed line sections and transformer phase shift are inherently accounted for in the proposed method. Coupling between sequence networks of three-phase and six-phase parts is derived. The use of the proposed method in transient stability analysis is demonstrated.

The paper is organized as follows. Section 2 gives a detailed formulation of the proposed method. Short circuit faults are discussed in Section 3 and open conductor faults are discussed in Section 4. Treatment of untransposed lines is presented in Section 5 while the coupling between three-phase and six-phase sequence networks is investigated in Section 6. The overall network solution is given in Section 7. The use of the proposed method in transient stability analysis is demonstrated in Section 8. Simulation results are given in Section 9, and finally, conclusions are extracted at Section 10.

2. Network modeling

In the proposed method, each branch is represented as shown in Fig. 1. Each branch between bus *i* and bus *j* is represented by series impedance $Z_k = R_k + jX_k$, where R_k is branch resistance and X_k is branch reactance, a voltage source E_k in the same direction of current to model the generators, and a voltage source V_k with polarity that opposes current direction to model the abnormal or special condition in which the branch is involved if exists such as short circuit, open circuit, and coupling with other branches. A transformer with complex turns ratio t_k is introduced in Fig. 1 to model the 30° phase shift in Δ/Y transformers in positive and negative sequence networks. For the positive sequence network:

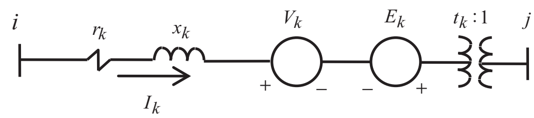

Figure 1 The network branch model.

$$t_k = \begin{cases} 1 & \text{If branch } k \text{ is a line} \\ 1\angle+30^\circ & \text{If branch } k \text{ is a } \Delta/\text{Y} \\ & \quad \text{transformer with Vector Group DY1} \\ 1\angle-30^\circ & \text{If branch } k \text{ is a } \Delta/\text{Y} \\ & \quad \text{transformer with Vector Group DY11} \end{cases} \tag{1}$$

The angle sign is reversed in negative sequence network and the turns-ratio is one in zero sequence network. The branch current is given by

$$I_k = \frac{1}{Z_k}(V_i - t_k V_j + E_k - V_k) \tag{2}$$

The E_k voltage sources exist only in generators' branches which are connected between generators' buses and ground. Line shunt admittances and load admittances are included in added branches between corresponding buses and ground.

For a network with n_{br} branches and n_{bus} buses, Eq. (2) can be written in the form

$$I_{br} = Z_{br}^{-1}(AV_{bus} + E_{br} - V_{br}) \tag{3}$$

where

$$I_{br} = [\,I_1 \quad \cdots \quad I_{nbr}\,]^T, \quad E_{br} = [\,E_1 \quad \cdots \quad E_{nbr}\,]^T,$$

$$V_{br} = [\,V_1 \quad \cdots \quad V_{nbr}\,]^T, \quad V_{bus} = [\,V_1 \quad \cdots \quad V_{nbus}\,]^T,$$

Z_{br} is a diagonal matrix with $Z_{br-kk} = Z_k$, and A is a modified branch to node incidence matrix with

$$A_{ki} = \begin{cases} 1 & \text{If branch } k \text{ starts at node } i \\ -t_k & \text{If branch } k \text{ ends at node } i \\ 0 & \text{Otherwise} \end{cases} \tag{4}$$

Multiplying both sides of Eq. (3) byA^{*T}, the conjugate transpose of matrix A, gives:

$$A^{*T} I_{br} = A^{*T} Z_{br}^{-1} A V_{bus} + A^{*T} Z_{br}^{-1} E_{br} - A^{*T} Z_{br}^{-1} V_{br} \tag{5}$$

The bus admittance matrix is given by [5]:

$$Y_{bus} = A^{*T} Z_{br}^{-1} A \tag{6}$$

And from KCL,

$$J_{bus} = A^{*T} I_{br} \tag{7}$$