Electrical Power and Energy Systems 96 (2018) 238–252

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A three-phase comprehensive methodology to analyze short circuits, open circuits and internal faults of transformers based on the compensation theorem

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ARTICLE INFO

Keywords:
Compensation theorem
Internal fault of transformer
Open circuit
Short circuit
Three-phase bus impedance matrix

ABSTRACT

Three-phase bus impedance matrix reveals some good potential in fault analysis in phase coordinates. In this paper, a comprehensive methodology is proposed to analyze a large variety of faults including short circuits in buses and lines, open circuits, open circuits with falling conductors and internal faults of transformer, separately or simultaneously, in unbalanced networks. Load effect is also considered. The methodology is based on the compensation theorem and Thevenin equivalent circuit which derives a fault side equation for each fault case. By combining the fault side and the network side equations, it replaces the fault side with equivalent injected current sources and calculates the voltage mismatch in every bus by using three-phase bus impedance matrix. A modified transformer model is also proposed to account for internal faults of transformer windings. The formulation is derived based on the initial three-phase bus impedance matrix and except for internal faults, there is no need to modify the impedance matrix during fault analysis which eliminates the demand for new factorization or inversion of a huge matrix. Moreover, a correction factor matrix is proposed which improves the results of a previous sequence component method in literature. The methodology is tested on IEEE 13-node and IEEE 34-node test feeders which are inherently unbalanced networks and it is implemented in MATLAB software.

1. Introduction

Power system analysis and evaluation of voltages and currents are of great importance when it comes to contingencies and abnormal conditions. The results dealing with system faults are determinant in proper design and operation of power systems. Fault analysis methods, as one of the key tools in power systems, are required in many studies such as relay setting, equipment sizing, earthing system design and transient stability analysis, etc. The idea behind this paper is to propose a methodology of fault analysis which is capable of analyzing different types of faults including short circuits in buses (SCBs), short circuits in lines (SCLs), open circuits (OCs), open circuits with falling conductors (OCFs) and internal faults of transformer windings (IFT), simultaneously or separately, while conserving the simplicity and low computational burden.

According to the literature, there are two well-known groups of fault analysis methods including methods based on symmetrical components [1–4] and methods in phase domain [5–16]. Some references [17] addressed hybrid methods using a combination of both. Symmetrical components method has been widely used for fault analysis and exploited by many short circuit analysis packages due to its simplicity and applicability. In spite of all its advantageous, the traditional symmetrical components method has some restrictions and is bounded to some constraints. For instance, it is valid only in complete feeders with all three phases present and not applicable to single-phase faults in phases other than *a* and to two-phase faults in phase pairs other than *bc*. The presence of unbalanced feeders and untransposed lines would make the three sequence networks be mutually coupled so that they could not be treated separately anymore. This will lead to the loss of the main advantage of symmetrical component method. Moreover, the traditional method is not suitable for analysis of internal faults of transformer windings and simultaneous faults. In [1], a modification is proposed which deals with the first problem and extends the range of validity of this method to incomplete feeders. The unbalanced single-phase and two-phase feeders are treated as three-phase ones by addition of dummy phases which makes it possible to use symmetrical component method. In [2], the coupling between 12 phases is eliminated by transforming variables to 12-sequence component coordinates. In [4], a methodology is proposed to analyze SCB and OC faults which considers untransposed lines, phase shift of transformers and coupling between three-phase and six-phase parts of the network. It forms the set of equations considering every network branch and solves

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http://dx.doi.org/10.1016/j.ijepes.2017.09.039
Received 16 June 2017; Received in revised form 12 September 2017; Accepted 27 September 2017

Nomenclature

v_a,v_b,v_c	voltage of phase *a, b* and *c*
v^0,v^1,v^2	Zero, positive and negative sequence voltage
A_{trad}	traditional Fortescue transform matrix
A_{mod}	modified Fortescue transform matrix
V_{ABC}	voltage at the primary side of transformer
I_{ABC}	current injected to the primary side of transformer
V_{abc}	voltage at the secondary side of transformer
I_f	vector of fault current
I_{abc}	current injected to the secondary side of transformer
Y_T	transformer admittance matrix
$Y_{bus-3\varphi}$	three-phase bus admittance matrix
$Z_{bus-3\varphi}$	three-phase bus impedance matrix
V	vector of bus voltages
I	vector of bus injected currents
s,d,t	the portion of winding between two nodes
V_{ft}	vector of fault terminal voltages
I_{out}	vector of output currents from the network to the fault side
Y_{eq}	equivalent fault admittance matrix
I_{inj}	vector of injected currents from the fault side to the network
V_{th}	vector of equivalent Thevinin voltage
Z_{th}	matrix of equivalent Thevinin impedance from fault location
I_{FC}	current vector of falling conductors
$y_{fc}(i,j)$	element *ij* of Y_{FC}
I_{line1}	vector of drawn currents from network in ground fault of line
Z_l	impedance matrix of line
Y_{eq2}^{line}	the equivalent fault admittance matrix for phase-to-phase SCL
i_l	drawn current in ground fault of line
F_T	total vector of phase indices involved in simultaneous faults
S_l	load apparent power for one phase
v_b,S_b	base voltage and apparent power
Eye(n)	identity matrix of size n
α, β	primary and secondary equivalent taps
Dv_m	voltage mismatch at bus m
$v_{pre}(m)$	pre-fault voltage of bus m
$v_{fault}(m)$	during fault voltage of bus m
v_{ft}	fault node voltage
y_{tr}	leakage admittance
i_f	fault current
z_f	fault impedance
f	index of fault node and phase in bus impedance matrix
Z_f	fault impedance matrix
Y_{cr}^l	equivalent admittance matrix for cross country fault of phase-to-phase SCL
F	vector of phase indices involved in fault
Z_n	matrix of neutral impedance to ground
i_p,i_q	injected currents to network phases in two-phase faults
y_{br}^{pre}	pre-fault branch admittance matrix
y_{br}^{OC}	branch admittance matrix after OC
Dy_{br}	the shunt virtual admittance to model OC
DY	shunt admittance matrix to model OC
m_a,m_b,m_c	indices of phase a, b and c in bus m
I_s	vector of shunt branch current
I_{shunt}	vector of drawn currents for shunt branch
V_{oc}	voltage vector of open circuited terminal
V_g	voltage vector of newly added bus
I_g	current vector injected to newly added bus
F_{oc}	vector of phase indices for OC fault
V_{FL}	voltage vector of fault location in line
Y_{FC}	admittance matrix of falling conductors
z_{fc_i}	impedance of the falling portion of line in phase i
I_{line2}	vector of drawn current from network in phase-to-phase SCL
Y_{eq1}^{line}	the equivalent fault admittance matrix for ground fault in line
Y_{eqT}	the total equivalent fault admittance matrix
i_{ll}	drawn current in phase-to-phase SCL
v_{ll}, v_{ln}	line-to-line and line to neutral voltage
z_{ij}^{new}, z_{ij}^{old}	element (i, j) of new and old bus impedance matrix

the corresponding equations to fault branches in sequence component coordinates. The model copes with analyzing simultaneous faults in sequence component coordinates, though it does not mention three-phase transformers. Additionally, for each case of fault, the fault branches must be modified which leads to change in the admittance matrix resulting in a new matrix inversion in calculations.

The other group of fault analysis methods relies on phase components which model the system in phase coordinates. Laughton [5,6] has proposed the phase models of system components such as three-phase transformers, generators, etc. and demanded them in two SCB analysis methods in phase coordinates. These methods employed a three-phase bus admittance/impedance matrix which is a $3n_b \times 3n_b$ matrix for an n_b-bus network. In [6], the fault analysis in phase coordinates is carried out by either solving the linear equations subject to constraints (distributed-source method) or exploiting the Norton and superposition theorems (Z-source transformation method). In the later method, the fault currents and the consequent voltage variations are calculated using network three-phase bus impedance matrix. Authors in [7,8] have proposed a methodology which is based on the current-injection method and could be used to study shunt, series and internal faults. For each case, the faults are modeled as RLC branches, the Jacobian matrix is constituted and the set of equations is solved by inverting it. The Jacobian matrix alters during each fault case. Hence, composing the matrix and depending on the number of iterations, several inversion operations are required for each fault case. Moreover, decomposing the variables into real and imaginary parts would double the equations number and raise the computational burden. In [9], two matrices are built from the topological characteristic of the network, including bus injection to branch current matrix (B_i) and $Z_{v\text{-}bc}$ the matrix describing the relationship between bus voltages mismatch and branch currents. These matrices are modified for every fault case in the network and the equations are solved. $Z_{v\text{-}bc}$ must be forged element-by-element. Moreover, only short circuit faults are considered. The series faults, internal faults and load effect are not mentioned. In [10], a methodology is proposed which defines a modification in Y_{bus} for each fault case: for shunt faults the diagonal elements and for series faults both diagonal and off-diagonal elements would be altered. For each set of faults, a matrix inversion is needed whose size will grow with the number of simultaneous faults in a set. In [11], two methods of fault analysis in phase coordinates are evaluated: 1) the node oriented approach and 2) the branch oriented approach. For shunt faults, the system of equations is written based on Norton or Thevenin theorems and series faults are