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An enhanced tool for fault analysis in multiphase electrical systems

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ABSTRACT

This paper describes a new methodology for the fault analysis of an *n*-conductor electrical system, in which the phase imbalances, neutral cables, groundings, and other inherent characteristics of distribution systems are considered. The proposed methodology, which is based on the current-injection method, allows faults to be represented in a simple way and may be used to analyze several fault types, including internal, series, and simultaneous faults. The results of several cases are presented to show the efficiency of the proposed method.

Introduction

One of the main objectives in the distribution system analysis is the development of methodologies that are able to represent electrical systems in detail, considering their different topologies and the variety of equipment present in these systems, especially in the context of smart grids [1–7]. The application of advanced methodologies allows engineers to achieve better operating conditions and plan more effectively.

Currently, several methodologies for fault analysis consider that electrical networks are symmetrical and balanced, and they model the equipment in a simplified manner, and, through the use of symmetrical components, it is possible represent various asymmetric faults [8–10].

It is noteworthy, however, that the method of utilizing symmetrical components often introduces simplifications in the analysis, making this approach not the most suitable for all cases. For example, the fault analyses in unbalanced systems introduce coupling between the sequence networks, causing the loss of the main advantage of the symmetrical components. This fact can be observed in single-phase, two-phase, or three-phase lines that are not perfectly transposed. Among the works that address studies of faults using symmetrical components, several improvements in the simplifications that are usually adopted have been proposed [9–11].

Several configurations are used in distribution systems, and the three-phase four-wire configuration with multiple neutral grounding is widely used. This configuration has a low installation cost, provides greater safety for people and equipment, and has a high sensitivity to faults [12]. It is emphasized that methodologies based on symmetrical components do not provide good results when used in this type of system. Also noteworthy is that the correct representation of the neutrals and groundings is essential for fault analysis in distribution systems.

In recent years, many researchers have proposed methodologies for fault analysis focusing on unbalanced systems. Previous studies have proposed the representation in phase coordinates, but with some simplifications; for example, the neutral cable is not explicitly represented and its effects in the phases are incorporated by Kron reduction or simply ignored, despite the large use of neutral cables in distribution systems [13–15]. This kind of simplification may lead to incorrect results, especially in unbalanced systems [12]. Some authors have proposed specific methodologies for fault analysis in distribution systems, thereby improving some aspects of the analysis [16–25].

Despite significant advances in the representation of systems with faults [25], many points can be improved. Cited as examples are fault between different voltages points, detailed representation of equipment, representation of magnetic couplings between different circuits, internal faults, improved representation of loads in high impedance faults, and simultaneous faults. These points, if addressed, will allow more accurate analyses and avoid misleading results that may pose risks to both human and equipment safety.

This paper proposes a method that allows the analysis of faults in any kind of multiphase electrical system, including internal,

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series, and simultaneous faults. When compared with other methodologies of fault analysis, several advantages can be cited for the *n*-conductor simultaneous fault method (NSFM):

i. It allows modeling of any electrical system in phase coordinates, including mutual impedances between phases of the same circuit or mutual impedance between circuits of the same or different voltage level.
ii. It allows the representation of any type of transformer connection in direct form.
iii. It allows the representation of faults in multiphase systems, e.g., single-phase, two-phase, and three-phase.
iv. It allows the representation of any type of electrical system (distribution, transmission, or industrial), radial or meshed, and dispersed generation.
v. It allows the explicit representation of groundings, ground wires, and neutral cables. Any type of grounding can be represented (isolated, high-impedance, low-impedance, solid-grounded, or any combination) including even safety groundings.
vi. It allows the representation of simultaneous faults in a simple and intuitive form.
vii. It allows the simulation of faults between different points in the system, e.g., the contact of a medium-voltage cable with a low-voltage cable in distribution systems.
viii. It allows the simulation of internal faults in equipment, e.g., transformers.

It is emphasized that all these points improve the results of fault analyses. It is noteworthy that all the advantages listed can be executed directly in NSFM without the need for additional calculations or simplifications, which are usually required in many current methodologies.

This paper is organized as follows: The NSFM is developed in Section '*n*-Conductor simultaneous fault method', numerical examples are provided in Section 'Applications', and conclusions are presented in Section 'Conclusions'.

n-Conductor simultaneous fault method

The *n*-conductor simultaneous fault method (NSFM) was developed to be a general methodology that allows the analysis of any faulted electric power system.

Methodology

In the NSFM, the network and the equipment are modeled in phase coordinates and electrical quantities (p.u. quantities are not used). The equations of the electrical system are written as equations of current injection in rectangular coordinates. The proposed method is presented in Fig. 1, where **z** is the state variable and **f** are current-injection equations for all the system nodes. The state variables are phase-to-ground voltage and are represented in rectangular coordinates using the real and imaginary parts.

In Step F.0 of the proposed algorithm (Fig. 1), all electrical system and equipment data are loaded, including the location and type of fault that will be simulated.
In Step F.1, the pre-fault conditions are calculated through a power flow program.
In Step F.2, the electric system is updated and additional nodes are created to simulate the faults informed in Step F.1; for example, if a fault is indicated in the middle of a transmission line, one or more additional nodes are created and the line is split.
In Step F.3, if an internal fault is indicated in a transformer, the procedure given in Section 'Transformers' is used to represent the equipment in fault.
In Step F.4, RLC (resistances, inductances, and/or capacitances) elements are inserted to represent the various types of faults, as shown in Section 'RLC components'.
The right-hand vector (**f**) and Jacobian matrix (**J**) are assembled in Steps F.5 and F.7.
In Step F.6, a convergence test is performed, $e = 10^{-6}$.
In Step F.8, increments are calculated and the equation is presented in (1). The contributions to right-hand vector (**f**) is calculated according to the equations presented in Sectio n 'Component models'. The contributions to the Jacobian matrix (**J**) are the first order derivative of **f** in relation to state variables (V_{Re} and V_{Im}). Derivative equations are not presented for space reasons.

$$\begin{bmatrix} \Delta V_{\mathrm{Im}_1} \\ \Delta V_{\mathrm{Re}_1} \\ \Delta V_{\mathrm{Im}_2} \\ \Delta V_{\mathrm{Re}_2} \\ \vdots \\ \Delta V_{\mathrm{Im}_{nb}} \\ \Delta V_{\mathrm{Re}_{nb}} \end{bmatrix} = -\begin{bmatrix} \mathbf{J}_{1,1} & \mathbf{J}_{1,2} & \cdots & \mathbf{J}_{1,nb} \\ \mathbf{J}_{2,1} & \mathbf{J}_{2,2} & \cdots & \mathbf{J}_{2,nb} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{J}_{nb,1} & \mathbf{J}_{nb,2} & \cdots & \mathbf{J}_{nb,nb} \end{bmatrix}^{-1} * \begin{bmatrix} \Delta I_{\mathrm{Re}_1} \\ \Delta I_{\mathrm{Im}_1} \\ \Delta I_{\mathrm{Re}_2} \\ \Delta I_{\mathrm{Im}_2} \\ \vdots \\ \Delta I_{\mathrm{Re}_{nb}} \\ \Delta I_{\mathrm{Im}_{nb}} \end{bmatrix} \tag{1}$$

where ΔV_{Re} and ΔV_{Im} are the solution, that increment of phase to ground voltage, real and imaginary respectively. ΔI_{Re} and ΔI_{Im} are the net current injected (Section 'Component models'). $\mathbf{J}_{k,m}$ is the partial first order derivative as shown in (2).

$$\mathbf{J}_{k,m} = \begin{bmatrix} \frac{\partial \Delta I_{\mathrm{Re}_k}}{\partial V_{\mathrm{Im}_k}} & \frac{\partial \Delta I_{\mathrm{Re}_k}}{\partial V_{\mathrm{Re}_k}} \\ \frac{\partial \Delta I_{\mathrm{Im}_k}}{\partial V_{\mathrm{Im}_k}} & \frac{\partial \Delta I_{\mathrm{Im}_k}}{\partial V_{\mathrm{Re}_k}} \end{bmatrix} \tag{2}$$

In Step F.9, state variables are updated.
In Step F.10, update load parameter. If $|V_{\mathrm{LD}}| \leqslant v_{\mathrm{Lim}}$, α and β is set to 2 (constant impedance – Section 'Loads'). If $|V_{\mathrm{LD}}| > v_{\mathrm{Lim}}$, α and β is set to original value. V_{LD} is the voltage in the load terminals and v_{Lim} is load minimum voltage.

The results are shown in Step F.11.

Component models

Transmission and distribution lines

The transmission and distribution lines are modeled as a coupled *n*-phase π-equivalent lumped-parameter circuit and the equations presented in (3) and (4) are used to model a distribution line connected between the sets of nodes *k* and *m* [8].

$$\mathbf{I}_{km,lin} = \begin{bmatrix} Z_{k1,m1} & Z_{k1,m2} & \cdots & Z_{k1,mn} \\ Z_{k2,m1} & Z_{k2,m2} & & Z_{k2,mn} \\ \vdots & & \ddots & \\ Z_{kn,m1} & Z_{kn,m2} & & Z_{kn,mn} \end{bmatrix}^{-1} \begin{bmatrix} V_{k1} - V_{m1} \\ V_{k2} - V_{m2} \\ \vdots \\ V_{kn} - V_{mn} \end{bmatrix} + \begin{bmatrix} Z_{k11} & Z_{k12} & \cdots & Z_{k1n} \\ Z_{k21} & Z_{k22} & & Z_{k2n} \\ \vdots & & \ddots & \\ Z_{kn1} & Z_{kn2} & & Z_{knn} \end{bmatrix}^{-1} \begin{bmatrix} V_{k1} \\ V_{k2} \\ \vdots \\ V_{kn} \end{bmatrix}, \tag{3}$$