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A new tool for multiphase electrical systems analysis based on current injection method

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ABSTRACT

This work presents a new methodology for steady state analysis of multiphase electrical systems, the N Conductor Current Injection Method – NCIM. It is based on the current injection method in rectangular coordinates that is defined directly in phase coordinates and applies the Newton–Raphson method in the solution process. The method can be used to analyze any electrical power system. NCIM has the capability to represent many features, such as unbalances, mutual couplings, multi-phase feeders and devices including neutral conductors and groundings, distributed generations and control actions, in such a way that the total dimension of the system of equations is the minimum required to obtain the solution. The method can be applied to analyze both balanced and unbalanced systems, radial or meshed, and can simulate the interconnected transmission, subtransmission and distribution networks, including large-scale systems. NCIM is shown to be very efficient and computationally robust.

1. Introduction

In the last years, the power system researchers have become more interested in a more detailed kind of modeling of diverse aspects of the electrical power systems. They are looking for more general methods that give more precise results, and that permit advanced analysis [1]. The three-phase analysis, for example, has been growing stronger, especially for distribution systems. More detailed studies have been demanded due to the great increase of the distributed generation (DG) and they have shown that the simulation of distribution and subtransmission together might be necessary.

Looking for improvements, many three-phase methodologies have been proposed for state-steady analysis in electrical power systems [2–17]. Each methodology has its own main applications, being that, particular characteristics and simplified models adopted can restrict the correct and precise use for just some electrical systems.

Among the new methodologies of analysis, there is one line of research based on the current injection method. The Three-Phase Current Injection Method – TCIM [7] has been proposed focusing on three-phase systems. New very efficient routines have been developed to perform matrix ordering and factorization and thus TCIM has become very robust computationally, especially for meshed DS, as well as in the presence of control devices [18]. In 2008 the Four-Conductor Current Injection Method – FCIM was conceived to include the explicit representation of neutral conductors and groundings [19].

Both TCIM and FCIM were constructed based on blocked structures. For example, in FCIM all components and controls have an 8×8 fixed dimension block for the Jacobian matrix, even when the equipment does not have the four nodes (related to the *a*, *b* and *c* phases and the neutral). And because of the blocked structure it was difficult to represent a component with more than four nodes in the same busbar. This blocked structure increased the system's dimension to be solved.

The objective of this work was to develop a new and improved methodology that could take advantage of all of the good characteristics of the FCIM, however it should be more flexible, without the fixed block structure, thus the N-Conductor Current Injection Method (NCIM) was developed. The key to such improvements was to extend the methodology to multiphase systems and to attain enhanced flexibility both on equipment modeling and on the structure of the Jacobian matrix. The NCIM is a multiphase method in which component models are built on an element by element basis. Thus the contribution of each element or phase of any equipment will reflect its physical construction, so that the final dimension of the Jacobian matrix will be the minimum required to represent the system. The fixed submatrix block structures used before are no longer necessary.

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Compared with many current methodologies, the following may be cited as some of the advantages of NCIM:

i. Deals directly with multiphase models, without the need for fixed blocked matrix representations, or sequence networks, or any other transformations or simplifications.
ii. The dimension of the system of equations to be solved is always kept to the minimum.
iii. Allows direct modeling of components that have asymmetric representative matrix.
iv. Allows the representation of all types of loads, including between phases and between phase and neutral, which are very common elements in distribution systems.
v. Generator models do not use conventional busbar types, allowing the representation of neutral groundings as well as different models for positive and negative sequence circuits.
vi. Controlled operation and loads characteristics of induction motors can be represented.
vii. The transformer model implemented does not use predefined matrices for each type of connection. The transformers are modeled from their own windings connections, which allows the representation of more complex types of transformers, for example, the wye-delta with a central tap, or a physical connection between the primary and secondary of the transformer, etc.
viii. The line model is general, allowing the representation of mutual couplings between phases or between lines even if different voltage levels are in the same right-of-way, communication cables, guard cables, neutral cables, groundings, etc.

It is important to emphasize that all of these representations can be done in the NCIM directly, without the need for additional calculations or extra iterative processes, which are common in many current methodologies.

The NCIM is a general methodology and can be used to simulate all kinds of systems; radial or meshed, from unbalanced multiphase systems that have equipments with n conductors, to the pure one-phase (or positive sequence) representations. All of this should be done with the same algorithm allowing the system to be solved, to have equipments with all these characteristics at the same time.

In this work, the proposed methodology, some equipment models and controls developed or improved for NCIM will be presented, as well as potential analysis.

2. N-conductor current injection method

2.1. Methodology

The NCIM was developed with the intention of being a methodology to analyze any electrical power system, and so it can be used to represent very detailed electrical systems, whenever possible allowing the execution of more complete analysis. To accomplish this, all of the systems nodes are treated individually, so the models are designed based on elements. Any structure connected between two nodes or from one node to the ground is called an element. The element models do not generate blocked matrices with pre-defined dimensions.

This new structure makes the methodology more flexible, the formation of models easier, represents the controls in a better way, and contributes to the optimization of the solution process. The set of equations to be solved by the proposed method will consequently always have the exact dimension.

The basis of the proposed methodology is the current injection method. Analyzing the current injections equations forms, it can be considered that in each node of the system, the current injection sum is made up of parts related to all elements connected in that node, and it can be considered that each system element creates a current injection contribution to the nodes in which it is connected. Therefore, the models of the majority of the components (system equipment) are actually formed by one or more elements, connected in many configurations.

When the component has another characteristic or extra function, commonly known as control action, it also needs to be represented. The basic procedure to incorporate the control actions in the proposed methodology is to model the control equipment, using additional equations to represent their actions, resulting in an enlarged system, and consequently an enlarged Jacobian matrix.

The elements and some control actions for the main components of the electrical systems will be presented in Section 2.2. Being that in NCIM, for each component of the system it is necessary to define (starting from its elements):

- The current injection contributions to all nodes in which the component is connected.
- Its contributions to the Jacobian matrix and independent vector from the current injection contributions.
- And control actions equations, if necessary.

The solution method can be summarized in the following steps:

(1) Construct the current injection equations for all the system nodes, starting from the contributions of all the elements, and the control equations when existent, making up a non-linear set of equations, this can be represented as:

$$\mathbf{f}(\mathbf{z}) = 0 \tag{1}$$

where $\mathbf{z}$ are the state variables and $\mathbf{f}$ are the current injection equations or the control functions.

In the NCIM the equations are written in rectangular coordinates, using the real and imaginary parts of the nodal phasor voltages (phase-to-ground) as the main state variables, besides others variables that are associated to the controls. And the current injection equations are separated into real and imaginary parts.

(2) Solve the set of non-linear equations and find the state variables of the system. In the NCIM the Newton–Raphson method is used. The mathematical expression of the linearized system (1), written in a matrix form, is given by the following equation:

$$\mathbf{J}(\mathbf{z})\Delta\mathbf{z} = -\mathbf{f}(\mathbf{z}) \tag{2}$$

where in each step of the iterative process: $\mathbf{J(z)}$ is the Jacobian matrix; $\mathbf{f(z)}$ is the independent vector (right-hand vector); $\Delta\mathbf{z}$ is the solution vector, that increment states variables.

In the NCIM the Jacobian matrix has a large amount of null or constant terms, making the use of sparsity techniques interesting for the solution of the set of equations.

An algorithm that represents the NCIM solution process is shown in Fig. 1.

2.2. Component models

2.2.1. RLC components

Many network components can be modeled with RLC (resistances, inductances and/or capacitances) elements being connected in different configurations, such as delta, wye, and grounded wye. Each RLC element of the given component can be