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Comparisons between the three-phase current injection method and the forward/backward sweep method

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ABSTRACT

This paper presents comparisons of two power flow methodologies for distribution system analysis: the three-phase current injection method – TCIM and the forward/backward sweep – FBS. These techniques were applied for large scale three-phase distribution systems, the advantages and drawbacks are emphasized and their computational performances are presented. The results presented in this work can be helpful to decide which one of the tested methods is the most suitable to solve a particular electrical system.

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1. Introduction

Electrical distribution utilities are required to be more competitive, to work more efficiently and to match the demand in an optimized way; therefore their systems need to be constantly improved. Electrical distribution systems have been restructured considering new available technologies such as Flexible AC Transmission Systems (FACTS) devices. Additionally, the considerable growth of distributed generation has imposed new operation philosophies, such as the increase of control equipments and new protection devices. Also in some distribution systems the enlargement in the number of loops to increase reliability, considering the advances in the protection system devices is becoming a common strategy.

The new distribution system characteristics reflect in their mathematical formulations for the power flow solution and have created certain difficulties and even limitations for the traditional solution methods. As a consequence the necessity of creating more robust methodologies or at least of using the most suitable method to deal with the above mentioned system characteristics has increased.

In recent years several methodologies have been proposed to solve the three-phase power flow [1–5]. In this work two methodologies will be compared in different aspects: one methodology is a three-phase implementation of the forward/backward sweep method (FBS) [2,6] and the other is the three-phase current injection method (TCIM) [4].

FBS is commonly used to solve radial or low meshed electrical systems [2] due its high computational performance and implementation simplicity, as a result FBS has become one of the most popular methodologies for the three-phase power flow solution in electrical distribution systems.

TCIM uses the Newton–Raphson method to solve the three-phase current injection equations. Although its computational implementation is considered more complicated than the FBS implementation, TCIM has proven to be numerically very robust, allowing the solution of highly meshed systems and with a large number of control devices [4,5]. The use of efficient routines that have been developed to perform matrix ordering and factorization, considering sparse techniques, has made the TCIM an excellent alternative to solve distribution systems power flows, even for simple radial systems.

The representation of new operation philosophies and new system characteristics, such as control devices, as well as the presence of meshed systems, created some difficulties and limitations for FBS method. Solutions have been proposed to overcome some difficulties [1,3,6–9], however they usually are not a general approach as in the TCIM technique. As a consequence the computational effort to solve the whole power flow problem, considering these

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new system features, increases considerably and a great deal of changes in the FBS algorithms is required. Then the number of iterations required to achieve the solution increases significantly, and the methodology robustness can be degenerated, and in some circumstances the convergence is not reached. Moreover, FBS presents serious difficulties to solve very meshed systems. On the other hand TCIM does not present the FBS limitations, and can be normally used, without any changes in the algorithm, for meshed systems and considering control devices.

This work presents comparisons of TCIM and FBS three-phase methodologies, in which the advantages and drawbacks related to each methodology are emphasized. The initial investigations of this work were presented in [10], since then new tests and important analyses have been done, and in the present work new aspects, detailed information and analyses, besides other results are presented. In this work two different approaches for TCIM were considered. Both methodologies have been optimized in terms of programming, using C++ and object-oriented modeling techniques.

Sections 2 and 3 present summaries of TCIM and of FBS techniques. In Section 4 qualitative comparisons between the two methods are presented. Some numerical results are presented in Section 5, and the conclusions in Section 6.

2. TCIM overview

In the TCIM method the three-phase current injection equations are written using phase coordinates and the complex variables are considered in rectangular form, resulting in a set of *6n* equations with *6n* state variables (where n is the number of system busbars). To solve this set of nonlinear current injection equations the full Newton method is applied. The Jacobian matrix is sparse and arranged in 6×6 dimension blocks with the same structure as the nodal admittance matrix [4].

2.1. Basic equations

The net current injection at each node of a system busbar k (Fig. 1) can be written in a general form as in (1). It is considered that each busbar can have three nodes which represent phases a, b and c.

$$I_k^s = \left(\frac{S_k^s}{V_k^s}\right)^* - \sum_{t\in\alpha_p} Y_{kk}^{st} V_k^t + \sum_{\substack{i\in\Omega_k\\ i\neq k}} \sum_{t\in\alpha_p} Y_{ki}^{st} V_i^t \quad (1)$$

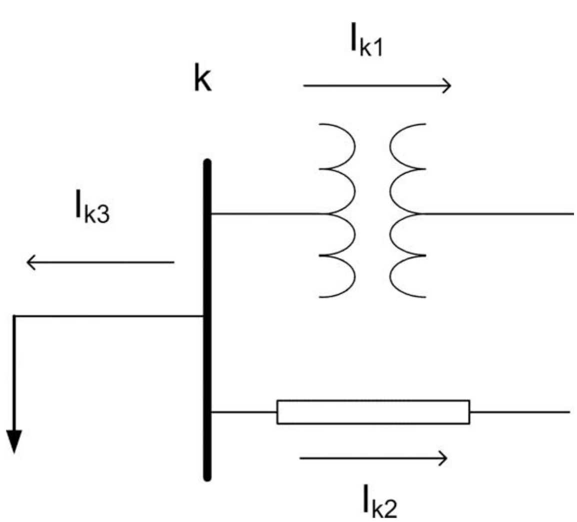

Fig. 1. Current injections in a node of busbar *k*.

where V_k^t is the phase t to ground voltage phasor at busbar k, V_i^t the phase t to ground voltage phasor at busbar i, $s, t \in \alpha_p; \alpha_p = \{a, b, c\}$ Ω_k the set of buses directly connected to busbar k, $V_k^s = V_{\mathrm{Re}_k}^s + jV_{\mathrm{Im}_k}^s$, $I_k^s = I_{\mathrm{Re}_k}^s + jI_{\mathrm{Im}_k}^s$, $Y_{ki}^{st} = G_{ki}^{st} + jB_{ki}^{st}$, $S_k^s = P_k^s + jQ_k^s$

Eq. (1) can be rewritten in terms of its real and imaginary parts and the Newton–Raphson method applied leading to a linearized system of:

$$\begin{bmatrix} \Delta I_{\mathrm{Im}_1}^{abc} \\ \Delta I_{\mathrm{Re}_1}^{abc} \\ \Delta I_{\mathrm{Im}_2}^{abc} \\ \Delta I_{\mathrm{Re}_2}^{abc} \\ \vdots \\ \Delta I_{\mathrm{Im}_n}^{abc} \\ \Delta I_{\mathrm{Re}_n}^{abc} \end{bmatrix} = - \begin{bmatrix} J_{11}^{abc} & J_{12}^{abc} & \cdots & J_{1n}^{abc} \\ J_{21}^{abc} & J_{22}^{abc} & \cdots & J_{2n}^{abc} \\ \vdots & \vdots & \ddots & \\ J_{n1}^{abc} & J_{n2}^{abc} & & J_{nn}^{abc} \end{bmatrix} \begin{bmatrix} \Delta V_{\mathrm{Re}_1}^{abc} \\ \Delta V_{\mathrm{Im}_1}^{abc} \\ \Delta V_{\mathrm{Re}_2}^{abc} \\ \Delta V_{\mathrm{Im}_2}^{abc} \\ \vdots \\ \Delta V_{\mathrm{Re}_n}^{abc} \\ \Delta V_{\mathrm{Im}_n}^{abc} \end{bmatrix} \quad (2)$$

The off-diagonal terms in the Jacobian matrix in Eq. (2) are equal to the corresponding elements of the nodal admittance matrix and thus remain constant throughout the iterative solution procedure. The diagonal terms will depend on the load model and its connection used, and must be updated every iteration.

Newton–Raphson iterations are performed until the convergence is achieved. Detailed description of TCIM is available in [4].

3. FBS overview

The FBS method is based on successive sweeps toward the layers in the system until the convergence is achieved. This method can be implemented in four steps [2].

The first step consists in separating (identifying) the layers in the radial system as shown in Fig. 2.

The second step consists of calculating the nodal current injection for each node of the system, as in (3). In this step the nodal voltages are considered fixed.

$$I_k^s = \left(\frac{S_k^s}{V_k^s}\right)^* \quad (3)$$

The third step, called *backward sweep* consists of calculating the summation of the branch currents, in all branches of the system, beginning from the last (lower) layer and working its way up towards the upper layers, as presented in (4).

$$J_k^s = -I_k^s + \sum_{m\in\Omega_M} J_m^s \quad (4)$$

where J_k^s is the total phase s current at branch k, Ω_M the set of branches directly connected to branch k, in the lower layer.

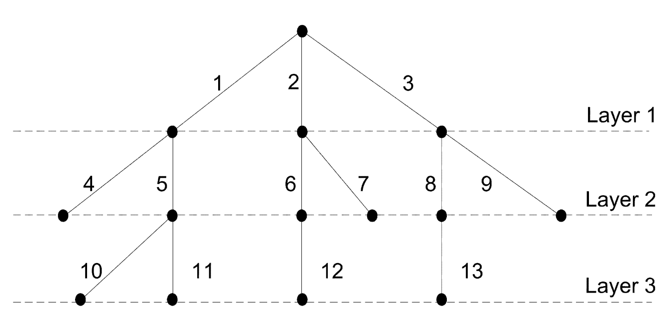

Fig. 2. Layers in a radial system.

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