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Sensitivity analysis of convergence characteristics in power flow methods for distribution systems

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ABSTRACT

This paper presents an evaluation of the main convergence characteristics of multiphase power flow methods in unbalanced distribution systems. Two widely used methods for solving unbalanced power flows are analyzed: methods based on Newton–Raphson (NR) and methods based on backward forward sweep (BFS). The limits and robustness of the BFS method and NR method are tested in the following aspects: (i) variation of the X/R ratio, (ii) load's increase up to the convergence limit, (iii) load model impacts (ZIP model), and (iv) voltage regulators modeling impacts. Some models presented in the literature were implemented and tested. Tests are performed on the IEEE 34 and IEEE 123 systems. Analytical explanations are also presented.

1. Introduction

Nowadays, electrical power distribution systems (DS) modeling has been attracting the attention of a growing number of researchers. The question of the unbalance and the new paradigm of efficiently representing smart grids are of great importance in the analysis of DS. Given these concerns, several methods for three-phase and multiphase power flow analysis have been published in recent years.

In spite of the great number of proposed methods for DS power flow, two methods stand out: Newton–Raphson (NR) based methods and backward forward sweep (BFS) based methods.

NR-based power flow calculation was proposed by Tinney and Hart [1], where the power equations were derived from nodal analysis by using the admittance matrix.

From this point, several variations of the NR method were proposed to solve the power flow problem, with the following variations being the main ones: (i) power injections in polar coordinates; (ii) power injections in rectangular coordinates; (iii) current injections in polar coordinates; and (iv) current injections in rectangular coordinates. A slight preference is noted for (i) in transmission systems and (iv) in DS.

The current injection method (CIM) for power flow calculations was first proposed by [2]. The results obtained inspired the development of a three-phase current injection method (TCIM) in [3], and an extension to include neutral representation in the four-wire three-phase current injection method (FCIM) [4]. A representation of the low voltage network was considered [5], and in [6] a modified augmented nodal analysis method was presented. In [7] a complete multiphase representation, called n-conductor current injection method (NCIM) was proposed.

The BFS method for radial DS was initially proposed by Kersting [8,9] and was followed by Shirmohammadi [10] where a solution for dealing with weakly meshed systems was proposed. The solution proposed by [10] is done through the conversion of the system into a strictly radial system by current injections and consequent application of the BFS method. A similar method was proposed in [11], where complex currents were replaced by active and reactive powers.

A real-time DS analysis method was presented in [12]. However, the proposed algorithm tends to diverge for systems that have many PV busbars and loops. As a result of this divergence and others problems, several improvements have been proposed for the BFS in recent years. In [13] a stable method to deal with weakly meshed DS was proposed, achieving good results. An extension of the BFS method to efficiently represent PV busbars was proposed in [14,15].

In [16] a method for representing four-wire three-phase DS was presented. In [17,18], models for representing of distribution transformers in several configurations were proposed. Voltage regulators were modeled in [19]. The main load models were studied in [20]. The issue of mutual impedances between circuits was addressed in [21]. Several techniques aiming to improve aspects related to BFS convergence were proposed in [22–24].

The BFS was also used for voltage security analysis [25,26]. These studies emphasize the importance of the robustness of the methods

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because the calculated solutions are close to the maximum loading point. In this situation, many methods show convergence problems.

Another important point is the X/R ratio. This issue was already reported by several authors. Problems appear for many methods when the X/R ratio decreases (or the R/X ratio increases, which commonly occurs in DS). This situation hinders or prevents convergence, and some authors indicate that the BFS performs for this problem better than other methods, such as those based on NR. However, extensive tests and analytical proof were not presented [27–30]. Questions that consider different performances and convergence problems with different load models and considering voltage regulators have already been raised in some works [19,20].

Bibliographic reviews of the different variations of BFS methods are reported in [31,32]. A comparison among BFS based methods and other methods is performed in [31,33]. The comparisons were performed in several test systems but were aimed only at common operating situations: light, medium, and heavy loads. The authors indicated that both types of methods are suitable for simulating DS; the BFS-based methods have a better computational performance for low load systems, and the NR methods have a better computational performance for high load systems. However, the methods were not tested in their extremes, that is, their robustness at convergence limits and their performances in different studies were not tested.

In this paper, the limits and robustness of BFS and NCIM methods are tested in the following aspects: (i) variation of the X/R ratio, (ii) load increase up to the convergence limit, (iii) load model impacts (ZIP model), and (iv) voltage regulators impacts. Several analyses are performed at critical points of convergence in both methods, and analytical evidence is presented to justify the results. Different models presented in literature were implemented and tested.

Detailed analyses and analytical explanations of the presented issues are the major contributions of this study. The use of only simple systems or DSASC systems [34] to allow replication of the results is also of considerable importance.

2. NR and BFS overview

2.1. Newton-Raphson based method

NCIM [7] is based on NR where the current injection equations are written using phase coordinates and the complex variables are considered in rectangular form. To solve this set of nonlinear current injection equations, the full Newton method is applied using sparse techniques. A flowchart of the method is presented in Fig. 1. Any control strategy can be implemented by writing the control equations and defining the new state variables. No extra procedure is required. A detailed description of NCIM is available in [7].where $\mathbf{z}$ is the state variables ($\mathbf{V_{Re}}$-real part of nodal voltage, $\mathbf{V_{Im}}$-imaginary part of nodal voltage and other control variables); $\mathbf{f(z)}$ is the current injection equations or the control functions; and $\mathbf{J(z)}$ is the Jacobian matrix.

2.2. Backward forward sweep based method

In BFS methods, the power flow problem is solved by successive

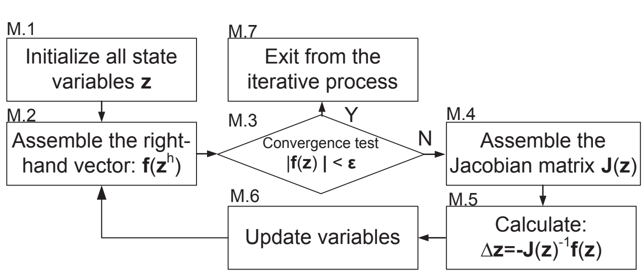

Fig. 1. NCIM algorithm.

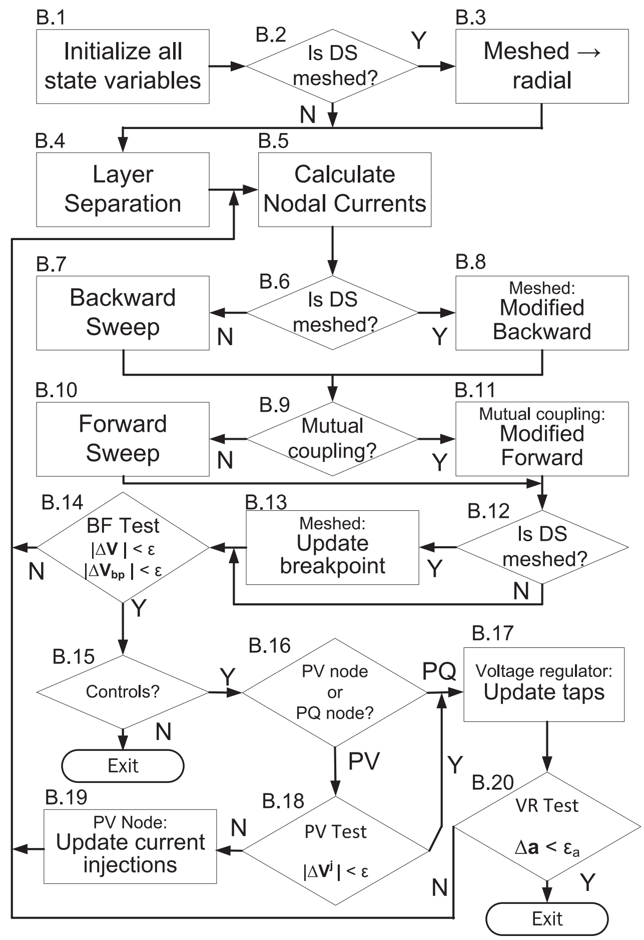

Fig. 2. BFS algorithm.

sweeps in the DS. To allow a comparison with the NCIM, in this work, a multiphase BFS based on [16] was implemented by using several procedures presented in the literature and listed in Section 1 as transformers [17,18], voltage regulators [19], distributed generations and voltage control [14,15], weak meshed networks [13], neutral cables and mutual coupling among circuits [21], in addition to several methods proposed in the literature to improve and speed up convergence [22–24,27–30]. Fig. 2 shows a flowchart of the method implemented in this work.

3. Convergence issues

The main problems related to the convergence of NR- and BFS-based methods are as follows:

3.1. Decoupled power flow methods

Decoupled methods were developed for transmission systems, where low values of resistance of transmission lines allow the separation in two weakly coupled subsystems. However, the feeders of DS have a high resistance value. With this, the decoupled methods present convergence problems when applied in DS, and their use should be avoided.

3.2. Linear system solution

The linear system solution routines are often an important part of the solution methods of NR-based power systems. Most linear system solution routines perform the factorization/decomposition of the