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Review

Developed Newton-Raphson based Predictor-Corrector load flow approach with high convergence rate

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ABSTRACT

In this paper, a new methodology called *Newton-Raphson-Predictor-Corrector* (NR-PC) is applied to solve the load-flow (LF) problem of well and ill-conditioned power systems. In the proposed LF method, the Predictor-Corrector mechanism is developed to achieve convergence rate of order $1+\sqrt{2}\approx 2.4$ instead of 2 for the standard Newton Raphson (NR). The proposed NR-PC LF method is validated on different test systems; IEEE 30-bus, 57-bus, 118-bus and 300-bus systems as well-conditioned test cases, 13-bus and 20-bus systems as naturally ill-conditioned test systems, 1354-bus, 2869-bus and 9241-bus systems as realistic very large-scale test systems. The sensitivity of the proposed method with different R/X transmission line ratios and loading conditions is validated and compared with well-known methods. The simulation results show that the proposed LF method has better convergence characteristics and low computation time compared with benchmark methods.

1. Introduction

The load-Flow (LF) calculation is considered one of the most common computational tools used in power system analysis. LF study is essential for planning expansion of power systems as well as determining the best operation of existing systems. LF solution is considered the starting point for many studies such as; continuation power flow, optimal power flow and on-line applications, which required fast computational time [1–3]. Consequently, there is a continuing search for new methods with fast convergence characteristics and robust solution, especially for ill-conditioned systems.

Gauss-Seidel method is considered the earliest method used to solve the LF problem [1,4,5]. This method suffers a slow convergence and high number of required iterations. Later, NR was proposed to solve the convergence problems of GS [4,6]. NR is considered as the standard LF method that widely used in industry applications. However, NR method started to lose its ability to converge fast with dramatically increasing in power systems size. In addition, the Jacobian elements of NR method have to be updated during the iterative process. Consequently, Fast Decoupled (FD) method was proposed to improve the computational speed of NR [7]. This method gives bad performance in case of ill-conditioned systems which have high R/X ratios or high loading values [8,9].

New approach based on current injection formulation has been developed to accelerate the convergence rate of NR method and avoid the updating of Jacobian elements [10]. However, this approach is more suitable in case of load buses (PQ-type) and exhibits low convergence rate in case of generation buses (PV-type). In [9,11–14], distinct efforts have been made to efficiency represent the PV buses and improve the convergence characteristics of the previous approach.

Ill-conditioned cases may provoke convergence problems in most of standard LF methods [15]. Several robust LF methods have been developed in order to solve the ill-conditioned systems. Robust LF methods can be broadly classified as; methods based on second order formulation [16–19] and other based on Continuous Newton's method [15]. Ref. [16], has presented Iwamoto's method (IM) which based on second order Taylor series. IM calculates an optimal multiplier each iteration, which minimizes the least squares cost function. This multiplier is then used to modify the corrector vector in order to avoid the divergence. This principle has been used by other authors in order to develop other robust LF solvers [17–19]. In [15], the Continuous Newton's method has been presented and applied to LF problem. This method establishes an analogy relationship between the LF and a set of autonomous ordinary differential equations. Therefore, any well-assessed numeric method can be used for solving the LF problem. In [15], the 4th order Runge-Kutta (RK4) formula has been successfully applied to LF problem and its robustness has been demonstrated. Results reported in [15], demonstrate that the RK4 is much more efficient than

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IM.

In [20], a simple modification of NR method has been proposed to achieve a convergence rate of order $1+\sqrt{2}\approx 2.4$ instead of 2 for the standard NR. In this approach, a Predictor-Corrector mechanism (NR-PC) has been proposed to accelerate the convergence characteristic of standard NR method. In this paper, load flow problem is efficiently solved by applying the NR-PC approach. The proposed NR-PC LF method is used to find the load flow solution of well and ill-conditioned small, medium and large-scale systems. The performance of LF method has been compared with different benchmark load-flow methods. The proposed NR-PC LF method gives accurate results with fast convergence characteristics and low computation time compared with the previous load flow methods.

The rest of the paper is organized as follows: Section 2 presents a brief description about LF problem. The developed NR-PC load flow method is presented in Section 3. Simulation results are given in Section 4. The main features of the proposed load flow approach are summarized in Section 5, followed by the conclusions in Section 6.

2. LF problem formulation

LF problem models the nonlinear relationships among the injected power at system buses, the power demands, the bus voltages and the circuit parameters. The basic information of LF solution are voltage magnitude and phase angle at each bus, real and reactive power flow in each transmission line. From these values, other additional information such as; current flow and power losses can be calculated. The active and reactive power mismatches for each bus can be given as:

$$\Delta P_i = P^{sch} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{1}$$

$$\Delta Q_i = Q^{sch} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{2}$$

where, ΔP_i and ΔQ_i are the active and reactive power mismatches at bus i respectively, P^{sch} and Q^{sch} are the injected active and reactive powers at bus i respectively, $V_i\angle\delta_i$ is the complex voltage at bus i, $Y_{ij}\angle\theta_{ij}$ is the $ijth$ element of admittance matrix and n is the total number of buses. The unknown vector of LF problem is defined as:

$$\boldsymbol{x} = \{\boldsymbol{\delta_{PV}} \cup \boldsymbol{\delta_{PQ}} \cup \boldsymbol{V_{PQ}}\} \tag{3}$$

where $\boldsymbol{\delta_{PV}}$ and $\boldsymbol{\delta_{PQ}}$ are the voltage angle vector of PV and PQ buses, respectively. $\boldsymbol{V_{PQ}}$ is the voltage magnitude vector of PQ buses. The unknown vector size is given as:

$$n_x = n_{PV} + 2n_{PQ} \tag{4}$$

where, n_{PV} and n_{PQ} are the number of PV buses and PQ buses, respectively. The LF process is repeated until the convergence condition is satisfied as:

$$\max\{|\Delta P_i| \cup |\Delta Q_i|\} \le \varepsilon\ \forall\ i \tag{5}$$

This means that the iterative process will be stopped when the maximum mismatch (1) and (2), is lower than the preset convergence tolerance ε. In order to simplify the notation, compact version of (1) and (2) will be used onwards:

$$g(\boldsymbol{x}) = 0 \tag{6}$$

3. Proposed NR-PC load flow method

In this section, the proposed NR-PC load flow method is presented. This method is based on the set of nonlinear equations solver developed in [20]. The section is divided into two subsections; standard NR and proposed NR-PC methods.

3.1. Standard NR method

Let us consider the solution of the generic nonlinear equation $f(x)=0$ with x as a variable. If x^0 is an initial estimate of the solution, $f(x)$ can be expanded around x^0 in Taylor series yields;

$$f(x) = f(x^0) + f'(x^0)(x-x^0) + \frac{1}{2!}f''(x^0)(x-x^0) + \cdots + \frac{1}{n!}f^{n}(x^0)(x-x^0) = 0 \tag{7}$$

By neglecting the second and higher order terms, Eq. (7) can be rewritten as:

$$f(x) \approx f(x^0) + f'(x^0)(x-x^0) = 0$$

The value of x can be obtained from

$$x = x^0 - \frac{f(x^0)}{f'(x^0)} \tag{8}$$

In general, the new estimated value of x for each iterative (k) is given as:

$$x^{k+1} = x^k - \frac{f(x^k)}{f'(x^k)} \tag{9}$$

or

$$x^{k+1} = x^k - \Delta x \tag{10}$$

where

$$\Delta x = \frac{f(x^k)}{f'(x^k)} \tag{11}$$

The above equations can be extended to solve the set of simultaneously non-linear equations in (6) as:

$$\Delta\boldsymbol{x}^{(k)} = \boldsymbol{J_x}(\boldsymbol{x}^{(k)})^{-1} g(\boldsymbol{x}^{(k)})$$
$$\boldsymbol{x}^{(k+1)} = \boldsymbol{x}^{(k)} + \Delta\boldsymbol{x}^{(k)} \tag{12}$$

where $\boldsymbol{J_x}$ is the Jacobian matrix of the system, which is the first-order partial derivatives of (6) with respect to unknown vector. Eq. (12) is a generic kth iteration of the NR process, which is repeated until the convergence criteria (5) is satisfied.

The performance of standard NR method is shown in Fig. 1. For the sake of simplicity, a problem with $n_x = 1$ is analysed. It can be observed that the iterative process starts in an initial guess point $x^{(0)}$, as derivative of $f(x^{(k)})$ at each point, the process is repeated until point x^*, which verifies $f(x^*)=0$.

3.2. Proposed NR-PC LF method

NR-PC proposes a slight modification of standard NR, which is able to reach a convergence rate of order $1+\sqrt{2}\approx 2.4$. The following are

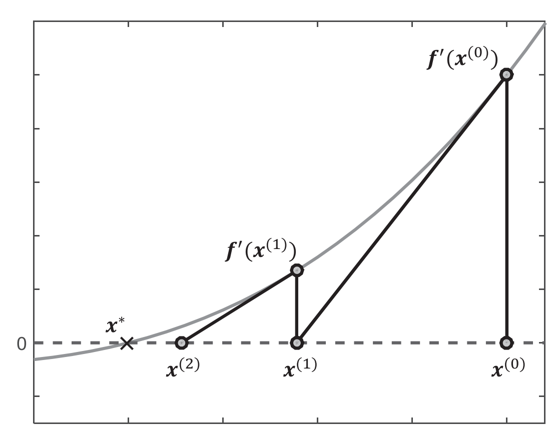

Fig. 1. Sketch of standard NR method.