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A new power flow method for radial distribution systems including voltage dependent load models

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Abstract

This paper presents a simple and efficient method to solve the power flow problem in radial distribution systems. The proposed method takes into account voltage dependency of static loads, and line charging capacitance. The method is based on the forward and backward voltage updating by using polynomial voltage equation for each branch and backward ladder equation (Kirchoff's Laws). Convergence ability and reliability of the method is compared with the Ratio-Flow method, which is based on classical forward–backward ladder method, for different loading conditions, R/X ratios and different source voltage levels, under the wide range of exponents of loads. Results demonstrate that the proposed power flow algorithm has a robust convergence ability when compared with the improved version of the classical forward-backward ladder method, i.e., Ratio-Flow.

Keywords: Radial distribution systems; Polynomial equation; Power flow; Voltage dependent loads

1. Introduction

In the last few decades, efficient and reliable load flow solution techniques, such as: Gauss-Seidel; Newton-Raphson; and Fast decoupled load flow [1–3], have been developed and widely used for power system operation, control and planning. However, it has repeatedly been shown that these methods may become inefficient in the analysis of distribution systems with high R/X ratios or special network structures [4–6]. Accordingly, there are a number of reported studies in the literature [7–17] specially designed for solution of power flow problem in radial distribution networks. Methods developed for the solution of ill-conditioned radial distribution systems may be divided into two categories. The first type of methods is based on the forward–backward sweep process for solution of ladder networks. On the other hand, the second group of methods is utilised by proper modification of existing methods such as, Newton-Raphson.

Shirmohammadi et al. [7] have presented a compensation-based power flow method for radial distribution networks and/or for weakly meshed structure using a multi-port compensation technique and basic formulations of Kirchhoff's Laws. The radial part is solved by a straightforward two-step procedure in which the branch currents are first computed (backward sweep) and then bus voltages are updated (forward sweep). In the improved version [8], branch power flow is used instead of branch complex current for weakly meshed transmission and distribution systems by Luo and Semlyen. In [9], Baran and Wu propose a methodology for solving radial power flow for analysing optimal capacitor sizing problem. In this method, for each branch of the network three non-linear equations are written in terms of branch power flows and bus voltages. The number of equations is subsequently reduced using terminal conditions associated with the main feeder and its laterals, and Newton-Raphson method is applied to this reduced set. Computational efficiency is improved by making some simplifications in the jacobian.

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Consequently, numerical properties and convergence rate of this algorithm have been studied using the iterative solution of three fundamental equations representing real power, reactive power and voltage magnitude by Chiang in [10].Renato Cespedes [11] makes use of well-known bi-quadratic equation, which relates the voltage magnitude at the receiving end to the voltage at the sending end and branch power flow for every branch. In this study, only voltage magnitudes are computed, bus phase angles do not appear in his formulation, which was also used by Das et al. [12]. Jasmon and Lee [13], have proposed a load flow technique for every branch, which leads to a pair of quadratic equations relating power flows at both ends with the voltage magnitude at the sending end for the voltage stability analysis of radial networks. Haque [14] have formulated power flow problem of distribution systems in terms of three sets of recursive equations and analysed power flow results for various voltage dependent load models. The effects of various load models on the convergence pattern of the method are also studied. The effect of voltage-dependency of load on the results of power flow solution are also analysed by Mok et al. [15]. Authors have shown a new approach for power flow analysis of distribution systems, which is based on Kirchoff's Laws and demonstrated the effect of different load models on the convergence ability of their method. In ref. [16] authors have proposed Ratio-Flow method, which is based on forward–backward ladder equation for complex distribution system by using voltage ratio for convergence control. This method was applied with the standard Newton-Raphson method for complex distribution systems, which have multiple sources or relatively strong connected loops with extended long radial feeders including laterals, to solve power flow problem. Ranjan and Das [17] have proposed a new method to solve radial distribution networks. They have used simple algebraic recursive expression of voltage magnitude and the proposed algorithm uses the basic principle of the circuit theory.

The aim of this paper is to propose a new power flow method for radial distribution networks with improved convergence characteristics. It is based on polynomial equation on the forward process and backward ladder equation for each branch of radial distribution system. In the proposed method, line shunt capacitance and exponents of static load are included in power flow solution. The proposed method is tested on two ill-conditioned radial systems for different voltage-dependent load models, and then it is compared with the results of Ratio-Flow method [16] and evaluated against a commercial grade power flow program PFLOW [18]. A series of tests are under taken to evaluate the proposed method for different loading conditions, different R/X ratios and different voltage levels, under wide range of exponents of loads in radial distribution systems. Results show that the proposed method has fast and reliable convergence ability when compared with Ratio-Flow method, which is known with its faster convergence characteristics amongst various sweep methods [16].

2. Power flow formulation for radial distribution systems

In conventional load flow studies, it is presumed that active and reactive power demands are specified constant values, regardless of the amplitude of voltages in the same bus. In actual power systems operation, different categories and types of loads such as residential, industrial and commercial loads might be present. The nature of these types of loads is such that their active and reactive powers are dependent on the voltage and frequency of the system. Moreover, load characteristics have significant effects on load flow solutions and convergence ability [14]. Common static load models for active and reactive power are expressed in a polynomial or an exponential form. The characteristic of the exponential load models can be given as:

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p} \tag{1}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{n_q} \tag{2}$$

where n_p and n_q stand for load exponents, P_0 and Q_0 stand for the values of the active and reactive powers at the nominal voltages. V and V_0 stand for load bus voltage and load nominal voltage, respectively. Special values of the load exponents can cause specific load types such as: 0, constant power; 1, constant current; 2, constant impedance. The polynomial load model is a static load model that represents the power–voltage relationship as a polynomial equation of voltage magnitude. It is usually referred as ZIP model, as it is made up of three different exponential load models: constant impedance (Z), constant current (I) and constant power (P) static load models. Common values for exponents of static loads are given in Table 1 [19–21]. For practical application, the evaluation of coefficients n_p and n_q requires use of parameter estimation techniques.

The structure of many distribution systems is like a tree with several laterals and sublaterals. Load voltage for branch of any distribution system, given in Fig. 1, can be calculated

Table 1
Common values for the exponents for different static load models

Load component	n_p	n_q
Battery charge	2.59	4.06
Fluorescent lamps	2.07	3.21
Constant impedance	2	2
Fluorescent lighting	1	3
Air conditioner	0.5	2.5
Constant current	1	1
Resistance space heater	2	0
Pumps, funs other motors	0.08	1.6
Incandescent lamps	1.54	0
Compact fluorescent lamps	1	0.35
Small industrial motors	0.1	0.6
Large industrial motors	0.05	0.5
Constant power	0	0