Electrical Power and Energy Systems 84 (2017) 168–181

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

An improved load flow technique based on load current injection for modern distribution system

Ujjwal Ghatak, V. Mukherjee *

Department of Electrical Engineering, Indian School of Mines, Dhanbad, Jharkhand, India

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 14 April 2016
Accepted 13 May 2016

Keywords:
Backward forward sweep (BFS)
Branch path set (BPS)
Distributed generation
Radial distribution system
Voltage depended load

ABSTRACT

This paper presents load current injection based improved load flow (LF) technique for modern distribution system. The proposed LF technique is derived by promulgating the concept of conventional backward forward sweep technique. This proposed technique uses a single load current to bus voltage (LCBV) matrix to perform both the backward and the forward sweeps of power flow calculation in a single step. Utilizing the concept LCBV, the bus voltages can be determined, directly, from the load current injections. Due to the distinctive solution technique of the proposed approach, the time-consuming lower–upper factorization and forward–backward substitution or any derivative operation required in the traditional LF technique are no longer necessary. These unique features make the proposed technique faster in operation. The proposed approach is flexible enough to accommodate any sort of change in network structure due to reconfiguration. Along with the modeling of various equipments of distribution system (*viz.* distribution transformer, voltage regulator, voltage dependent loads, distributed generations, etc.), special treatments for weakly meshed system are also presented in this work. It is experimented on several test systems of varying complexities (*viz.* 28-, 69- and 30-bus balanced radial distribution system (RDS), 10-bus and IEEE 34-bus unbalanced RDS and 33- and 69-bus weakly meshed system) and the obtained results demonstrate the effectiveness of the proposed approach while comparing to the existing methodologies. Furthermore, it is revealed that the proposed algorithm is, computationally, faster, robust and more suitable for modern distribution network than the contemporary techniques available in the state-of-the-art literature.

Introduction

Nowadays the implementation of smart grid technologies into the modern distribution system is gaining increased attention due to the offered numerous advantages which cannot be achieved in conventional distribution system. The incorporation of smart grid technologies not only enables flexible and reliable operation of the distribution network but also increases the optimization of the system assets and allows the integration of distributed generations (DGs) at distribution level. However, this modernization of distribution system has introduced several challenges in system analysis. Firstly, due to the incorporation of DGs, the direction of power flow in many branches may change and, as a result, the applied load flow (LF) technique may diverge. Secondly, the system topology changes continually due to the self-healing capability of smart grid and reconfiguration application that are assumed to be essential features of modern distribution system in smart grid environment [1]. In this process, an existing network may be reconfigured either as a radial feeder or as a weakly meshed feeder according to the requirement. This reconfiguration problem may lead the distribution feeder to be updated with inaccurate load flow solutions (LFSs). Thus, for continuous monitoring of the state of this modern system and for controlling the system components, a power system practitioner should have an advance LF technique which exhibits the following properties.

The LF technique should be:

(a) Capable of exhibiting high convergence speed to detect any abnormality in the existing system very quickly.
(b) Very much flexible to accommodate any kind of change in the existing network topology due to reconfiguration and produces accurate LFSs.
(c) Capable enough to handle DG sources efficiently in LF calculations.

Since 1950s, numerous LF techniques are available in the literature to analyze the power system. In the earlier stage of research,

* Corresponding author. Tel.: +91 326 2235644; fax: +91 326 2296563.
E-mail addresses: contactujjwalranaghatak@gmail.com (U. Ghatak), vivek_agamani@yahoo.com (V. Mukherjee).

http://dx.doi.org/10.1016/j.ijepes.2016.05.008
0142-0615/

Newton–Raphson (NR) [2] and fast-decoupled [3] method of power flow calculation came out as the most popular LF techniques as these techniques exhibit very good convergence characteristics while analyzing 'well-conditioned' transmission system. However, these techniques fail, grossly, in case of analyzing the of 'ill-conditioned' distribution system having higher R/X ratio. In the first stage of distribution system research, the researchers suggested the modified NR and fast-decoupled [4–6] approaches to analyze the distribution system. However, these are found to be, computationally, burdensome.

In the later phase, the most popular backward-forward sweep (BFS) approach has been evolved. In this 'KCL-KVL' based technique, the branch currents are calculated in the backward sweep while the forward sweep is utilized to determine the bus voltages. This BFS technique is probably first, successfully, implemented in [7] using a multi-port compensation based technique wherein a weakly meshed system is first converted into a radial network by breaking the loops and supplying equivalent current injections to the breakpoints. Finally, the radial part is solved by utilizing the BFS. Further improvement of this approach is found in [8] where it is made suitable for unbalanced real-time distribution feeders. Other modifications of [7] are reported in [9–11]. In [9], the compensation based LF technique is made more adaptive and various components of a practical distribution network (such as 3-phase non-linear loads, lines, capacitors, transformers and disperse generations) are modeled in the LF formulation. LF techniques, reported in [10,11], contain little more modifications. A set of simple algebraic equations of receiving end bus voltage are used here to calculate the branch currents. Another extensions of the approach framed in [7] are reported in [12,13] where loop based analytical approach is utilized to produce the final LFSs. A new LF technique is reported in [14] to analyze both the radial as well as the weakly meshed system. This method utilizes some unique equations to perform the backward sweep to determine the bus voltages. Another efficient LF technique is presented in [15] to analyze heavily meshed system. A new load stepping technique is introduced here to deal with the convergence problem of BFS approach at higher degree of loading.

All of these methods are capable enough to produce accurate LFSs, However, these methods exhibit some common limitations. All BFS based LF techniques use time expensive branch numbering scheme to perform both the sweeps. Designing of distributed transformer in such sweep based methods is also a difficult task. Furthermore, the analysis of weakly meshed system, using multi-port compensation, is complicated and becomes computationally cumbersome. Beside, in the conventional BFS technique, any receiving end bus voltage of the distribution network has to be calculated as a function of the corresponding sending end bus voltage. This chained calculation procedure limits the convergence speed to a considerable extent.

This shortcoming of BFS technique has been overcome by the matrix formulation based BFS techniques, reported in [16–20] where all the bus voltages may be determined as a function of substation bus voltage and the branch currents. The most cited matrix formulation based LF approach is reported in [16], where the backward and forward sweeps are performed using bus injection to branch current matrix and branch current to bus voltage matrix, respectively. Necessity of any time consuming branch numbering scheme is eliminated in this work. However, involvement of two separate matrices increases the CPU time and also provides a research scope for further improvement. Furthermore, this work does not contain any direction to model distribution transformer.

A three-phase power-flow for unbalanced RDS by direct Z_{BR} method is reported in [17]. This approach utilizes 'K' matrix and 'Z_{BR}' matrix to perform the backward and the forward sweep, respectively. The basic concept of graph theory is utilized here to construct these two matrices by incorporating a matrix inversion operation, which is one of the most time consuming operation. Furthermore, for the successful implementation of graph theory, a special branch numbering scheme is introduced. Beside, the authors of [17] have suggested the use of multi-port compensation technique along with this Z_{BR} approach to solve weakly meshed system. However, the multi port compensation itself is a time expensive technique and, at the same time, complicated too. The modeling of distribution transformer and non-linear loads are also not presented. A fast and flexible radial power flow technique is presented in [18] to analyze three-phase unbalanced RDS. The backward and the forward iterative steps of LF calculation are performed in this approach by using section bus matrix and bus section matrix, respectively. This reported method involves a time expensive inversion operation of a radial configuration matrix to construct the other two matrices. Also, the input line data have to be arranged according to the adopted branch numbering scheme and this causes extra time involvement. A generalized single-equation based LF formulation is reported in [19] that may be applicable for unbalanced RDS. This reported technique performs LF calculation based on impedance matrix and nodal current injections. Modeling of various components (like distribution transformer, voltage regulators) is also presented in this work. However, this reported technique is not capable to produce LFSs for weakly meshed distribution system. An improved LF technique, to analyze unbalanced RDS, is reported in [20]. In this method, the conventional backward sweep step is performed using a current transformation matrix to calculate the branch currents directly from the bus injections and the forward sweep step remains unaltered. Due to the separate operation of the two sweeps, CPU time consumption increases. Additionally, modeling of distribution transformer and treatment of weakly meshed system are not presented in this work. Apart from the drawbacks stated earlier, the LF techniques reported in [16–20] are only applicable for passive distribution system and are not extended to analyze the active distribution system. This common limitation has set a barrier for these existing LF techniques to be applicable for modern distribution system.

Some efficient LF techniques are reported in [21–24] to analyze active distribution system. These reported algorithms are capable enough to handle PV nodes efficiently. However, the building process of these LF techniques is not automated to handle network reconfiguration problem. Furthermore, the loads considered in these works are assumed to be constant sink of power. However, it is worth to note that, in practical system, the loads are non-linear and their magnitude depends on the magnitude of voltage at that bus. Thus, these reported LF techniques may not be always reliable for the modern distribution system.

It is revealed from the literature review that the LF techniques available in the literature have their own limitations to handle modern distribution system. It has been noticed that some of the methods exhibit slower converging characteristic. In some cases, good convergence characteristic has been observed for solving radial distribution system (RDS) only. In case of analysis of weakly meshed network, those approaches fail grossly. Some existing approaches are found to be capable to solve RDS and weakly meshed system but are having neither that much of flexibility to accommodate any change in the existing network topology nor capability to handle DGs in LF calculation.

In this light, this paper presents an improved LF technique for modern distribution system, as an extension of the conventional BFS technique. The proposed technique of the present work uses a single load current to bus voltage (LCBV) matrix to perform both the backward and forward sweeps of LF calculation in a single step to determine the bus voltages directly from the load current injections. Due to this distinctive solution technique of the proposed