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Decomposed Newton algorithm-based three-phase power-flow for unbalanced radial distribution networks with distributed energy resources and electric vehicle demands

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A B S T R A C T

This paper proposes a three-phase power-flow algorithm using graph theory, injected current, and matrix decomposition techniques for unbalanced radial distribution networks. A decomposed Newton-Raphson (DNR) method is applied to solve the set of nonlinear power equations described in polar form. Unlike conventional Newton-Raphson-based methods, the proposed DNR algorithm does not involve calculating the lower and upper triangular matrix (LU) factorization, Gaussian elimination, and inversion of the full bus admittance matrix or Jacobian matrix and building the bus impedance matrix; it also requires less computation time and has high robustness with respect to the X/R ratio and load changes. The mathematical component models, such as three-phase conductors, transformers, automatic voltage regulators (AVRs), ZIP load demands, shunt capacitors/reactors, inverter-based distributed energy resources (DERs) and electric vehicle (EV) demands can easily be integrated into the proposed algorithm by using the injected current technique. Therefore, a three-phase power-flow problem can be decomposed into three single-phase power-flow problems with individual phase representation. To validate the performance and effectiveness of the proposed algorithm, four three-phase IEEE test systems and a practical Taiwan Power Company (Taipower) distribution system are used for comparisons. The results reveal that the proposed algorithm has good potential for improving the computational efficiency of optimal planning and design and also real-time power dispatch applications, even for ill-conditioned distribution networks.

1. Introduction

1.1. Background

In social and economic progress, the development of the electric power industry plays a critical role. Therefore, sustainable use of energy is of increasing concern. Distributed energy resources (DERs) and electric vehicles (EVs) are being widely used in modern power systems. They offer several advantages such as reduction in greenhouse gas emissions and use of petroleum-based energy. However, new problems related to power quality and network safety issues may arise. The deterministic power-flow solution is often used in planning and operating studies, such as energy loss evaluation [1,2], DER impact analysis [3–5], and voltage variation evaluation [6], for power and energy systems.

In the power and energy industry, Gauss and Newton-Raphson (NR)-based algorithms are the two most common techniques used for power-flow solutions. A conventional Gauss-based algorithm is a fixed-step iteration scheme with linear convergence. In general, the Gauss-based algorithms require a large amount of computations [7,8]. On the other hand, the NR-based algorithm has become the preferred way to solve power-flow problems owing to its quadratic convergence behavior [9,10]. However, it often fails to converge for ill-conditioned distribution systems, e.g., small X/R ratio of underground cables and unbalanced loads. The characteristics of the distribution networks are different from that of the transmission system and are listed as follows:

1) Radial or weakly meshed topology arrangements
2) Untransposed feeders
3) Uncompleted three-phase feeder arrangements
4) Non-symmetrical conductor spacing
5) Single-phase loads and unbalanced three-phase loads
6) Extremely large number of branches and nodes
7) Wide-ranging resistance and reactance values

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1.2. Literature review

The above-mentioned characteristics may deteriorate the performance of the existing power-flow solution algorithms. Therefore, power-flow techniques have been developed for distribution networks. In practice, these power-flow algorithms can be categorized into two groups: 1) backward/forward sweep (BFS)-based methods [11–13] and 2) improved NR-based methods [14–30]. The BFS-based methods are designed for radial distribution systems. Based on the phase frame, the network components can be modeled without any simplification. In recent years, the BFS-based methods have become popular owing to intuitive solution produces. In the power industry, the power system simulation tools, viz., CYMDIST and GridLAB-D are based on the BFS method. On the other hand, the improved NR-based methods are used to solve power-flow problems for general network structures. For this kind of method, the sequence component frame has been used to develop a three-phase power-flow solver. Three-phase power-flow algorithms, in the sequence component frame, for microgrids and active distribution systems were previously proposed [21,23]. Two different algorithms were used in this sequential power-flow method. The single BFS method is used for power-flow analysis of single laterals [11], and the three-phase sequence-components frame power-flow is used for the analysis of three-phase networks [18]. The current injection method (CIM) [9–11], a full Newton method, is based on the current injection equations of rectangular form. For planning and operation studies of distribution system, OpenDSS is a comprehensive power system simulation tool that is based on the CIM. The largest computational task is to solve the lower and upper triangular matrix (LU) factorization of Jacobian matrix [20]. Therefore, the NR-based methods may take longer computation time for large-scale power distribution systems. Apart from the aforementioned power-flow solution methods, the radial basis function neural networks (RBFNNs) methods [31–35] were recently proposed for solving the microgrid operation problems with a fixed network topology. However, this kind of methods is not suitable as a solution engine for optimization problems.

1.3. Aim and contributions

The main difficulties in most NR-based power-flow algorithms reside in dealing with the LU decomposition or inversion of Jacobian matrix, and the mutual coupling among phases. The objective of the proposed decomposed Newton-Raphson (DNR) based algorithm is to develop a methodology that can improve the solution procedure of the NR-based method. In the proposed algorithm, the problem of LU factorization, Gaussian elimination, inverse of the full bus admittance matrix or Jacobian matrix, and complicated building process of the bus impedance matrix can all be avoided. In previous studies [36–43], the matrix decompositions-based approach was successfully used for analyzing some critical power system problems. The proposed DNR algorithm is based upon power equations in polar form. By the individual phase representation, the coupling-free component models such as three-phase conductors, transformers, automatic voltage regulator (AVR), ZIP load demand, shunt capacitor/inductor, DER and EV demand can be integrated into the proposed algorithm. A set of decomposed Jacobian matrices can be obtained by the proposed algorithm, where the time-consuming inversion procedure or LU decomposition of Jacobian matrix can be avoided. In this study, the conventional NR, CIM and BFS methods are adopted as benchmarks for practical considerations. In order to validate the performance and effectiveness of the proposed method, four three-phase IEEE test systems and random test systems are used for comparisons. The results demonstrate the superiority and accessibility of the proposed method for solving optimization problems.

1.4. Paper organization

In this study, Section 1 briefly introduces the background and objectives of this paper. Some related literatures are also reviewed in this section. Section 2 presents the basic concepts of graph theory. Section 3 introduces the mathematical component models via individual phase representation. Section 4 presents the formula derivation of the proposed algorithm. In Section 5, the numerical results of four IEEE test systems and a practical Taipower distribution system are exhibited. Finally, Section 6 draws a brief conclusion.

2. Basic concepts

2.1. Graphs

In power and energy engineering, graph theory is generally used to represent the geometric relation of a network. In other words, the incidence matrix can be used to describe the topology of a power system network. A graph is a collection of the vertices, and edges, which connect pairs of vertices. In electrical networks, the terms ‘nodes’ and ‘elements’ are used for vertices and edges, respectively. For a graph with n nodes, e elements, b branches and ℓ links, some important relationships are shown as follows [44]:

$$b = n-1 \tag{1}$$

$$\ell = e-b = e-n+1 \tag{2}$$

Different incidence matrices may correspond to different network structures of power systems. Based on the graph theory, the determination of element-bus incidence matrix **A** and branch-path incidence matrix **K** of the oriented graph for representing a distribution network [44] are described in the following sections.

2.2. Element-bus incidence matrix *A*

An element-bus incidence matrix **A** describes the incidence of elements on buses in a given graph *G*. The dimension of the matrix **A** is $e \times (n-1)$, where e is the number of elements and $(n-1)$ is the number of buses in the graph *G*. Selecting the swing bus as reference, the entries of element-bus incidence matrix **A** are described as follows:

$\mathbf{A}(k,i) = 1$ if the kth element is incident to and oriented away from the ith bus
$\mathbf{A}(k,i) = -1$ if the kth element is incident to and oriented toward from the ith bus
$\mathbf{A}(k,i) = 0$ otherwise.

2.3. Branch-path incidence matrix *K*

A branch-path incidence matrix **K** describes the incidence of branches on paths in a given graph *G*. The dimension of the matrix **K** is same as above. A path is directed from a bus to the reference node. The entries of branch-path incidence matrix **K** are described as follows:

$\mathbf{K}(k,i) = 1$ if the kth branch is in the path from the ith bus to the reference and directed in the same direction
$\mathbf{K}(k,i) = -1$ if the kth branch is in the path from the ith bus to the reference and directed in the opposite direction
$\mathbf{K}(k,i) = 0$ otherwise

For the sample system shown in Fig. 1, the corresponding **A** and **K** matrices are represented as (3) and (4). The incidence matrices can be represented by a standard sparse structure for fast calculations.