



A novel branch-based power flow algorithm for islanded AC microgrids



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ABSTRACT

Interest in microgrids is reaching the viral level, fed by the growing research attention and industry investment they are attracting. With its ingrained islanding capability, a microgrid can operate in isolation from the main grid while still keeping its load supplied for enhanced reliability and supply security. These microgrids represent the building block for future smart distribution systems. For steady-state studies of this type of isolated operating mode, an accurate, fast, scalable, efficient power flow analysis tool is crucial. Conventional power flow analysis face challenges when applied to isolated microgrids such as singularity results from system radiality, high R/X ratio, relatively small rated distributed generation (DG) units and thus absence of conventional slack bus, extensive computational burden, convergence issues and extensive solution time. Although branch-based power flow techniques are more preferred for distribution systems to overcome some of the aforementioned challenges, these techniques are incompatible with isolated microgrids as they necessitate the availability of a slack bus. This paper presents a novel branch-based methodology based on the use of power sweeps to solve the steady-state power flow problem. The proposed forward-return-forward-backward sweep (FR-FBS) includes consideration of inherent isolated microgrid characteristics, such as its variable frequency and the absence of a slack bus. The proposed approach also incorporates practical operating modes for DG units and a variety of load characteristics. In addition, the inversion-free nature and consequent speed of the algorithm avoid excessive computational time, thus making it suitable for large distribution networks. The proposed algorithm has been applied to test systems and the obtained results were compared to those obtained with time-domain simulations as well as newton trusted region load flow method. In addition, the effect of load changing on microgrid's voltage profile and power sharing among different DGs were studied. The results show the accuracy and effectiveness of the proposed algorithm. This tool therefore offers support for online energy management, self-healing applications, and emerging techniques for clustering power systems into adaptive self-adequate microgrids.

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1. Introduction

According to the U.S. Department of Energy (DOE), a microgrid is defined as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects [to] and disconnects from such [a] grid to enable it to operate in both grid-connected and island mode” [1]. Microgrids are thus characterized by predefined electrical boundaries that enclose both generations and loads and act behind these boundaries as single

controllable entities that can link to or be isolated from the outer network. The increasing incorporation of distributed generation (DG) units into distribution systems has led to the introduction of the concept of clustering a distribution system into self-adequate microgrids [2,3]. This new concept was aimed at improving reliability [4] and enabling self-healing in the context of smart distribution grids (SDGs) [5] through the clustering of the power system into microgrids with fixed boundaries. As a further development, a novel adaptive self-adequate microgrid with a dynamic boundary that accounts for the stochastic behavior of the load and renewable generation was introduced in Ref. [6]. However, the study of self-adequacy in Refs. [1–6] covered power flow only in grid-connected mode with no analysis in islanded mode, hence making successful islanding questionable. In addition, the small-signal stability analysis of a microgrid [6–9] requires that a power flow solution

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Nomenclature

Symbols

A	Network connectivity matrix
i	Bus index
$I_{i,j,k}$	Current flow in the line connecting nodes i and j at iteration k
K_{pf}, K_{qf}	Active and reactive power frequency-dependency factor
$m_{p,eq}$	Equivalent power-frequency droop slope for multiple DGs
$m_{p,i}$	$P - f$ droop slope
$m_{q,i}$	$Q - V$ droop slope
N	Total number of nodes (buses)
N_{dg}	Total number of DGs
P_G, Q_G	Generated active and reactive power
P_i	Active power at DG_i
$P_{i,j,k}$	Active power flow from nodes i to j at iteration k
$P_{j,k}$	Active power injected at node j
P_{Load}, Q_{Load}	Loaded active and reactive power
$P_{Loss(i,j,k)}$	Active power loss in the line between nodes i and j at iteration k
$P_{L,j,k}$	Active power of the load connected at node j at iteration k
$P_{o,i}, Q_{o,i}$	Real and reactive load at node i at the nominal voltage and frequency
P_{total}	Total active power in the microgrid
$P_{err,k}$	Mismatch in reactive power at iteration k
Q_i	Reactive power at DG_i
$Q_{i,j,k}$	Reactive power flow from nodes i to j at iteration k
$Q_{j,k}$	Reactive power injected at node j
$Q_{Loss(i,j,k)}$	Reactive power loss in the line between nodes i and j at iteration k
$Q_{L,j,k}$	Reactive power of the load connected at node j at iteration k
Q_{total}	Total reactive power in the microgrid
r_{ij}	Resistance of the line connecting nodes i and j
$S_{i,max}$	Rating of DG_i
$S_{pivot,max}$	Rating of the DG connected to the pivot node
V	Voltage magnitude
$V_{i,k}$	Voltage magnitude at node i and iteration k
$V_{pivot,k}$	Voltage magnitude of the pivot node at iteration k
$V_{ref,i}$	Reference voltage magnitude at DG_i
x_m	Reactance of the line connecting nodes i and j
$Z_{i,j,k}$	Reactance of the line connecting nodes i and j
α, β	Voltage exponents of the active and reactive loads
$\delta_{j,k}$	Voltage angle at node j and iteration k
$\Delta\omega$	Angular frequency deviation
ρ	Share ratio
$\omega_{ref,i}$	Reference angular frequency at DG_i
$\omega_{cor,i}$	Angular frequency correction for DG_i
$\omega_{cor,k}$	Angular frequency correction at iteration k
$\omega_{err,k}$	Error in the angular frequency of the microgrid at iteration k
ω_k	Angular frequency of the microgrid at iteration k

Abbreviations

DG	Distributed generator
FBS	Forward-backward sweep
FR	Forward return
SDG	Smart distribution grid

ω^* , etc.). These operating points were input from real-time simulations (i.e., MATLAB/SIMULINK or PSCAD/EMTDC), which demand significant time for model construction and simulation and involve an excessive computational burden, thus rendering them suitable only for very small-scale microgrids. A fast, simple, expandable, accurate tool that is capable of solving the power flow problem for isolated operating mode is therefore essential for the planning [1–6]; management [10–14]; operation [15,16]; and stability analysis [6,7,9,17] of microgrids.

The power flow problem in isolated microgrids has been addressed in recent reports published in the literature. The conventional power flow approach proposed in Ref. [18] can be used in conjunction with the selection of a larger DG as a slack bus. However, this assumption becomes invalid when the practical operating strategies and constraints associated with microgrids in isolated mode are considered. In microgrids, DGs are relatively small, and none is large enough to be capable of regulating the microgrid frequency and acting as an infinite bus with a constant voltage. Although the DGs in isolated microgrids are usually controlled via decentralized droop control [6,19–22], this mode of operation is not taken into account in the conventional power flow formulation [19]. An algorithm based on a Newton trust region, which was introduced in Ref. [23], includes consideration of the distinguishable characteristics of a microgrid as a means of overcoming the limitations of conventional power flow methods. However, because this algorithm is inversion-based, with a dogleg step calculation method that uses the inverse of a Hessian matrix for calculating the steps, it hence has a time complexity of $O(n^3)$. In the case of common distribution systems, as the number of buses increases, this inversion step results in excessive increases in the solution time and thus makes the algorithm inappropriate for online applications. An additional factor is that the solution is centralized because the power flow problem is formed as an optimization problem that minimizes an error through an iterative technique. Similarly, the forward/backward sweep technique presented in Ref. [24] is based on a centralized approach with matrix-based calculations of line flows and bus voltages. These centralized approaches therefore conflict with the trend towards distributed management in SDGs. Another technique based on modified Newton Raphson was recently introduced in Ref. [25], however this technique is inversion-based and thus is similar to the NTR in terms of the computational burden. Moreover, NR techniques are derivative-based and require the formulation of the Jacobian matrix which suffers from singularity problems when applied for distribution systems [26,24]. Formulation of load flow problem as an optimization problem was presented in Ref. [27] however this approach still requires extensive computational burden and takes excessive simulation time to converge. In addition DC PF approach presented in Ref. [28] is applicable only for systems with negligible R and thus not suitable for distribution systems which are characterized by high R/X ratio. For distribution systems, branch-based power flow methods are dominant [23] but involve challenges with respect to providing solutions for systems with multiple sources (e.g., DGs) and with no conventional slack bus.

In this paper, a novel branch-based power flow technique is proposed. This power flow is capable of incorporating practical isolated microgrid operating constraints and can handle cases involving multiple DGs and droop-control operating mode. The methodology developed is derivative-free and inversion-free hence it is fast and scalable for a large number of buses with no overwhelming computational time and no diminishment in accuracy. Unlike the technique presented in Ref. [24], the proposed approach is not centralized and the methodology presented shows better convergence even with frequency-dependent load models. Moreover, the proposed algorithm decouples active and reactive power flows and hence no complex calculations are required thus the proposed algo-

(operating point) be obtained for a variety of microgrid parameters (DG ratings, droop slopes m_p and m_q , droop references V^* and

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