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Power flow modeling of islanded AC microgrids with hierarchical control

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ABSTRACT

This paper presents the power flow modeling of droop-controlled distributed generation units with secondary frequency and voltage restoration control for hierarchically controlled islanded microgrids. These models are incorporated in the conventional Newton-Raphson power flow method as a new bus, without the necessity of a slack bus, and include the gains of the control systems that influence the steady-state solution. Two case studies are addressed. In the first case study, comparisons of the proposed models against the steady-state solutions obtained with PSCAD and Simscape Power System of Simulink, where the closed-loop controls are explicitly modeled, are presented. In the second case study, the proposed method is contrasted against the droop-based approach. The results obtained exhibit low computing effort, reliability, and effectiveness of the proposed models since quadratic convergence behavior is maintained independently of the size and topology of the microgrid. Besides, it is demonstrated that hierarchical and droop controllers lead to different solutions, which confirms the necessity of including the hierarchical control in the power flow model.

1. Introduction

Microgrids (MGs) have been introduced as a groundbreaking technology to modernize the electric power systems [1–4]. Therefore, important research efforts are currently underway to develop mathematical models and techniques to evaluate and improve their performance, both in the transient and steady state [5,6]. Regarding the computation of the steady-state solution, this is not a simple task for nonlinear periodic switched networks. One way is to implement the system in professional time-domain simulation programs, such as PSCAD, Simulink, RSCAD, among others, and simulate until the transient disappears. Even though this is a direct method, it presents some drawbacks, i.e., the controller has to be stable, and the initial condition has to be within the attractor, but the controller tuning and the calculation of proper initial condition are already complicated problems in themselves. Some other techniques based on iterative processes can be used instead of only direct time domain simulation. Some of these techniques are in the time domain [7–9], frequency domain [10,11], extended harmonic domain [12,13] and hybrid domain [9]. These techniques present better convergence properties such as shorter computation time, the computation of unstable solutions, and those based on the Poincaré map give as byproduct the Floquet multipliers of the computed solution; however, these methods also have drawbacks, such as, the computational burden, the sensitivity of the correct computation of the transition matrix, among others, for more details see these references [14,15]. In power systems industry, the common way to compute the steady-state is solving the power balance equation using the Newton method [16]. As compared with synchronous generators in conventional power systems, the injected active and reactive power by the distributed generation (DG) units in microgrids are not usually known at the starting of the Newton iterations since they depend on their specific control systems [17–19]. Additionally, in the islanded operation mode, the frequency of the system can be different from the nominal and the so-called slack bus is missing [20,21]. Despite that the slack bus could be reassigned or distributed in an islanded situation, the DG unit selected as slack bus should be able to provide all the missing active and reactive power, but it could not always be possible due to their limited and not dispatchable capacity [2,22].

Microgrids control requirements and strategies to perform local balancing and to maximize their benefits have led the MGs to fulfill a wide range of functionalities, such as power flow control to avoid exceeding line capacities, voltage and frequency regulation, energy balance, among others [18,23–26]. In this way, practical MGs include hierarchical control schemes to achieve the desired operational

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requirements. Consequently, since the hierarchical controls modify the steady-state operation of the MG, they have to be included in the methods for the computation of the steady-state. Hierarchical control systems increase the difficulty of the power flow modeling since their secondary and tertiary controls change the operating points of the MGs, such that, the active and reactive power injected by the DG units differ from those injected by DG units with only droop control. Keep in mind that the tertiary control level typically operates in the order of minutes [17]. Therefore, their outputs can be considered constant in the power flow modeling; however, the operation time of the secondary control, such as the frequency and voltage restoration control, is close to the primary control operation time. Hence, the outputs of the secondary control cannot be assumed as constant inputs to the primary control. For these reasons, the power flow model must include primary and secondary controllers.

In the literature, it can be found that several authors have addressed the power flow problem for islanded droop-controlled microgrids [2,20,22,27–34]. For example, a three phase generalized power flow for islanded microgrids using a Newton trust region method is presented in [22], it takes into account the droop characteristics of the DG units and unbalances in the microgrid, furthermore, a comparison with PSCAD is performed using a six-bus MG, achieving maximum errors of 0.5% and 0.05% in phase and voltage magnitude, respectively. In [20], a modified interior point-based power flow for balanced droop based microgrids is developed, this method transforms the power flow problem into a nonlinear optimization problem increasing the size of the system to be solved due to the restrictions needed for the optimization, additionally, the algorithm does not have quadratic convergence rate. The method is compared against PSCAD using a six-bus MG, the maximum absolute error achieved is 1.689×10^{-2}; besides, the computing time needed by the method was 0.23748 s. Virtual impedances have been included in the power flow computation in [2]. A particle swarm optimization to solve the power flow problem in islanded microgrids is performed in [27], where the stability of the system is also ensured. In [28], the authors proposed the inclusion of the droop equations in the conventional power flow formulation, with the purpose of having a straightforward method that can be integrated into current commercially available power system software. Comparisons against PSCAD were presented in the paper, being the maximum voltage magnitude and phase angle error achieved of 2×10^{-4} and 8.5×10^{-3}, respectively. An AC/DC load flow algorithm for islanded microgrids taking into account the droop characteristics is presented in [29], the load flow is solved sequentially, having as subsystems the AC system and the DC system, using a modified directed forward-backward sweep method. In [30], a branch-based power flow for islanded microgrids is shown, a forward-return-forward-sweep method including droop controls is proposed in this work. In [31] a review of power flow methods for droop-based islanded microgrids is addressed, the authors compare the algorithms in terms of accuracy and convergence time, besides, a method based on particle swarm optimization is presented. Reference [33] presents a methodology to extend the conventional power flow method to islanded microgrids using a two-nested-loop iterative method. In this method, the frequency and active power are computed in the first loop, then in the second loop the reactive power and voltages are computed. This method does not report quadratic convergence rate, additionally, it only considers droop controls. The authors present a seven-bus case and the method converges in 2.065 s. A generic modeling approach for droop-controlled and isochronous MGs is presented in [32]; the authors develop models for different primary control operation schemes and unbalanced conditions; however, only includes primary controls. Recently, Ref. [34] presents a generalized microgrid power flow method for radial and weakly meshed topologies, which includes primary and secondary control schemes. The authors use a direct backward/forward sweep method, where the power flow problem is solved sequentially in a double-loop process deteriorating the convergence rate; a case study is presented, but no comparison results against other methods are performed, and only uses linear loads. Additionally, the authors state that the algorithm convergence depends on the stability of the microgrid controllers.

This paper presents the power flow modeling of the hierarchically controlled DG units with primary droop-based and secondary frequency and voltage restoration controls to cope with the problems mentioned above. The obtained models are represented as a new bus type embedded in the conventional Newton-Raphson power flow [16]. Therefore, the method maintains its quadratic convergence regardless of the microgrid topology, stability, control tunning, and its nonlinear loads. Furthermore, the method preserves explicitly the control gains that influence the steady-state solution.

One of the main issues of islanded microgrids, in the context of the power flow formulation, is that the slack bus does not exist [2]. In this regard, it is demonstrated that the frequency restoration term is related to the bus phase angle where the secondary control regulates the voltage. Consequently, this phase angle becomes the reference angle for the DG units, thus, the slack bus is not needed, but all the units (grid-forming units) participate in sharing the injected power according to the hierarchical control. This feature is a fundamental advantage because it avoids the use of an adaptive slack bus [34] or the fixing of a bus phase angle to zero [2]. The steady-state solutions obtained with the proposed Newton-Raphson based power flow are compared against the steady-state solutions obtained with time-domain implementations in industrial electromagnetic transient simulation programs.

The paper is organized as follows: Section 2 describes the hierarchical control considered for the proposed power flow formulation. Section 3 introduces the formulation of the proposed power flow model which includes the primary droop control and the secondary frequency and voltage restoration control. Section 4 describes the microgrid used as the test system. Section 5 outlines the case studies and presents results obtained. Finally, Section 6 provides the conclusions of this work.

2. Hierarchical control

In order to operate the microgrid in a controlled manner, a two-level hierarchical control scheme is included [18]. The scheme is composed by a local primary control, a secondary control for frequency and voltage restoration, and a synchronous reference frame phase-locked loop (SRF-PLL) [35] for measuring the voltage magnitude ($|V_m|$) and frequency (ω_m) of the m-th bus of the system, as seen in Fig. 1.

The primary control level, which is modeled in the dq-reference frame, is responsible for performing the grid-forming function, and its structure is shown in Fig. 2. This level consists of a conventional droop control, in which, the active and reactive power contribution of the n-th DG unit depends on the frequency/active power (P-ω) and voltage/reactive power (Q-V) droop characteristic curves, respectively, being expressed as [36],

$$\omega_n = \omega^{*} - K_n^{p} P_n \tag{1}$$

$$|V_n| = |V_n^{*}| - K_n^{q} Q_n \tag{2}$$

where ω^{*} is the nominal angular frequency of the system, $|V_n^{*}|$ is the

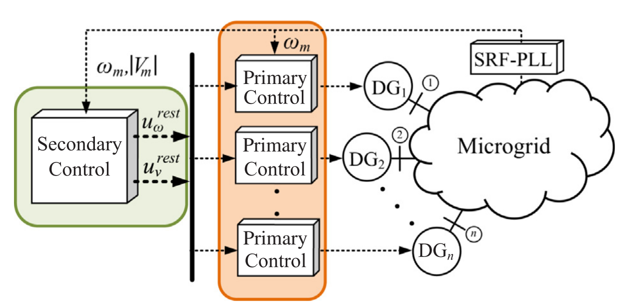

Fig. 1. Hierarchical control scheme.