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Economic droop parameter selection for autonomous microgrids including wind turbines

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ABSTRACT

Droop control is a key strategy for operating islanded microgrid systems. The droop settings of the different distributed generation (DG) units in an islanded microgrid determine the operational characteristics of the island. This paper presents an algorithm for choosing the optimal droop parameters for islanded microgrids with wind generation in order to minimize the overall island generation costs in the absence of a microgrid central controller (MGCC). A detailed microgrid model is adopted to reflect the special features and operational characteristics of droop controlled islanded microgrid systems. The proposed problem formulation considers the power flow constraints, voltage and frequency regulation constraints, line capacity constraints and unit capacity constraints. Numerical case studies have been carried out to show the effectiveness of the proposed algorithm as compared to conventional droop parameter selection criteria typically adopted in the literature.

1. Introduction

The widespread implementation of the distributed generation (DG) concept is creating regions within the electrical distribution network with enough generation capacities to meet all or most of its local loads [1,2]. Such regions are defined as microgrids. The recent IEEE Standard 1547.4 [2] depicts the main features of a microgrid system as 1) capable of operating in parallel to the main grid (i.e. grid-connected mode) or autonomously in isolation from the main grid (i.e. islanded or autonomous mode) and 2) of a configuration that is intentionally planned prior to the isolation incident [3]. The islanded operation of microgrid systems can bring several benefits to the distribution utilities and to the customers. Such benefits include: 1) improving customers' reliability, 2) resolving overload problems, 3) resolving power-quality issues, and 4) allowing for maintenance of system components without customers interruption. Such benefits can motivate an increased operation of microgrid systems in islanded mode. Hence the connection between a microgrid and its upper stream main grid might be arbitrary open [2]. Consequently, given the expected increase in the time span of islanded microgrid operation a thorough consideration of the islanded operational planning is mandated.

In the grid-connected microgrid mode of operation, DG units' generation is controlled to supply a pre-determined amount of active and/or reactive power required for the fulfilment of a pre-specified system requirement (e.g., peak shaving, exporting power to the main grid, etc.). Any difference between the microgrid total demand and the active and reactive generation by the DG units is absorbed or supplied by the main grid. Thus the frequency and voltage regulation at the different system buses can be accomplished. Accordingly, similar to conventional distribution systems, the DG units in grid-connected microgrid systems can be controlled and modelled as PV or PQ buses [3,4]. In this case, the DG units' output voltage reference is often taken from the grid voltage sensing via a phase-locked-loop (PLL) circuit, while an inner current loop ensures that the DG unit acts as a current source fulfilling its required function. On the other hand, in islanded microgrid mode of operation, given that the main grid is not available, the generation of the DG units within the island cannot be predetermined and must achieve real-time response to ensure that the microgrid generation is equal to its demand. Moreover, in the islanded microgrid mode of operation, the task of controlling the system voltage and frequency is shared by the DG units forming the island [5].

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A power electronic converter is usually adapted to interface DG resources to islanded microgrid systems [3–5]. The accommodation of such converters within the requirements of the islanded microgrid operation is usually achieved in the literature through one of two operational paradigms, namely Master/slave or decentralized droop control schemes. Master/slave control schemes use high bandwidth communication links to exchange dynamic power sharing signals between a master DG unit (or multiple master DG units) and the other DG units in the islanded microgrid. In most cases, such schemes are found to be costly because of the high bandwidth communication that it requires. Moreover, such schemes are unreliable as it depends on the communication links in its operation [3,4]. On the other hand, droop control is based on using locally measured quantities to control the DG units in a way that mimics the behaviour of synchronous generators operating in parallel. Droop control is capable of achieving appropriate sharing of the islanded microgrid demand among the different DG units using only local signals and without mandating the existence of a communication infrastructure.

The settings of the different DG units' droop characteristics affect their steady-state active and reactive power generation when operating in the islanded microgrid mode of operation [4]. The conventional approach adopted in the literature to choose the DG units' droop based on the DG units rated capacities [1–4]. Generally, such conventional approach can provide a near exact active power sharing between DG units in proportion to their rated capacities. Nonetheless, the settings based on the rated capacity fail to satisfy other system operational constraints; where 1) it does not optimize the operation in regards to minimizing the system generation costs [6–10], 2) it cannot achieve an exact reactive power sharing between the DG units i.e., mismatches in the power line impedances lead to large circulating reactive power and 3) it can only satisfy the voltage regulation constraints at the DG units' PCC. Voltage drops along the feeders can still result in voltage constraints violation at other load points in the island.

In the literature, different methods have been proposed to optimally choose the DG units droop characteristics in a way that overcome the aforementioned drawbacks [6–10]. In Refs. [6,7] the droop characteristics are optimized in a way that minimizes the island fuel consumption. Nonetheless, the work in Refs. [6,7] suffered from the drawback of not considering system voltage and frequency regulation constraints as well as the network losses. In Ref. [8] a multistage optimization algorithm was presented to overcome these drawbacks by minimizing the islanded microgrid fuel consumption while taking into consideration the system losses and operational constraints. In Refs. [9,10], emissions were minimized alongside the system fuel consumption. Nevertheless, the previous work in the literature; proposed to optimally choose the droop characteristics, assumed the existence of a microgrid central controller (MGCC) and a non-critical low bandwidth communication infrastructure [5–11]. In such scenario, a higher level central coordinated management function at the MGCC performs the required optimization of the islanded microgrid droop characteristics. By receiving periodic measurements of the island available generation and required demand, the MGCC periodically updates the DG units' droop characteristics in a manner that achieves optimal dispatch of the DG units in the system. Accordingly previously proposed techniques in the literature alleviated the need for considering the stochastic nature of the microgrid renewable generation and demand in the choice of the optimal droop characteristics by presupposing the existence of a MGCC and a noncritical communication infrastructure and hence allowing for a periodic update of the droop characteristics depending on the varying generation and demand. However, for microgrids in remote areas; with long connection distance between DG units, the operation without a MGCC is still the viable solution [11]. In these scenarios, no periodic updating of the DG units droop settings will take place, and they must be designed offline to account for all the states in which the islanded system may exist. To the authors' best knowledge the problem of optimally choosing the droop settings for the different DG units in an islanded microgrid operating in the absence of a MGCC has not been previously addressed in the literature.

Based on these considerations, this paper proposes a new probabilistic analytical approach to optimally choose the droop characteristics of the different DG units in an islanded microgrid in order to minimize its operational costs in the case of the unavailability of a MGCC taking into consideration the intermittent nature of wind DG units and the load variability; under the islanded microgrid paradigm. To this end, the proposed approach adapts a microgrid model that reflects the special features of droop controlled islanded microgrid operation as well as an analytical generation load model to describe all the possible islanded microgrid states and their respective probabilities. The remainder of this paper is organized as follows; Section 2 presents the droop controlled islanded microgrid model that reflects its special philosophy of operation. In Section 3, a probabilistic load-generation model that incorporates the stochastic nature of droop controlled islanded microgrid components is introduced. The models presented in Sections 2 and 3 are then used in formulating the proposed approach in Section 4. Section 5 presents the numerical results that verify the effectiveness of the proposed approach. Finally, Section 6 concludes the paper and summarizes its findings.

2. Droop controlled islanded microgrid modelling

In a droop control structure, active power sharing is achieved by drooping the frequency of the output voltage of the DG unit as the active power generated by the DG unit increases. Similarly, the magnitude of the output voltage of the DG unit is drooped as the reactive power generated by the DG unit increases [4]. Accordingly, for a droop controlled DG unit connected to the ith bus, the DG output voltage frequency, ω, and magnitude $|V_i|$, can be given as follows:

$$\omega = \omega_i^* - m_{\text{pi}} \times P_{\text{Gi}} \tag{1}$$

$$|V_i| = |V_i|^* - n_{\text{qi}} \times Q_{\text{Gi}} \tag{2}$$

where ω_i^* and $|V_i|^*$ are the droop controlled DG unit output voltage frequency and magnitude at no-load, respectively, m_{pi} and n_{qi} are the active and reactive power static droop gains, respectively, and P_{Gi} and Q_{Gi} are the injected active and reactive power by the DG unit, respectively. Equations (1) and (2) show that droop characteristics can provide a means of negative proportional feedback that controls active and reactive power sharing in the island. The negative feedback relation in (1) also guarantees that all of the DG units are producing voltages with the same steady-state angular frequency [3,4].

The representation of droop controlled islanded microgrids steady-state operation differs from that of conventional distribution system in three main points; 1) in the islanded mode, DG units' representation has to reflect its droop characteristics. Hence the DG generation cannot be pre-specified and is controlled by the DG droop characteristics. This is different from conventional distribution system were the DG units are usually represented as PQ or PV buses, 2) in the islanded microgrids the DG units forming the island are all of small and comparable sizes and there is no one DG unit that is capable of performing the slack bus function. This is different