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Fuel-saving benefit analysis of islanded microgrid central controllers

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ABSTRACT

The operation of microgrids in islanded mode brings numerous benefits to both customers and utilities. Because of the special characteristics of islanded microgrid (IMG) operation, robust control schemes are required to provide reliable service and help achieve customer-driven objectives. To that end, several previous works emphasized the importance of implementing a supervisory microgrid central controller (MGCC), while others showed that from the technical perspectives there is no real need for the implementation of such costly controllers. Evaluating the benefits of implementing a MGCC is thus a key point that microgrid designers need to appropriately analyze. To this end, this paper proposes a probabilistic analytical approach for evaluating the fuel-saving benefit that a supervisory MGCC can bring to the operation of IMG systems taking into consideration the intermittent nature of renewable energy resources and the loads variability as well as the special features and operational philosophy of droop controlled IMG systems.

1. Introduction

Driven by an urgent need to develop cleaner and more efficient and reliable power grids, the electric power distribution networks are currently moving toward accommodating higher penetration levels of renewable and distributed generation (DG) units [1]. The increased application of DG technologies is creating microgrids, within distribution networks, with sufficient generation capacities to feed most or all of their entire local loads [2]. The recent IEEE standard 1547.4 defines additional characteristics of the functionality of microgrid systems such as being intentionally planned and their capability of operating in grid-connected and islanded modes. In the grid-connected mode of operation, the DG units forming the microgrid are controlled to supply a pre-specified amount of active and/or reactive power in order to achieve a specific set of system requirements. In this mode, the main grid delivers or absorbs the difference between the microgrid's generation and demand and it acts in a way that provides a means of controlling the system frequency and voltage profile. In the islanded mode of operation, however, a set of unprecedented challenges in terms of controlling the islanded microgrid (IMG) voltage and frequency and achieving an appropriate sharing of the load demand among the DG units forming the island is introduced.

Droop-based control scheme is the primary control that is widely implemented to mitigate the operational challenges of IMG without communication [2–4]. The majority of DG units in microgrids are interfaced through a voltage-source converter coupled with a passive output filter [3,4]. By controlling the interfacing converters of the DG units in order to mimic the intrinsic behavior of synchronous generators operating in parallel, droop control could attain appropriate sharing of the load demand among the different DG units in the island and controls the IMG voltage and frequency regulation. The settings of the droop parameters implemented for the individual DG units in the island influence their output steady-state active and reactive power generation [5,6]. Originally, it was recommended to operate IMG in a decentralized control mode using solely local measurements at the DG units' point of common coupling (PCC) without communication. Under this paradigm, the droop characteristics of the individual DG units are designed offline, for a possible operational planning horizon, in order to minimize the cost of operation [7] or to share the load demand in proportion to the DG units' rated capacities [8]; i.e., no real-time updates of the DG units droop characteristics take place in this paradigm. Alternatively, the IMG operation can be complemented by the deployment of a microgrid central controller (MGCC) accompanied by a non-critical low-bandwidth communication infrastructure [9,10]. In the latter paradigm, periodic measurements of the IMG generation and

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Nomenclature

Acronyms
DG distributed generation
IMG islanded microgrid
MCS Monte Carlo simulation
MGCC microgrid central controller
OPF optimal power flow
PCC point of common coupling
PDF probability density function

Indices
i, j, k index of system buses
st index of states parameters
$C_j(.)$ fuel consumption rate for the DG unit connected to the jth bus as a function of its active power generation
n_{states} number of islanded microgrid states
P_{Li}, Q_{Li} active and reactive nominal load power at bus i, respectively
$S_{Gi,\max}$ apparent power generation capacity at bus i
$S^{st}_{\text{loss\&spare}}$ apparent power loss and spare capacity requirements for islanded microgrid operating at state st
$v_{\min,st}$, $v_{\max,st}$ wind speed limits of state st
ρ^{st}_G, ρ^{st}_L, ρ^{st}_{IMG} probability of generation, load, and combined states, respectively
ρ^{st}_{wind} probability of a wind state st
σ_j fuel price for the DG unit connected to the jth bus

Sets
B set of all system buses
B_{droop} set of all droop-controlled buses in the system
N^{st}_G, N^{st}_L, N^{st}_{IMG} set of all possible generation, load, and combined generation-load states, respectively

Variables
I^{st}_{ik} magnitude of the current flowing in the line between buses i and k when operating in islanded microgrid at state st
m_{pi}, n_{qi} active and reactive power static droop gains for droop-controlled DG unit at bus i, respectively
P_{Gi}, Q_{Gi} generated active and reactive power at bus i, respectively
$P_{Gi,\max}$, $Q_{Gi,\max}$ active and reactive power generation capacities at bus i, respectively
$|V_i|^*$, ω^*_i no-load output voltage magnitude and frequency of droop-controlled DG unit at bus i, respectively
$|V_i|$, δ_i voltage magnitude and angle at bus i, respectively
x unknown droop setting variables for all droop-controlled DG units in the system
x_j unknown droop setting variables for the droop-controlled DG unit at bus j
$|Y_{ik}|$, θ_{ik} frequency-dependent Y-bus admittance magnitude and angle, respectively
ω steady-state frequency of droop-controlled DG units output voltages

load are sent to a MGCC. Using these measurements, the MGCC periodically performs a higher level management function by solving an IMG optimal power flow problem and consequently updates the individual DG units droop characteristics to optimally dispatch the different DG units in the island.

The operation of droop controlled IMGs, with or without MGCCs, has been extensively investigated in the literature. In [3,4], the operation of IMGs without MGCC was examined in order to ensure that the DG units in the island share the overall demand in proportion to their respective capacities. The impacts of voltage and reactive power constraints on the operation of IMGs in the absence of MGCCs were investigated in [11]. The work in [5] discussed the optimal operational control of IMGs lacking a MGCC in order to minimize the expected customer interruptions. In [12,13] a MGCC has been used to minimize the overall IMG fuel consumption without considering the system operational constraints. In [9] a MGCC multi-stage optimization algorithm has been presented to minimize the fuel consumption of droop controlled IMGs while accounting for system losses, reactive power requirement, as well as voltage and frequency operational constraints. Similarly, in [10,14] different algorithms have been presented for the operation of IMG systems using MGCCs to minimize the IMG's harmful gases emissions along with the islanded system fuel consumption. In [15], a centralized optimal VAR scheduling algorithm has been developed with the consideration of DG units' voltage droop control as well as the uncertainty of wind farms. Similarly, another algorithm for proportional reactive power sharing has been proposed in [16]. In [17] an algorithm was presented for the determination of the optimal droop settings for an IMG in terms of minimizing the system losses when a MGCC is present.

Despite the volume of literature on IMG operation, to the authors' best knowledge the problem of evaluating the fuel-saving benefit that a MGCC will bring to the IMG operation has not been previously addressed. As shown in the aforementioned literature survey, the operation of IMGs can be technically and economically feasible with or without a MGCC. Performing a fuel saving benefit evaluation is thus crucial in determining the economic viability of installing a MGCC as well as its anticipated impact on the IMG economics. Hence, this paper proposes a probabilistic approach for evaluating the fuel-saving benefit of installing a MGCC. The proposed approach accounts for the special features and operational philosophy associated with droop-controlled IMG systems, and the stochastic nature of loads and renewable DG systems. The proposed approach can be an effective and powerful tool, for IMG planners and operators, in deciding whether to install a MGCC. The remainder of this paper is organized as follows: Section 2 presents the modeling of droop-controlled IMG systems to account for its special operational philosophy as well as the stochastic nature of its generation and demand. The proposed fuel-saving benefit evaluation approach is introduced in Section 3. Section 4 provides the simulation results for a variety of case studies that demonstrate the significance and effectiveness of the proposed approach. Section 5 concludes the paper and summarizes its main contributions.

2. Droop-controlled IMG modeling

The accurate evaluation of the fuel-saving benefit that a MGCC can bring to the IMG operation should take into consideration: 1) the special features and operational philosophy of IMG systems, and 2) the stochastic nature of both the IMG generation and loads. This section presents the details of the IMG modeling adopted in this work to facilitate the proposed study:

2.1. Steady-state model

In droop control structure, active power sharing is attained through drooping the output voltage frequency as the active power generated by the droop-controlled DG unit increases. Similarly, the output voltage magnitude of the DG unit is drooped as the reactive power generated by the DG unit increases [8]. Accordingly, for a droop-controlled DG unit connected to bus i, the DG output voltage frequency, ω, and magnitude, $|V_i|$, can be given as:

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