Optimum Droop Parameter Settings of Islanded Microgrids With Renewable Energy Resources

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***Abstract*—Droop control is a key strategy for operating distributed generation (DG) islanded systems, i.e., islanded microgrids (IMGs). The droop parameter settings of the DG units can significantly impact the ability of an IMG to feed its demand. This paper proposes a new probabilistic algorithm for determining the optimum choice for such droop settings for the individual DG units in a distribution network in cases when a microgrid central controller is unavailable. The proposed algorithm adopts a constraint hierarchy approach to enhance the operation of IMGs by satisfying the operational constraints of the system and expanding its loading margin. The new algorithm takes into consideration the variety of possible IMG configurations that can be initiated in a distribution network (multi-microgrids), the uncertainty and variability associated with the output power of renewable DG units as well as the variability of the load, and the special features and operational philosophy associated with droop-controlled IMG systems. Simulation studies show that the proposed algorithm can facilitate the successful implementation of the IMG concept by reducing the customer interruptions and enhancing the IMGs' loadability margins.**

***Index Terms*—Droop control, hierarchy constraints, islanded microgrid (IMG), renewable resources, voltage regulation and security.**

NOMENCLATURE

A. Acronyms

DFIG	Doubly fed induction generator.
DG	Distributed generation.
DNO	Distribution network operator.
IID	Island isolation device.
IMG	Islanded microgrid.
LIB	Limit-induced bifurcation.
MCS	Monte Carlo simulation.
MGCC	Microgrid central controller.
PCC	Point of common coupling.
PDF	Probability density function.
SNB	Saddle node bifurcation.

B. Functions

$eC_p(.)$	Error function of the preferred constraint level p in a given constraint hierarchy C.
$F^{(\mathrm{is,st})}(.)$	Power flow equations of islanded microgrid "is" at state "st."
$f(.)$	Distribution probability of wind speed.

C. Indices

i, j, k	Index of system buses.
is	Index of islanded microgrids.
ℓ	Index of system loading points.
p	Index of preference level in a constraint hierarchy.
st	Index of states.

D. Parameters

n_{bus}	Number of system buses.
n_{levels}	Number of constraint hierarchy levels of preference.
n_{MG}	Number of possible islanded microgrids in the system under study.
$n_{\mathrm{states}}^{(\mathrm{is})}$	Number of islanded microgrid "is" 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.
$S_{\text{loss \& spare}}^{(\mathrm{is,st})}$	Apparent power loss and spare capacity requirements for islanded microgrid "is" operating at state "st."
$v_{\mathrm{st,min}}$, $v_{\mathrm{st,max}}$	Wind speed limits of state "st."
$\Gamma^{(\mathrm{is,st})}$	Parameter indicating the priority of islanded microgrid "is" at state "st."
$\Gamma_i^{(\mathrm{is,st})}$	Parameter indicating the priority of load point i when operating in islanded microgrid "is" at state "st."
$\lambda_{\mathrm{ub}}^{(\mathrm{is,st})}$	Upper bound on the loading factor of islanded microgrid "is" at state "st."
$\rho_{\mathrm{st}}^G, \rho_{\mathrm{st}}^L, \rho_{\mathrm{st}}$	Probability of generation, load, and combined states, respectively.

E. Sets

B	Set of all system buses.
$B^{(\mathrm{is})}$	Set of all buses in islanded microgrid "is."
B_{droop}	Set of all droop-controlled buses in the system.
$B_{\mathrm{droop}}^{(\mathrm{is})}$	Set of all droop-controlled buses in islanded microgrid "is."
C_0	Set of mandatory constraints in a given constraint hierarchy C.
C_p	Set of preferred constraints of p preference level in a given constraint hierarchy C.
N_{st}^G, N_{st}^L, N_{st}	Set of all possible generation, load, and combined generation-load states, respectively.

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Z_0 Set of all admissible solutions to a constraint hierarchy.

Z_p Set of all constraint hierarchy solutions that satisfy constraints up to and including level p.

F. Variables

$h^{(\text{is,st})}$ Vector of state variables of islanded microgrid "is," operating at state "st" including system frequency, voltage magnitudes, and angles.

$I_{ik}^{(\text{is,st})}$ Magnitude of the current flowing in the line between the buses i and k when operating in islanded microgrid "is" 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.

$|V_i|^*, \omega_i^*$ No-load output voltage magnitude and frequency of droop-controlled DG unit at bus i, respectively.

$|V_i|, \delta_i$ Voltage magnitude and angle at bus i, respectively.

$\Delta V_i^{(\text{is,st})}$ Binary variable indicating the voltage regulation status of load point i when operating in islanded microgrid "is" at state "st."

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.

z Solution of constraint hierarchy.

ω Steady-state frequency of droop-controlled DG units output voltages.

$\lambda^{(\text{is,st},\ell)}$ Loading factor of islanded microgrid "is" at state "st" for loading point ℓ.

I. Introduction

DRIVEN by the urgent need to develop cleaner and more efficient, reliable, resilient, and responsive power grids, the energy sector is currently moving toward an era of smart grids [1]. The main pillar of a smart grid setup is the evolution from a vertically integrated electric power network to a decentralized one that enables interactions among customers, network operators, and power producers. In response to smart grid initiatives, the distribution systems are undergoing a major transition to active distribution systems with a high penetration of distributed and renewable energy resources [2]. Active distribution systems will be clustered into a new set of management layers based on a microgrid structure, which is considered as the building block of future active distribution systems [3], [4]. A typical microgrid configuration is formed of a cluster of loads and distributed generation (DG) units connected to a distribution network [5]–[7]. The microgrids will provide several benefits for the utilities and customers, the most important of which is the increased reliability for microgrid customers. During upstream disturbances, the microgrids can be isolated from the main grid in order to maintain the continuity of electric power service. The majority of DG units in microgrids are interfaced through a voltage–source converter coupled with a passive output filter [8], [9]. In an islanded microgrid (IMG) operating mode, these DG units are responsible for maintaining the system voltage and frequency while sharing the load demand. The literature includes descriptions of two proposed operational schemes for controlling such DG units operating in IMGs: centralized and droop control schemes [9], [10]. Dependent on the availability of high-bandwidth communication links, a centralized control scheme is usually found to be 1) impractical and costly because it requires the distribution of high-bandwidth dynamic sharing signals among the DG units that form the IMG and 2) unreliable due to the single point of failure associated with the use of a centralized control approach. These limitations can be overcome through a decentralized droop control scheme that depends on locally measured signals without high-bandwidth communication links for achieving appropriate sharing of the load demand while still controlling the voltage and frequency of the IMG.

In IMGs, droop-controlled DG units are controlled so that they mimic the droop characteristics of synchronous generators operating in parallel. The settings of the droop characteristics for the individual DG units thus affect their steady-state active and reactive power generation. Conventionally, the droop characteristics are designed so that the DG units forming the IMG share the load demand in proportion to their rated capacity [11]. Generally, such conventional droop settings are capable of providing nearly exact active power sharing among DG units in IMGs. Nonetheless, these settings might not satisfy other system operational requirements, where the reactive power sharing between the DG units is inexact and dependent on the system parameters; i.e., mismatches in the power line impedances can lead to high levels of circulating reactive power. Also, conventional droop settings can ensure voltage regulation at the DG units' points of common coupling (PCCs); however, a voltage violation might occur at some load points due to voltage drops along the feeders, and previous work [12] has shown that the voltage and reactive power constraints have a significant impact on the successful operation of IMGs. A final factor is that the conventional droop settings fail to take into consideration the system's maximum loadability which is a key consideration in the case of IMGs because the system is fed from a group of small DG units with limited capacities.

In the literature, several researchers have proposed methods for the optimal selection of DG units' droop parameter settings in order to enhance the droop-controlled IMG operation [13]–[18]. However, these methods presuppose the existence of a microgrid central controller (MGCC) and a noncritical low-bandwidth communication infrastructure to complement the droop control scheme. In this paradigm, the optimization of the IMG operation is performed centrally by a higher level coordinated management function at the MGCC. Using periodic measurements of the IMG generation and loads, the MGCC updates the DG unit droop settings (i.e., characteristics) in order to optimally dispatch the different DG units in the IMG.

Nevertheless, the operation of IMGs without an MGCC is still a viable solution in a number of scenarios [12], the most critical