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Stabilizing plug-and-play regulators and secondary coordinated control for AC islanded microgrids with bus-connected topology

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HIGHLIGHTS

- Distributed control scheme for guatanteeing stability in Islanded microGrids (ImGs).
- Modular procedure for designing Plug-and-Play controllers in bus-connected ImGs.
- Automatized update of the primary layer when units plug in/out. Stability ensured.
- Definition of a secondary layer for bus voltage tracking and reactive power sharing.
- Feasibility of the proposed control design framework validated through experiments.

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ABSTRACT

This paper presents a distributed hierarchical control architecture for voltage and frequency stabilization and reactive power sharing in AC islanded microgrids. In the primary control layer, each generation unit is equipped with a local regulator for voltage and frequency stability acting on the corresponding voltage-source converter. Following the plug-and-play design approach previously proposed by some of the authors, whenever the addition/removal of a distributed generation unit is required, feasibility of the operation is automatically checked by designing local controllers through convex optimization. The update of the voltage-control layer, when units plug-in/-out, is therefore automatized and stability of the microgrid is always preserved. Moreover, local control design is based only on the knowledge of parameters of power lines and it does not require to store a global microgrid model. In this work, we focus on islanded microgrids with bus-connected topology and enhance the primary plug-and-play layer with local virtual impedance loops and secondary coordinated controllers ensuring bus voltage tracking and reactive power sharing. In particular, the secondary control architecture is distributed, hence mirroring the modularity of the primary control layer. We validate primary and secondary controllers by performing experiments with both linear and nonlinear loads, on a setup composed of three bus-connected distributed generation units. Most importantly, the stability of the microgrid after the addition/removal of distributed generation units is assessed. Overall, the experimental results show the feasibility of the proposed modular control design framework, where generation units can be added/removed on the fly, thus enabling the deployment of virtual power plants that can be resized over time.

1. Introduction

Islanded microGrids (ImGs) are autonomous energy systems composed of the interconnection of Distributed Generation Units (DGUs) and loads. In view of their capability of supplying loads in absence of a connection to the main grid, ImGs provide a flexible solution for bringing power to remote areas or islands [1–7]. The growing interest in ImGs is also motivated by microgrids that normally operate in *grid-connected* mode and that can transfer to *islanding* mode for two main reasons [8]. The first one is the so-called preplanned islanded operation, i.e. if any events in the main grid are presented (such as long-time voltage dips or general faults among others), islanded operation must

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Nomenclature

DGU	Distributed Generation Unit
ImG	Islanded microGrid
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LMI	Linear Matrix Inequality
PCC	Point of Common Coupling
PI	Proportional Integral
PMS	Power-Management System
PnP	Plug-and-Play
PoL	Point of Load
QSL	Quasi Stationary Line
RMS	Root Mean Square
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VSC	Voltage-Source Converter
C_{ti}	shunt capacitance of the *i*-th VSC
$\mathscr{E}$	set of the edges of the graph associated with the ImG
e_{ij}	edge of the graph associated with the ImG
$\mathscr{G}$	graph associated with the ImG
I_i	current flowing through the power line connecting PCC *i* to the PoL in a bus-connected ImG
I_{ij}	current flowing through the power line connecting PCCs *i* and *j* in a load-connected ImG
I_L	current absorbed by the common load in a bus-connected ImG
I_{Li}	current absorbed by the *i*-th local load in a load-connected ImG
I_{ti}	output current of the *i*-th VSC
K_i	matrix gain of the *i*-th PnP controller
K_{IQ}	integral coefficient of the coordinated control scheme for reactive power sharing
K_{IV}	voltage proportional coefficient of the coordinated control scheme for voltage tracking at the PoL
$K_{I\phi}$	phase integral coefficient of the coordinated control scheme for voltage tracking at the PoL
K_{PQ}	proportional coefficient of the coordinated control scheme for reactive power sharing
K_{PV}	voltage integral coefficient of the coordinated control scheme for voltage tracking at the PoL
$K_{P\phi}$	phase proportional coefficient of the coordinated control scheme for voltage tracking at the PoL
L_i	inductance of the power line connecting PCC *i* to the PoL in a bus-connected ImG
L_{ij}	inductance of the power line connecting PCCs *i* and *j* in a load-connected ImG
$L_{i,v}$	virtual inductance of the *i*-th VSC
L_{ti}	filter inductance of the *i*-th VSC
N	number of DGU in the microgrid
$\mathscr{N}_i$	set of neighbors of DGU *i*
Q_i	reactive power injected by the *i*-th VSC
R_i	resistance of the power line connecting PCC *i* to the PoL in a bus-connected ImG
R_{ij}	resistance of the power line connecting PCCs *i* and *j* in a load-connected ImG
$R_{i,v}$	virtual resistance of the *i*-th VSC
R_{ti}	parasitic filter resistance of the *i*-th VSC
T_{IQ}	integral time constant of the coordinated control scheme for reactive power sharing
T_{IV}	voltage integral time constant of the coordinated control scheme for voltage tracking at the PoL
$T_{I\phi}$	phase integral time constant of the coordinated control scheme for voltage tracking at the PoL
T_i	time constant of the approximate first-order transfer function describing the *i*-th DGU equipped with PnP regulator
$\mathscr{V}_{DGU}$	vertex set of the graph associated with the ImG
V_i	*i*-th controlled voltage
$V_{i,v}$	voltage output of the *i*-th virtual impedance loop
$V_{PCC,i}$	voltage at the *i*-th PCC
V_{PoL}	average of the estimated voltage amplitudes at the PoL
V_{ti}	voltage command input to the *i*-th VSC
Z_i	impedance of the power line connecting PCC *i* to the PoL in a bus-connected ImG
Z_{ij}	impedance of the power line connecting PCCs *i* and *j* in a load-connected ImG
ΔV_i^Q	voltage output of the *i*-th coordinated control scheme for reactive power sharing
ΔV_{PoL}	voltage output of the coordinated control scheme for voltage tracking at the PoL
$\Delta\phi_{PoL}$	phase output of the coordinated control scheme for voltage tracking at the PoL
μ_i	gain of the approximate first-order transfer function describing the *i*-th DGU equipped with PnP regulator
τ_i	approximate time delay induced on the *i*-th estimate of the PoL voltage by the output impedance of VSC *i*
ϕ_{PoL}	average of the estimated phases of the voltage at the PoL
ω_0	nominal angular frequency of the grid

be started. This can be done by disconnecting the microgrid from the main grid by means of a static transfer switch. As this is a decision taken by the microgrid, it can be safe. The second cause of switch from grid-connected to islanding mode is the non-planned islanded operation: if there is a blackout due to a disconnection of the main grid, the microgrid should be able to detect this fact by using proper algorithms, otherwise it could damage other equipment or injury people that is arranging the grid “upstream”.

From a practical point of view, ImGs find application as parallel Uninterruptible Power Supply (UPS) systems, in which modular UPS systems can operate in parallel, thus requiring accurate power sharing and good level of frequency/voltage regulation [9]. Another example of real-world application for ImGs is the parallel operation of battery-based inverters, also named line-interactive UPS systems [10,11]. These units (whose interconnection forms an ImG) can be very far way one from the other; in this case, power sharing is necessary to avoid the discharge of a battery unit over another.

Self-sufficient and flexible generation islands also promote the deregulation of the energy market and they have been advocated as a key component of future smart power systems [12].

One of the key issues of ImGs is scalability, i.e. how to add and remove DGUs without compromising the safe operation of the whole system. This problem is not trivial, as voltage and frequency stability must be guaranteed by regulating the Voltage-Source Converter (VSC) of individual DGUs. Furthermore, in order to make online computations grow nicely with the ImG size, decentralized control architectures (where each DGU is equipped with a local regulator) must be used [13–15]. Since each local controller measures variables of the corresponding DGU only, the plugging-in or -out of a DGU can easily destabilize the whole ImG if the control layer is not properly updated [16]. In order to overcome this critical issue, in [1,16] the authors present a methodology for designing local primary regulators to allow Plug-and-Play (PnP) operations [17,18] while preserving voltage and frequency stability of the overall ImG. The PnP approach has several advantages in terms of safety and scalability. First, if a DGU issues a plug-in/unplugging request, a local automatic test (involving only the