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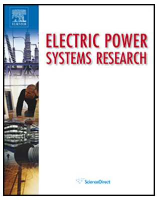

Supplementary mechanisms for smooth transition between control modes in a microgrid[☆]

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ABSTRACT

Performance requirements and/or operational integrity of a microgrid subject to major changes, e.g., transition from a grid-connected to an islanded condition, transfer switch operation within the microgrid, or control communication failure, can necessitate the controllers (or a subset of them) to change their modes of operation, e.g., P/Q mode to V/f mode. Transfer in the control mode can further exacerbate the transients due to the original disturbance. This paper proposes mechanisms for smooth transition between control modes. Emphasis of the reported work is on control mode change subsequent to (1) grid-connected to islanded condition and (2) control communication failure. The proposed mechanisms are based on (1) an observer (or state estimator) and (2) an auxiliary tracking controller. The effectiveness of the proposed mechanisms are investigated based on digital time-domain studies in the PSCAD/EMTDC environment and verified in an RTDS-based hardware-in-the-loop platform.

1. Introduction

In an interconnected power system, each controller of a classical generation unit has a prespecified mode and performs a specific control function, irrespective of possible changes in the system [1]. To the contrary, controllers of a DER unit of a microgrid may need to assume multiple modes, i.e., voltage/frequency instead of real/reactive power control, either to enable an acceptable microgrid performance or even to ensure integrity of the microgrid operation [2–4]. The reasons are:

- Multiple microgrid operating conditions, i.e., grid connected, islanded, and transition between the two,
- Presence and significant changes in the amount and/or location of non-dispatchable generation in a microgrid,
- Inherent susceptibility of the microgrid to significant and abrupt changes in the amount and/or location of loads,
- Inherent susceptibility of the microgrid to major changes in the (1) configuration, e.g., due to the operation of a transfer switch, or (2) amount/location of dispatchable resources,
- Proliferation of sensing, monitoring, and information and communication technologies (ICTs) in the legacy distribution system that enables new control strategies and functionalities.

These have resulted in a significant effort in the development of various micrograde control strategies, concepts, and the associated technologies [5–11]. Regardless of the adopted microgrid control strategy, a microgrid controller must exhibit an adequate degree of robustness [12,13], to accommodate a wide range of possible changes in the microgrid due to (1) operation condition (grid-connected/islanded) changes, (2) load changes, (3) generation changes, (4) configurational variations, and (5) communication failures when the controller relies on signal communications. Based on the decentralized robust control strategy of [12,13] that envisions more than one control mode for a DER unit, this paper proposes supplementary mechanisms to ensure smooth transfer from one control mode to another with emphasis on the (1) transition from the grid-connected mode to the islanded mode, and (2) failure or unavailability of the communication.

Transition between a grid-connected condition and an island condition is either planned, e.g., due to an operational requirement or a market signal, or accidental, e.g., due to a fault in the main grid, upstream to the microgrid PCC [14]. In either scenario, controllers within the microgrid must maintain the system variables within acceptable limits to ensure smooth transition, and prevent equipment damage and/or tripouts. Naturally, transients due to an

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Nomenclature

Variables/parameters

X_c	controller state-space matrices
C_A, u_A	active controller and its input
C_L, u_L	latent controller and its input
D_P, D_Q	droop control parameters
F_i, G_i	observer state-space matrices for ith controller
H	virtual inertia constant for VSC
I_{dq}	current d/q components
K_D	damping constant
P_m	DER mechanical input power
P_{out}	DER output power
Q	reactive power
R_g, X_g	equivalent resistance and reactance of grid
T_L	auxiliary tracking controller
t_{SW}^-,t_{SW}^+	right before/after instant of switching
x, u, y	state, input, and output vectors
$\hat{x}$, $\hat{u}$, y_{obs}	observer state, input, and output vectors
$v_{abc,i}$	three-phase instantaneous voltage of PCC$_i$
$V_{t,dq,i}$	d/q components of VSC$_i$ terminal voltage
$V_{dq,i}$	d/q components of PCC$_i$ terminal voltage
ω	voltage angular frequency
δ	phase angle

Abbreviations

CB	circuit breaker
DER	distributed energy resource
EMTDC	electromagnetic transient direct current
EMS	energy management system
GPS	global positioning system
HIL	hardware-in-the-loop
ICT	information and communication technology
I/O	input/output
LC	local controller
NI-cRIO	National Instrument-Compact Reconfigurable Input/Output
PCC	point of common coupling
PSCAD	power system computer-aided design
PI	proportional integral
RTDS	real-time digital simulation
(S)PWM	(sinusoidal) pulse-width modulation
S/H	sample and hold unit
VSC	voltage-sourced converter

accidental islanding event are noticeably more severe than those of a planned islanding event. To minimize the transients during a transition process, two options can be considered:

- The same set of controllers (single control mode) remain in service and provisions for further capabilities are considered to mitigate the transients [15–23].
- Two control modes corresponding to pre- and post-transition conditions, with additional mechanisms that are activated during the transition time interval, are envisioned [24–26]. Such mechanisms are based on either communication [24,26], or indirect current control and a special PLL design [25]. These mechanisms are often case dependent and necessarily cannot be generalized.

The first group of papers [15–22] are not generally applicable because they use the same controllers for both modes of operation and no additional smooth transition scheme is required. Among the second group, [24] uses a controller change of reference to achieve a smooth transition and no provisions are included for the second controller. The work in [26] focuses on single phase systems, and [25] proposes the smooth transition for a single inverter system based on a PLL design, which is not generally applicable to multi-DG microgrids. In this paper, based on the decentralized robust control of [12,13], we propose a generalized supplementary control strategy, based on an "active" and a "latent" controller (two control modes) to ensure smooth transition between the grid-connected and islanded conditions. The active controller operates based on tracking the DER output power and the latent controller regulates the PCC voltage of the DER.

The role of ICTs in the microgrid control is relatively new [27]; however, all indications point toward a significantly higher degree of ICT utilization. Based on the controller strategy of [12,13], this paper also proposes a droop-based backup "latent" controller that takes over the microgrid control when the "active" communication-based voltage control is subjected to communication failure or unavailability.

Based on time-domain stimulation studies in the PSCAD environment [28] and RTDS-based hardware-in-the-loop test cases [29], this paper demonstrates feasibility and effectiveness of the proposed approach for the microgrid control, subject to the transition process and the communication failure. In either case a "bumpless" control signal [30] is retained.

2. Transition to islanded condition

In this section we propose an observer-based microgrid smooth transition control mechanism to enable a smooth transition process of the microgrid. The focus is on the transition from the grid-connected to the islanded condition since it can entail severe transients and even result in instability, especially when a significant amount of power is exchanged between the main grid and the microgrid immediately prior to the transition. The process causes both the (1) transition of the microgrid power circuit from the grid-connected to the islanded condition, and (2) transfer of the grid-connected control mode to the islanded control mode.

To minimize the transients due to the transition process, a smooth control signal should be retained prior and subsequent to the transition, i.e., $u_A(t_{SW}^-)=u_L(t_{SW}^+)$, where t_{SW} is the instant of switching from the grid-connected condition control mode to the islanded condition control mode, and u_A and u_L are the active and the latent control outputs, respectively. Smooth transition can be achieved by appropriately initializing the voltage controller state variables. Since the controller states are available and modifiable, owing to its digital implementation, an observer-based method is proposed.

2.1. Smooth transition scheme based on a state observer

In the grid-connected condition, DER units control their output real/reactive power components. The approach is based on the inverter inner current control method [31]. The set points for real/reactive power components (P_{ref} and Q_{ref}) are translated into the set points for the d and q components of DER unit output currents by

$$\begin{aligned} I_{d,ref} &= \frac{2}{3}\left(\frac{V_dP_{ref}+V_qQ_{ref}}{V_d^2+V_q^2}\right),\\ I_{q,ref} &= \frac{2}{3}\left(\frac{V_qP_{ref}-V_dQ_{ref}}{V_d^2+V_q^2}\right), \end{aligned} \tag{1}$$

where V_d and V_q are the d and q components of the PCC voltage. Current set points are then fed into the current controllers which provide tracking of these set points and indirectly controls the output real/reactive power of the DER unit at the PCC.