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A control plan for the stable operation of microgrids during grid-connected and islanded modes

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ABSTRACT

This paper presents a control technique that enhances microgrids stability during the grid-connected and islanded modes. The proposed technique is compared with several existing control strategies in the context of microgrids integration into smart grids. The Lyapunov control theory is utilized in this paper to investigate the operation stability of DG units operating along with the utility grid. As the main contribution, the proposed technique compensates for the instantaneous variations of the reference current components of DG units in the ac-side of the converters. The presented method also considers and properly addresses the dc-voltage variations in the dc-side of the interfacing system. Under the proposed control strategy, DG units are able to deliver active and reactive power to the local loads and/or the main grid in fundamental and harmonic frequencies, with a fast dynamic response and without any interruption. Several simulation scenarios are carried out to demonstrate effectiveness of the proposed control strategy in microgrids during the transient and steady-state operation.

1. Introduction

The renewable energy sources integration in the form of distributed generation (DG) provides several benefits for the utility grid considering the environmental regulations and the cost of power generation [1]. Integration of DG units into the main power grid can improve the power quality and increase the reliability of the electricity supply by mitigating the problems associated with the peak demand loads and the grid failure. Compared to individually operated DGs, a systematic integration of DG units, in the form of a microgrid, can further increase the grid reliability and power quality [2,3].

A microgrid can operate either in the grid-connected or islanded mode; for each operation mode, several control techniques have been developed to perform active and reactive power sharing as well as frequency and voltage regulation [4,5], such as potential-function based method for secondary and tertiary control of a microgrid [6], unit output power control (UPC) and feeder flow control (FFC) [7], power management strategies [8], droop-control concepts with L_1 control theory [9], and other proposed control strategies [10–12].

In [13], two distinct strategies are discussed for controlling the active power and frequency of multiple DG units in a microgrid. Another control strategy is proposed in [14] for the integration of microgrids into the main power grid, and a voltage-control technique is presented in [8]. In [15], a power control and sharing technique is discussed for the electronically coupled DG units, in which the output active and reactive power of DG units can be properly controlled in both the islanded and grid-connected modes. A two-degree-of-freedom (DOF) controller is utilized for a DG-based system as an uninterruptible power supply (UPS) to keep the voltage of AC bus at the desired value in presence of the stochastic behaviour of the loads [16]; this proposed DG model demonstrates a smooth transition from the grid-connected mode to the islanded mode. In [17,18], a control strategy is proposed based on the spatial repetitive controller (SRC) that utilizes the Lyapunov direct method to control the power consumption of the loads, maintaining the

Abbreviations: WTS, wind turbine system; DG, distributed generation; SVPWM, space vector pulse width modulation; PCC, point of common coupling; S, switch; CHP, combined heat and power; CC, capacity curve; VSI, voltage source inverter; DLCM, direct lyapunov control method; LPF, low pass filter; PMSG, permanent magnet synchronous generator; PI, proportional-integral.

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Nomenclature

Indices

i	1,2
k	a,b,c
z	d,q

Variables

i_{cki}	DG current components in abc frame
v_{dci}	dc-link voltage
i_{fki}	currents of filter capacitors in abc frame
v_k	voltage at the PCC in abc frame
s_{ki}	switching functions of DG units
u_{eqki}	equivalent switching function of DG units
i_{czi}	DG current components in dq frame
v_{zi}	voltage at the PCC in dq frame
i_{fzi}	currents of filter capacitors in dq frame
u_{eqzi}	equivalent switching function of DG units
i^*_{czi}	reference current components of DG units
$\tilde{I}_{\mathrm{av}_d}, \tilde{I}_{\mathrm{av}_q}$	average values of reference currents
f^*_i	reference frequency of DG unit
E_i	amplitude of voltages at PCC
E^*_i	reference amplitude of PCC voltages
Δf_i	frequency variation of DG units
ΔE_i	variation of voltage amplitudes at the PCC
U_{eqzi}	dynamic state switching function
i_{llz}	local load currents in dq frame
i_{mlz}	main load current in dq frame
I_{lld1}	d-component of local load current in main frequency
I_{mld1}	d-component of main load current in main frequency
m	slope of $P-f$ curve
n	slope of $Q-E$ curve
P_{mech}	output mechanical power
C_p	power coefficient
λ	tip speed ratio
β	blade angle
U_m	wind speed
ω_m	mechanical angular velocity of generator
v_{zm}	machine voltages in d–q frame
λ_m	flux linkage amplitude
ω_r	angular frequency of the Stator Voltage
V_z	reference synchrony frame voltages
$i^*_{\mathrm{h1}_{\mathrm{di}}}$	completing d-component reference current
T_e	electromagnetic torque
u^*_{eqzi}	reference switching function of DG units
v^*_{dci}	reference voltage of dc-link
v_{mi}	maximum voltage amplitude at the PCC
i^*_{fzi}	reference currents of filter capacitors
i^*_{dci}	reference current of dc-link
I^*_{avzi}	average values of reference currents of DG
P_{DGi}	DG active power
Q_{DGi}	DG reactive power
$\tilde{i}_{\mathrm{czi}}$	average value of current in DG units
$\tilde{v}_{\mathrm{dci}}$	average value of dc-link voltage
P_{DGimax}	maximum active power of DG units
Q_{DGimax}	maximum reactive power of DG units
P^*_{DGi}	reference active power of DG units
Q^*_{DGi}	reference reactive power of DG units
ΔP_{DGi}	variation of active power in DG units
ΔQ_{DGi}	variation of reactive power in DG units
$\tilde{i}_{\mathrm{lld}}$	harmonic current components of local load
$\tilde{i}_{\mathrm{mld}}$	harmonic current component of main load

Parameters

L_{zm}	machine inductance
R_{zm}	machine resistance
r	rotor radius
A	wind turbine rotor swept area
ρ	air density
R_g	resistance of utility grid
L_g	inductance of utility grid
R_{ci}	resistance of DG unit
L_{ci}	inductance of DG unit
C_{dci}	capacitor of DG unit
C_{fi}	capacitor of filter
ω	grid angular frequency
(α_i, β_i)	constant coefficients for the dynamic state switching functions

load voltage at the reference value. A switching pattern is proposed in [19] that is based on the space vector pulse width modulation (SVPWM) and controls a single stage current source boost inverter in order to achieve a desired frequency and voltage magnitude for both the islanded and grid-connected modes. In [20], a combinatorial droop control technique is proposed that utilizes a derivative controller in the islanded mode and an integral controller in the grid-connected mode to maintain the microgrid desired operation; the small-signal stability of the controller is also investigated for both scenarios. In [21], a control technique is proposed based on the direct-voltage control and optimized dynamic power sharing to eliminate the disturbances and minimize the switching actions in transition operating condition; it is demonstrated that this technique enhances the performance of the active damping controller and improves the dynamic response of the system. The integration of distributed battery energy storages into a local microgrid system is discussed in [22,23]. In [24], a microgrid consisting of a hybrid combination of inertial and converter interfaced DG units along with a nonlinear and unbalanced load is considered; it is demonstrated that it is possible to improve the power quality for such a system by allocating a DG unit as a power quality compensator for the load. In [25], a feed-forward current control technique is proposed for a microgrid converter that allows the interfaced converter to change its injected active and reactive power in the grid-connected mode by changing the voltage component and frequency.

Several other control algorithms have been proposed to address different challenges associated the microgrids operation [26–28].

In this paper, a new control technique is proposed based on the Direct Lyapunov Control Method (DLCM) to determine the stable operating region of DG units in a microgrid. The impact of the instantaneous variations of the reference current components in the ac-side of the converters is carefully considered; also, the dc-voltage variations in the dc-side of the interfaced converters are discussed and properly addressed. Including these two problems in the proposed method is the main contribution of this work compared to the other existing control techniques.

The rest of the paper is organized into four sections. Following the introduction, general schematic diagram of the proposed microgrid system is introduced in Section 3 and its dynamic and state-space analysis are explained. Application of DLCM for the control and stable operation of DG units in different operating conditions is presented in Section 4. Moreover, simulation studies are carried out to demonstrate the efficiency and applicability of the developed control strategy in Section 5. Finally, conclusion is provided in Section 6.