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A reference current perturbation method for islanding detection of a multi-inverter system

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ABSTRACT

An active islanding detection method without destabilizing the system gives the advantage of accurate decision and the capability to keep the micro-grid energized while islanding occurs. Harmonic and perturbation current injection are such active methods, but none in the literature has discussed about islanding detection in multi-inverter systems. This paper proposes an active islanding detection method for multi-inverter systems which works based on perturbation of direct (*d*-) and quadrature (*q*-) axis reference currents of inverters. The perturbations are synchronized according to voltage phase at point of common coupling (PCC) to avoid interaction. The *q*-axis voltage at PCC is considered as the output of system and the frequency response (FR) of system is obtained analytically for normal and island modes. The results show that the FR of system especially its phase has a noticeable difference in normal and island modes, which islanding can be detected by comparing the phase of system FR with a proper threshold. At the end, the analytical results are confirmed by some simulations using the software PSCAD/EMTDC.

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1. Introduction

The nature of today distribution system (DS) is rapidly changing from passive into active due to the connection of distributed generation (DG) units to it. In an active DS, DG continues to supply local loads, while the utility grid is missed. This kind of operation is called island mode, and the process of switching to this mode is called islanding. This phenomenon must be detected as soon as possible, and DG must be disconnected from DS to ensure the safety of utility service personnel and to prevent equipment damages due to the instability of frequency and voltage in the islanded section. In addition, during the restoration of the utility grid or reclosing of feeder recloser, DG must be disconnected from DS to avoid unsynchronized connecting or reclosing [1]. Hence, standards for interconnecting DG like IEEE 1547 [2] and UL 1741 [3] enforce quick disconnection of DG when islanding occurs (within 2 s).

Islanding detection methods (IDM) are categorized into remote and local classes [4]. Remote IDMs are based on communication between the utility and DG, while local IDMs including passive and active make decision according to measurements at DG site. However, remote IDMs have high reliability, but on the other hand have high cost and complexity, which makes local IDMs more attractive to engineers. Passive IDMs evaluate system parameters such as frequency and voltage at PCC to detect islanding [5–7], which may fail or take long time to operate in balanced or small power mismatch conditions, and so mostly have a large non-detection zone (NDZ). In a micro-grid operation, the probability of a balanced or small power mismatch condition is high, and therefore the inefficiency of passive IDMs increases.

Active IDMs inject a disturbance into DS or use positive feedback to force wider variation of the system parameters after islanding occurrence like frequency drifting [8,9] and positive feedback methods [10–13]. Hence, islanding can be detected even in small power mismatch conditions. Some active IDMs analyze the response of the injected disturbance to detect islanding without destabilizing the system. These methods give the capability to keep the micro-grid energized while islanding occurs [14]. Harmonic current injection [15–17], negative sequence current injection [18], reactive power variation [19], reference current perturbation [20–23] and high frequency signal injection [24] are active IDMs without destabilizing the system.

Although, the active methods of [15–23] detect islanding occurrence without destabilizing the system, but no one has discussed about islanding detection in multi-inverter systems. High frequency signal injection was proposed in [24] for islanding detection of a multi-inverter system. The disadvantage of the proposed method is that only master inverter injects the disturbance, which in the case of master inverter failure or its absence in islanded section, other inverters may fail to detect islanding. In a multi-inverter system, injected perturbations by all DG units must be

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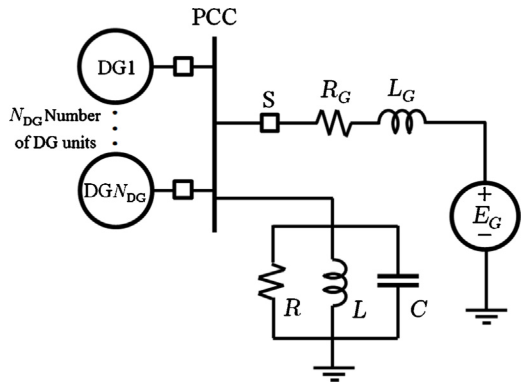

Fig. 1. A simplified representation of a multi inverter system containing N_{DG} number of DG units.

synchronized according to a reference phase, so that all DG units will be simultaneously able to inject disturbance into the system without interaction. This paper presents an active IDM for multi-inverter systems without destabilizing the system based on the methods proposed in [21,22].

Periodic perturbation of q-axis reference current was proposed in [22]. In island mode, frequency varies according to the perturbation of q-axis reference current. Thus, deviation from nominal value of frequency at PCC shows an islanding occurrence. Switching events and faults cause deviations on frequency and voltage, which may be same as an islanding event, and the method may have a wrong detection. This problem is solved in [21] by defining average absolute frequency deviation value (AFDV), but its performance was not validated in fault conditions. None of [21,22] has discussed about islanding detection in multi-inverter systems.

The current paper introduces an active method that periodic perturbations of 60 Hz are added to d- and q-axis reference currents of DG units. The perturbations are synchronized according to voltage phase at PCC. It is shown that the frequency response (FR) of system at 60 Hz (q-axis voltage as output) especially its phase has an extensive difference between normal and island modes. So, islanding can be detected by comparing the phase of system FR with a proper threshold value. The phase of system FR is obtained by the discrete Fourier transform (DFT) in the online system. The correct performance of the method is confirmed by simulations for islanding and non-islanding events.

In the next section, analytical studies on FR of system in normal, fault and islanding conditions will be presented. The calculation procedure of system FR by measurements will be given in Section 3. Simulation results are included in Section 4. At the end, Section 5 presents concluding remarks.

2. Analytical studies on FR of system

A simplified representation of a multi inverter system with N_{DG} number of connected inverter-based DG units is illustrated in Fig. 1. The load is considered as a parallel RLC branch, which is a proper representation for all load types in a fixed operating point. In this study, a small perturbation is added to d- and q-axis reference current of DG around a fixed operating point. Considering the static constant impedance load (RLC branch) will not reduce the generality of the analysis, because any dynamic load can be considered as a static load in a fixed operating point (constant voltage). The utility grid is modeled by its Thevenin equivalent, which is considered as a voltage source and impedance in series (R_G, L_G and E_G).

In this study, each of DG units is a distributed resource (considered as a constant DC voltage source) that is connected to the PCC through a voltage source convertor and a transformer. The electrical configuration and control section of DG units are depicted in Fig. 2. R_{fk}, L_{fk} and C_{fk} represent the filter inductor and capacitor (the parameter k refers to DG number). The transformer winding resistance and leakage inductance are represented by R_{Tk} and L_{Tk}, respectively. All elements in Figs. 1 and 2 have been transferred to the low voltage side of the transformer, and the transformers have been eliminated. The abc → dq block is the Park's transformation that is defined in Appendix A. The values of parameters and elements are provided in Table 1.

Table 1
The value of parameters and elements used in this paper.

Section	Parameter	Value	Unit
Parameter values of Fig. 4	$\omega_b (f_b)$	377 (60)	rad/s (Hz)
	V_b	0.6	KV, L–L
	S_b	2.5	MVA
	R_G	0.0131	pu
	L_G	0.0495	pu
	E_G	$1\angle 0$	pu
	R	1	pu
	L	0.5538	pu
	C	1.8050	pu
	R_{Tk}	0.01	pu
	L_{Tk}	0.05	pu
Filter parameters of DG units	R_{fk}	6.25	mΩ
	L_{fk}	1.25	mH
	C_{fk}	150	μF
Transformer parameters of DG units	ϕ_{Tk}	30	degree
	Voltage ratio	4.16 (D): 0.6 (Y)	KV, L–L
PI constants of CCL for all DG units	K_{pd}	0.5	pu
	K_{id}	333	pu
	K_{pq}	0.5	pu
	K_{iq}	333	pu
PI constants of PLL for all DG units	K_p	50	$1/s$
	K_i	900	$1/s^2$
Perturbation frequency	ω_p (f_p)	377 (60)	rad/s (Hz)

Inverters are supposed to work in constant current mode. The operation of phase locked loop (PLL) keeps v_{tkq} equal to zero. So, active and reactive powers (in per-unit) provided by the kth DG are obtained by

$$P_{DGk} = v_{tkd} i_{tkd} \tag{1}$$

$$Q_{DGk} = v_{tkd} i_{tkq}. \tag{2}$$

According to above equations, the operation of current control loop (CCL) can regulate P_{DGk} and Q_{DGk} by adjusting proper d- and q-axis reference currents.

The CCL regulates i_{tkd} and i_{tkq} according to reference currents i^*_{kd} and i^*_{kq}, respectively. In this study, periodic perturbations are added to d- and q-axis reference currents of DG units. So, i^*_{kd} and i^*_{kq} must be defined as

$$i^*_{kd} = i^r_{kd} + m_{pdk} \cos\left(\omega_p t + \phi_{pdk}\right) \tag{3}$$

$$i^*_{kq} = i^r_{kq} + m_{pqk} \cos\left(\omega_p t + \phi_{pqk}\right) \tag{4}$$

where m_{pdk}, m_{pqk}, ϕ_{pdk}, ϕ_{pqk} and ω_p are the magnitudes, phases and frequency of the perturbations for the kth DG, respectively. The transfer functions (TF) of d- and q-axis CCL for the kth DG are defined by

$$H_{CCLdk}(s) = \left.\frac{I_{tkd}(s)}{I^*_{kd}(s)}\right|_{i^*_{kq}=0} \tag{5}$$

$$H_{CCLqk}(s) = \left.\frac{I_{tkq}(s)}{I^*_{kq}(s)}\right|_{i^*_{kd}=0} \tag{6}$$

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