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Voltage positive feedback based active method for islanding detection of photovoltaic system with string inverter using sliding mode controller

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ABSTRACT

Islanding is an undesirable condition that is potentially dangerous to the maintenance or repair staff and may cause damages to sensitive equipments. Therefore, islanding detection is a mandatory feature for distributed generators (DGs), including grid–connected photovoltaic systems (GCPVSs). This article presents a new active islanding detection method for GCPVSs with string inverter based on sliding mode controller. In the proposed method, a feedback of point of common coupling (PCC) voltage has been inserted to the reference signal of sliding mode controller as a new maximum power point tracking (MPPT) technique. Through applying this voltage positive feedback (VPF), the inverter output power and consequently, the PCC voltage decreases in islanding condition. This procedure is repeated until the PCC voltage falls below the under voltage (UV) relay setting. The conventional VPF technique attempts to increase and decrease the output power in elevated and declined PCC voltage cases after grid disconnection, respectively. However, due to the input power limitation and MPPT in GCPVSs in the PCC voltage raised cases, the output active power cannot be elevated any further. In this study, the active power perturbation has been only applied in deceleration mode, considering the disturbance definition in the inverter voltage control loop. Therefore, unlike the conventional VPF scheme, it has the advantage of not violating the "conservation of energy law". The performance of the proposed method is evaluated by simulating a GCPVS with string inverter supplying a local load, connected to the grid. Simulation results show troubleshooting the conventional VPF scheme drawbacks as well as successful operation of the proposed method in islanding and non–islanding conditions even in multi–inverter systems.

1. Introduction

The worldwide installation rate of distributed generation has rapidly escalated due to market deregulation, reduction of fossil fuel resources, energy security and environmental concerns. Among distributed generator (DG) technologies, photovoltaic systems, especially those of grid–connected type, have mainly attracted more popularity according to the benefits such as easy installation and maintenance, pollution free operation, etc. Therefore, the global cumulative installed capacity of grid–connected photovoltaic systems (GCPVSs) show an exponential growth (Tyagi et al., 2013).

Despite the favourable features, the connection of GCPVSs to the distribution network is associated with some problems such as protection coordination, power quality problems and islanding. Islanding is a condition that the DG continues to inject power to the local load after the main is disconnected. This condition is dangerous to the utility staffs that presume the downstream line is de–energized. Also, voltage or frequency in islanded area can deviate from their permissible ranges and this may harm sensitive equipments. Furthermore, unsynchronized reclosing of the upstream line can lead to high voltage transients and damages the inverter. Thus, islanding condition should be detected rapidly (Velasco et al., 2010).

Many islanding detection techniques have been presented in the literature. These methods can be classified into two major groups; remote and local (Velasco et al., 2010). Remote methods such as power line signalling are based on communication between grid and DGs (Xu et al., 2007). In this method, the connection is continuously monitored by communication signals between the signal generator and signal detectors, embedded in the upstream substation (grid side) and DG locations, respectively. The islanding is detected when at least one detector does not receive the signal broadcasted by the generator (Xu et al., 2007). However, these methods can be applied to all DG technologies even in multi–DG systems, according to the high cost, they are not commonly used especially for small DGs.

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The measurement of the local parameters in the point of common coupling (PCC) is the basis of local schemes (Fig. 1). These techniques are divided into passive, active and hybrid categories. Passive methods are based on the fact that when islanding occurs, active/reactive power injected/received from the grid is interrupted which would change either voltage or frequency. If this power imbalance in islanded area is large enough, voltage/frequency will be outside of the acceptable range. In this case, islanding is detected and DG is disconnected from the grid. Over/under voltage (Vieira et al., 2005), over/under frequency (Vieira et al., 2006), rate of change of frequency (ROCOF) (Affonso et al., 2005) and rate of change of phase angle difference (ROCPAD) (Samui and Samantaray, 2011) are most widely used passive methods. Although these methods can be easily implemented, they suffer from large non detection zone (NDZ), i.e. the active/reactive power imbalance conditions that islanding cannot be effectively detected.

Active methods are introduced for inverter–based DGs to decrease NDZ. In these approaches, a disturbance is injected to the inverter output current and the result is observed on the voltage/frequency of PCC. In normal operating condition, the inserted disturbance does not affect the mentioned parameters due to inverter connection to the utility. However, this disturbance drifts voltage/frequency of the PCC outside the permissible range in islanding conditions. Active frequency drift (AFD) (Lopes and Sun, 2006), slip mode frequency shift (SFS) (Liu et al., 2012), and impedance measurement (IM) (Cai et al., 2013) are among the examples of active methods. Degradation of power quality and improper performance in multi–inverter systems are two major problems of active methods.

Furthermore, hybrid methods are reported to lessen the drawbacks of the aforementioned methods, i.e. large NDZ and power quality degradation in passive and active methods, respectively. In these methods when the islanding cannot be detected by one method, the other technique is applied (Yu et al., 2008). However, the control technique of these methods is complicated and expensive in some circumstances.

IEEE 1547 (IEEE Standard 1547, 2008) and IEC 61727 (IEC 61727, 2002) standards are provided to limit the inserted disturbance of active methods to guarantee the acceptable power quality. Summary of these standards dealing with interconnection of GCPVS to the grid, is represented in Table 1.

Based on the above standards, abnormal voltage condition occurs when root mean square (RMS) of PCC voltage (V_{PCC}) is out of the 88–110% range. In these situations, inverter should stop injecting energy to the grid within the clearing time, i.e. time between the start of the abnormal condition and the instant DG ceases to energize the power system. Based on IEEE 929, GCPVS should respond to these abnormal conditions as follows (IEEE 929, 2000) (see Table 2).

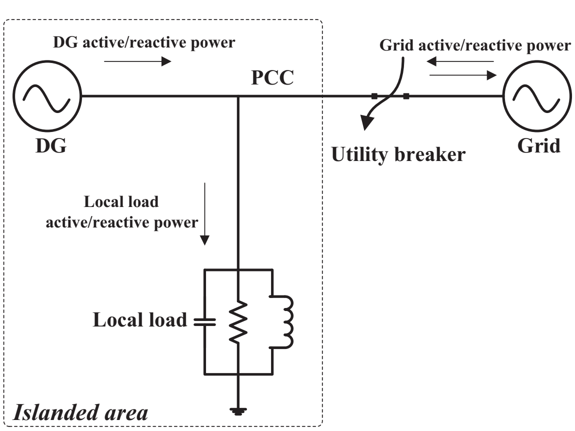

Fig. 1. The interconnection of DG and local load to the utility.

Table 1
Summary of standards corresponding to the interconnection of GCPVS to the grid.

Issue	IEEE 1547	IEC 61727
Nominal power	10 kWp	30 kWp
Maximum current THD	5%	5%
Permissible voltage range	88–110%	88–110%
Permissible frequency range	59.3–60.5 Hz	49–51 Hz

The voltage positive feedback (VPF) concept as a new active islanding detection method, has been initially introduced for three phase inverter–based DGs (Du et al., 2010; Kim et al., 2011). This method applies the concept of decoupled active and reactive power control in the synchronous reference frame ($dq0$). In this way, the inverter output current is decoupled into the reference direct ($I_{d,ref}$) and quadrature ($I_{q,ref}$) components to control the inverter reference active power (P_{ref}) and reference reactive power (Q_{ref}), respectively. According to this current regulator (controller) scheme, the voltage positive feedback disturbance is inserted to $I_{d,ref}$ through two consecutive V_{PCC} samples and the active power command (K_{pf}):

$$I_{d,ref} = \left[(P_{ref} - P_{inv}) \times PI\right] + \left[K_{pf} \times (V_{PCC}(k) - V_{PCC}(k-1))\right] \tag{1}$$

where PI and P_{inv} represent the proportional–integral controller and inverter output active power, respectively. The performance of the conventional VPF technique can be explained by Eq. (1) and the following equation:

$$P_{inv} = V_{PCC}^2 / R \tag{2}$$

where R is the resistive part of the parallel RLC circuit which models the local load, as defined in IEEE 929.

In islanding condition and when V_{PCC} increases, the d–axis reference current increases (Eq. (1)). This raise results in inverter output active power and V_{PCC} increase (Eq. (2)). The procedure will continue until this voltage goes above the allowable threshold and therefore, islanding can be detected. For the declined measured voltage case, VPF works in such a way that reduced active power drifts V_{PCC} under the permissible voltage. The VPF performance for increasing V_{PCC} case can be seen in Fig. 2. In this paper, as discussed later, the current control topology is employed in the stationary reference frame ($\alpha\beta$) and hence, the disturbance is injected to the α–axis reference current ($I_{\alpha,ref}$) instead of $I_{d,ref}$.

The simulation results show successful islanding detection of VPF method in different active power imbalances and quality factors, even in multi–DG system. The VPF scheme has been also developed for constant power and current controlled inverter–based DGs (Samui and Samantaray, 2013). The small signal analysis is used to determine the lower bound of disturbance gain that results in effective islanding detection. Furthermore, this parameter is limited according to the stable performance of DG, i.e. the cases that the small step changes of PCC voltage results in acceptable output power variation.

The conventional VPF methods have been reported for inverter–based DGs like GCPVSs, however it seems they have

Table 2
Response to abnormal voltage conditions.

V_{PCC}	Maximum clearing times (cycles)
Less than 50%	6
50–88%	120
88–110%	Normal operation
110–137%	120
More than 137%	6