Implementation of Active Anti-Islanding Methods Protection Devices for Grid Connected Photovoltaic Systems

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***Abstract*—Single-phase grid tied inverter is one among types of inverters widely used in photovoltaic generation systems due to the advantages they offer, in the absence of the grid, islanding situations occur. This paper describes model and simulation of such inverter in operation as distributed generation in electrical power system under islanding phenomena. In this configuration, it is imperative that the inverter automatically disconnects from the grid without remaining any residual voltage that can be dangerous for the plants and stakeholders. It is important to detect the islanding situation. For this purpose several techniques are used. We present in this article the implementation of the method called Slide-Mode frequency Shift (SMS) in the control of a single phase photovoltaic inverter, for which we provide a description of our SIMULINK implementations and their evaluations performed on the basis of comparison with Active Frequency Drift (AFD) method. Simulation results show that the developed algorithm detects the islanding phenomenon in the time approaching that required by the IEC and IEEE standards that secures the PV system connected to the grid.**

***Index Terms*—PV systems, electrical grid, islanding detection methods, single phase PV inverter, distributed generation systems**

I. Introduction

Islanding phenomena is a situation where the utility grid is disconnected from the distributed generation which still supplies local loads. Normally, the distributed generation is required to sense the absence of utility-controlled generation and cease energizing the grid. Otherwise, damages can occur to Very Small Power Producer (VSPP) equipment as the generation in the islanding area, is not under utility control and operates outside of normal voltage and frequency conditions. Besides, customer and utility equipment can be damaged if the main grid recloses into the island out of synchronization. Thus the anti islanding function is one of requirement protection of grid inverter based systems and must follow the specific regulations for connecting inverters to the grid: 5 seconds according to DIN VDE 0126 - 1-1 [1] and [2] and two seconds according to IEC 62116 [3].

Several techniques and methods are used to detect the islanding phenomenon. ‘Passive’ method which is necessarily built into the control of any inverter. It is based on the analysis of changes in voltage, frequency or phase [4]. Other methods known as 'active' as the ‘Slip Mode frequency Shift’ (SMS), Sandia frequency Drift (SFS) ,... which are based on the observation of the effects of the disturbances intentionally created on the grid and for whose it is recommended to minimize the area of Non-Detection Zone (NDZ).

In this article, we discuss two active methods called Slide-Mode frequency Shift (SMS) and Active Frequency drift (AFD) [5]. We have chosen these methods because they are easy to develop analytically, simple to implement in the inverter control under Matlab environment and also easy to verify experimentally test them on a prototype.

A. Presentation of a Single Phase Grid Connected Photovoltaic System

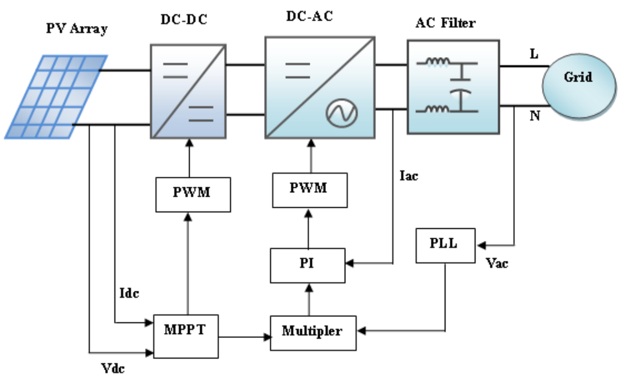

Figure 1. A block diagram of a PV system using single phase grid PV inverter with a current control.

In this study, the single phase photovoltaic system has been proposed. Fig. 1 shows a block diagram of a voltage source inverter using a current control technique, applied for a PV grid-connected system.

This configuration is common for most available commercial units. The main components are a PV Panel,

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a DC-DC converter, a DC-AC converter, and a AC filter, a Phase Lock Loop (PLL), a Maximum Power Point Tracking (MPPT) unit, a PI controller and a Pulse Width Modulation (PWM) for switching scheme.

Power characteristics including power quality, grid interaction behavior and load sharing that are important aspects in their operation as grid connected inverter will be simulated and analyzed.

II. The Islanding Detection Methods

A. *Presentation of the Active Frequency Drift (AFD) Method*

Among the techniques for detecting islanding situation we focus on the method called 'active frequency drift' or AFD. This technique is based on the injection of a current waveform distortion to the original reference current of the inverter, to force a frequency drift in case of islanding operation. By introducing a zero conduction time tz at the end of each half cycle as shown in Fig. 2 the phase angle of the fundamental component of the current is shifted [5] and [6].

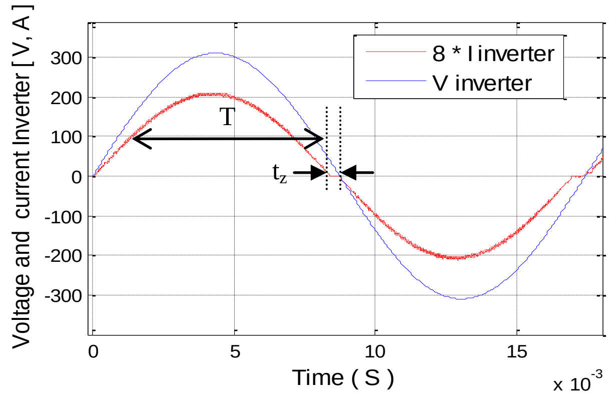

Figure 2. Simulated waveform used by AFD.

During normal grid connected operation the inverter usually operates with unity power factor and is synchronized to the grid voltage and will operate at grid frequency. In islanding operation, the added distortion to the current will produce a permanent drift in the operating frequency towards the local load resonance frequency in order to keep unity power factor. This drift will eventually reach the frequency boundary limits set for islanding detection. The dead time tz in which zero current is forced and the period of the original signal T can be related to each other to define the chopping factor Cf used to perturb the waveform as:

$$C_f = \frac{2t_z}{T} \tag{1}$$

where: T is the period of the electrical network.

Fig. 2 shows the waveform simulation used by the AFD technic. This wave is characterized by tz which is defined as the dead time during which the current is forced to zero, Cf is the factor used to disrupt the cutting waveform. It defines the rising edge of the drift introduced in the frequency f and is expressed as [5] and [7].

The reference current AFD shown in Fig. 2 is defined as follows [5]:

$$i_{afd}(t) = \begin{cases} I\sin(2\pi f' t) & \rightarrow 0 \le \omega t < \pi - t_z \\ 0 & \rightarrow \pi - t_z \le \omega t < \pi \\ I\sin(2\pi f' t) & \rightarrow \pi \le \omega t < 2\pi - t_z \\ 0 & \rightarrow 2\pi - t_z \le \omega t < 2\pi \end{cases} \tag{2}$$

where f is the frequency of the grid voltage, f' the frequency of the AFD current and which is expressed by:

$$f' = f\left(\frac{1}{1 - C_f}\right) \tag{3}$$

B. *Presentation of the Slide-Mode Frequency Shift (SMS)*

The SMS method consists in controlled the phase angle of the grid-connected converter output current is controlled as a function of the PCC voltage frequency. The converter output current can be expressed as [8].

$$i_{Con} = I_m \sin(2\pi f + \theta_{SMS}) \tag{4}$$

where f is the PCC voltage frequency and θ_{SMS} is the phase angle for SMS method. This phase angle is set as a sinusoidal function of the grid nominal frequency fg:

$$\theta_{SMS} = \frac{2\pi}{360}\theta_m \sin\left(\frac{\pi}{2}\cdot\frac{f - f_g}{f_m - f_g}\right) \tag{5}$$

where θ_m is the maximum phase angle of the inverter, fg is the rated frequency (the frequency of normal operation), and fm is the frequency corresponding to the maximum phase angle of the inverter.

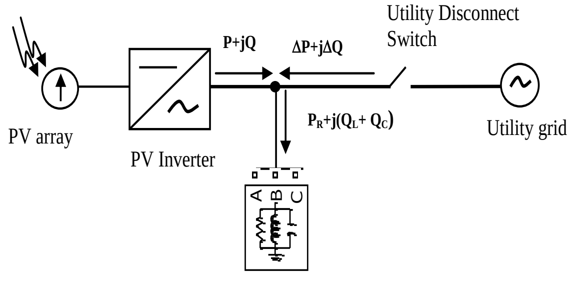

Figure 3. PV inverter test circuit for islanding.

In the circuit shown in Fig. 3, the islanding test procedure of the IEEE Std. 929-2000 [1] and [9] is based on the quality factor Qf (Eq. 6) of the islanded circuit set to 2.5.

$$Q_f = \frac{\sqrt{Q_L \times Q_C}}{P} \tag{6}$$

From Eq. (4), quality factor is defined as the maximum stored energy to the energy dissipated per cycle at a given frequency in case of parallel RLC resonant load. As the quality factor gets larger, it is more difficult to detect islanding at the resonant case. From quality factor 2.5 and

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PV generated power 3.8 kW, the quantitative value of local load RLC can be calculated as Table I. In this case, we suppose that PV inverter is controlled to operate with a unity power factor at 50 Hz line frequency, so effective power P of PV inverter is equal to 3.8 kW and inverter reactive output power Q is 0.

Eq. (6) represents the load line with respect to the frequency of inverter output voltage. From the given data of Table I, the load line θ_{load} can be plotted.

From (5), θ_{SMS} is almost zero when the utility frequency is at its rated value. Once the grid is disconnected, the SMS algorithm is solely stimulated by an uncontrollable, externally supplied perturbation caused by noise, measurement inaccuracy and quantization errors in practice [8]. If such perturbation is small enough, this method may fail to detect the islanding within the time specified by IEEE Std 929-2000.

Frequency limits have been taken as follows:

fm has been set at 50.5 Hz, and fr has been set at 50 Hz. We consider the worst quality factor of load Qf= 2.5 and take θ_m to be 10°. The inverter current is modeled by using the following dependency:

$$i_{PV} = I_m \sin(\omega_a(t-t_1)+\theta) = \frac{\sqrt{2}\,P_{PV}}{V_{rms}\cos\theta_{load}}\sin((t-t_1)+\theta) \quad (7)$$

$$\theta_{load} = -\tan^{-1}[R(2\pi fC - \frac{1}{2\pi fL})] \quad (8)$$

where Im is the amplitude of the inverter current, ωa is the angular frequency of the load voltage, Va, and t1 is the time moment that corresponds to the onset of positive zero crossing of Va.

A natural simplification of our model follows from the fact that no stable running state is needed in islanding. Hence, the phase–frequency curve can be approximated quite well by a straight line as follows:

$$\theta = 15.(f-50) \quad (9)$$

In order to cover the islanding cases typical for the inverter with characteristic curve presented in (10), the biggest slope of Eq. (5) on the interval of 49.5–50.5 Hz is chosen as the slope of the straight characteristic line. The advantage of Eq. (9) is obvious: it allows for an easier implementation compared to the original sinusoidal representation of the phase angle–frequency relation (Fig. 3).

From Eq. (5) :

$$\theta_{F,[K]} = \theta_m \sin(\frac{\pi}{2}.\frac{f_{[K-1]}-50}{f_m-50}) \quad (10)$$

where $\theta_{F,[K]}$ is the input filter value of PLL at the present period K, and f[K-1] is the sensed lined frequency at the previous period (K - 1), and fM is the reference frequency at maximum input filter value.

$$\frac{d\theta_F}{df_{at50Hz}} = \frac{\theta_m\pi}{2(f_m-50)} > \frac{d\theta_{load}}{df} \quad (11)$$

From Eq. (11), the reference frequency fm of SMS line equation must be lower than 51.07Hz. To have higher power quality, the reference frequency is chosen as 50.5 Hz to frequency relay thresholds.

$$\theta_F = \begin{cases} -\theta_m & if\ \ f_{[K-1]} < 49.5\,Hz \\ \theta_m \sin[\frac{\pi}{2}\frac{f_{[K-1]}-50}{f_m-50}] & if\ 49.5 < f_{[K-1]} < 50.5\,Hz \\ \theta_m & if\ \ f_{[K-1]} > 50.5\,Hz \end{cases} \quad (12)$$

$$\theta_{load} + \theta_F = 0 \quad (13)$$

As a result, the designed SMS line of the PLL input filter θ_F is presented as Eq. (12). Fig. 4 shows the designed SMS line and the calculated load line from IEEE Std. 929- 2000, and Eq. (13) determines the operating frequency when the grid is disconnected. From the simulation results in Fig. 4, all of the operating points can move beyond the frequency relay thresholds due to the small perturbation when the islanding occurs.

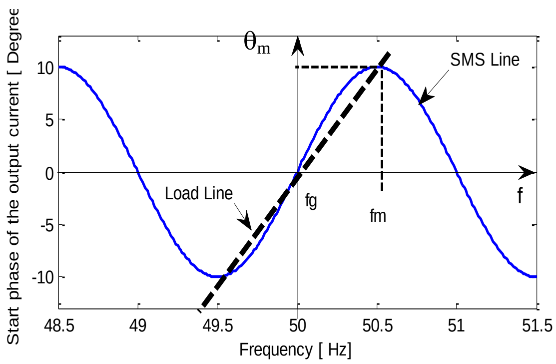

Figure 4. SMS sinusoidal frequency shift.

III. Simulation Results and Discussions

A 3.8 KW pv inverter is simulated using MATLAB/SIMULINK. The specific parameters are shown in Table I.

The circuit diagram is shown in Fig. 1. The power stage consists of a boost converter and a voltage-source inverter. The boost converter provides maximum power point tracking (MPPT) function and the voltage source inverter makes a stable dc link voltage from an unregulated output voltage of solar array. The PV inverter is feeding a paralleled-tunable RLC circuit as shown in Table I.

In addition, the total harmonic distortion (THD) of the inverter is controlled to be less than 5% under the grid-connected condition for having best precision in the analysis.

TABLE I. DG Circuit Parameters

Parameter	Value
Nominal line frequency (f_0) [Hz] Voltage	50
Nominal line RMS voltage (V_{line}) [V]	220 V
Local resistive load (P_R) [W]	3000
Local inductive load (Q_L) [var]	7500
Load Local capacitive load (Q_C) [var]	7500
Resistance (R) [ohm]	16.1
Inductance (L) [mH]	17.1
Capacitance (C) [μF]	414

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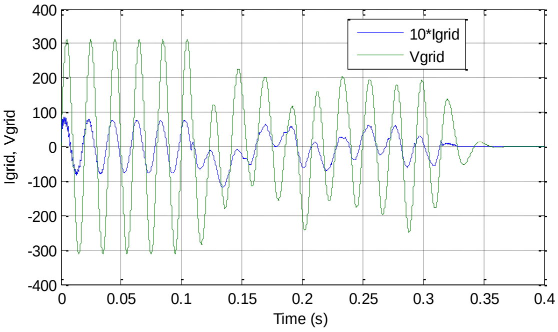
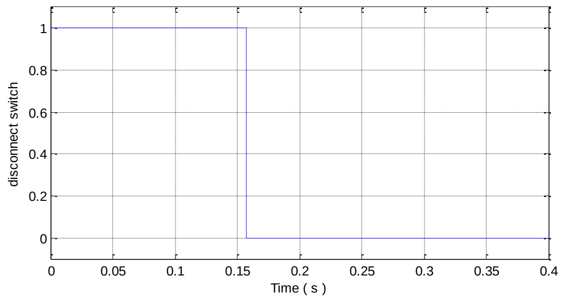
Fig. 5 (a) shows the voltage and the current shape, when using the phase shift anti-islanding method.

The islanding tests results of the SMS method is shown in Fig. 5 (a) and Fig. 5 (b), we can see, by using this method, that it takes around 0.16 S to detect islanding phenomenon at around zero grid power flow condition. In the case of the AFD method it takes around 0.18 S to detect islanding at around zero grid power flow condition (see Fig. 6 (b). Even in the worst conditions (quality factor of load Qf = 2.5 and Cf = 0.046) the THD is 4.91% less than the 5% recommended by the IEEE Std. 929-2000 standard.

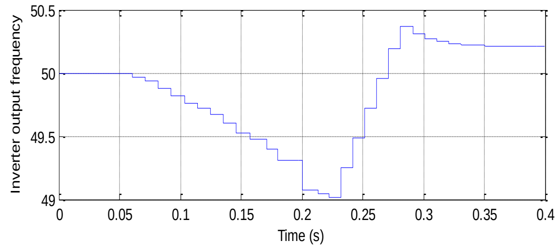
The main result is that the proposed methods can detect islanding at around zero power flow to the grid within 2 s.



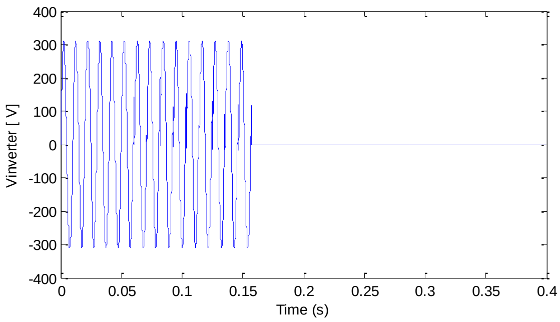
(a)



(b1)

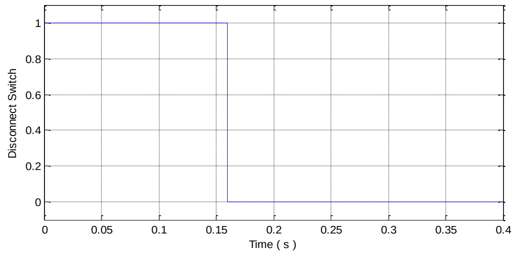


(b2)

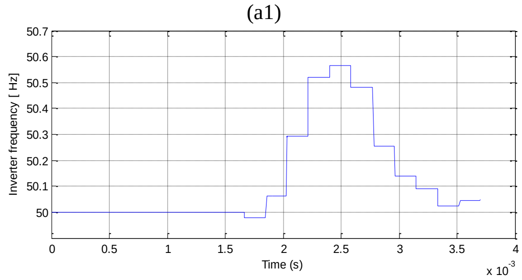


(c)

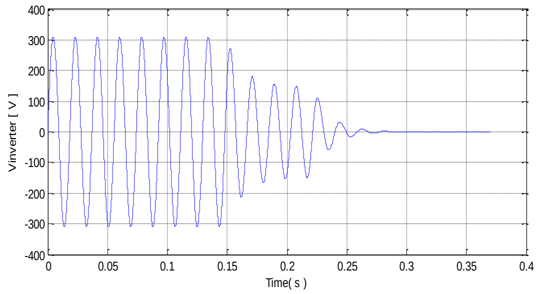
Figure 5. Islanding test results at around zero grid power flow condition: SMS method.



(a1)



(a2)



(b)

Figure 6. Islanding test results at around zero grid power flow condition: AFD method.

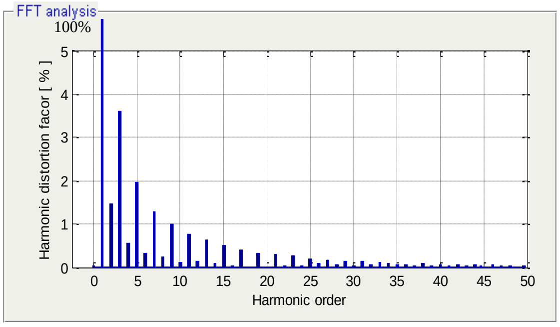


Figure 7. Harmonic spectra of inverter output currents with AFD method.

Fig. 7 shows the Harmonics spectra of the inverter output currents. The THD in the current measured using FFT Analysis under Matlab Simulink is less than 5%. Moreover, the third and the fifth harmonic (<4%) are below the limits set by the standard. This results are consistent with those appearing in the literature [10] for the case of Cf = 0.046.

IV. Conclusion

This paper presents the modeling and simulation of a single phase photovoltaic inverter that operates in islanded mode and utility-connected mode. Modeling and simulation results are given to demonstrate the ability of the developed inverter to provide advanced control functions such as power flow voltage regulation.

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We used the Simulink software platform to develop the single-phase inverter model and the control algorithms, the control designs have been developed in such a way that they could be implemented on a hardware dSPACE platform.

This work aims to find the best solutions that lead to a reduced THD reference current but with same or better NDZ features.

In the next step, the model of the inverter and the control algorithms that we have developed in Matalb / Simulink will be implemented on dSPACE hardware platform. The elaborated algorithm for the AFD and SMS method should be improved to reduce THD to a level required by international standards used in this field.

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