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AN APPLICATION OF PHASOR MEASUREMENT UNIT TO MONITOR A GRID CONNECTED SOLAR ENERGY GENERATION SYSTEM

BY

MAHBOUBI MERIEM*, BENTARZI HAMID and OUADI ABDERRAHMANE

Signals and Systems Laboratory, Institute of Electrical and Electronic Engineering,
University M'hamed Bougara of Boumerdes

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Abstract. While renewable energies are gaining more interest among today's power sources, solar panels are increasing their contribution to the power grid day by day due to the greatest potential they have. Identical to all other types of power generation plants, the integration of solar energy sources into the grid increases its complexity and poses challenges to maintain the system's stability. In this paper, an adaptation of a phasor measurement unit (PMU) based solution is proposed for solar plants integration in regular power grids. PMUs can measure the stamped phasors of the utility, which are critical parameters for the operation of power devices feeding power into the grid. This paper discusses the use of PMUs for providing the phase angle to system synchronization in the case of high penetration of solar energy into the grid, where the instantaneous monitoring of the voltage, current and power flow is an important requirement.

Keywords: Phasor Measurement Unit (PMU); Frequency estimation; Phasor estimation; Solar energy; Synchronization.

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*Corresponding author; *e-mail*: mahboubimeriem92@gmail.com

1. Introduction

In the last few years, the oil industry has seen an acceptance that renewable energies are going to dominate the energy market, due to the decline of the oil era. Furthermore, environmental considerations, like global warming, and the present world coronavirus crisis, might add a significant pressure to topple the dominant energy source. One of the most abundant green energies in the earth that may be used is the Solar energy. Thus, the integration of the solar energy source in the power grid has an impact on its operation, especially that the photovoltaic system's output fluctuates according to the weather conditions, season, and geographic location. Those fluctuations can cause stability issues. Then, monitoring, analysing, protecting and controlling the system operating conditions became highly required for the secure operation of power systems. The traditional monitoring methods were used to detect and measure the errors in the system without phasor measurements, since the synchronization of measurements at different locations was judged difficult to realize. The motivation to make the power system smarter and reliable has attracted many researchers. Significant efforts have been dedicated to the development of efficient and precise measurement algorithms. The development of global positioning system (GPS) technology has overcome the synchronizations' difficulties and leads to the development of phasor measurement units (PMUs) (Phadke and Thorp, 2008). PMU is a standalone, monitoring device, developed in mid 1980s. It measures the electrical waves at specific nodes in the power system. It provides the real time phasor parameters, magnitude, frequency, phase angle and rate of change of frequency (ROCOF), of the voltage and current signals in the grid to determine the health of the system by making it completely observable at any moment. Data provided by PMUs are generated at different locations, in real synchronized time. They are time stamped for synchronization by a reliable and accurate time source; the Global Positioning System (GPS).

To understand the concept of synchro-phasors, the phasor is first defined as an analytical and time-invariant vectorial representation of an AC signal with sinusoidal waveform. Consider the pure sinusoidal signal:

$$x(t) = X_m \cos(\omega t + \varphi) \quad (1)$$

Where ω being the frequency of the signal, Φ is the phase angle and X_m the peak amplitude. $x(t)$ can be represented by a unique complex number known as a phasor, given by:

$$x(t) = Re\{X_m e^{j(\omega t+\varphi)}\} = Re\,[\{e^{j(\omega t)}\}\, X_m e^{j\varphi}] \quad (2)$$

$$x(t) \leftrightarrow X = (X_m/\sqrt{2})\, e^{j\varphi} = (X_m/\sqrt{2})\,[\cos\varphi + j\sin\varphi] \quad (3)$$

The frequency is not explicitly stated in the phasor representation. The magnitude of the phasor is the rms value of the sinusoid, its phase angle is φ in (1), measured in a counterclockwise direction from the real axis. A sinusoidal signal and its phasor representation are illustrated in Fig. 1. Then, a synchro-phasor is defined as the magnitude and angle of a fundamental frequency waveform as referenced to an absolute point of time. It is a phasor tagged with a unique, highly accurate clock time stamp; GPS.

By referencing all PMUs to a common time base, PMU measurements become comparable over a wide area of measurement. This leads to valuable information for several electric power network-based applications.

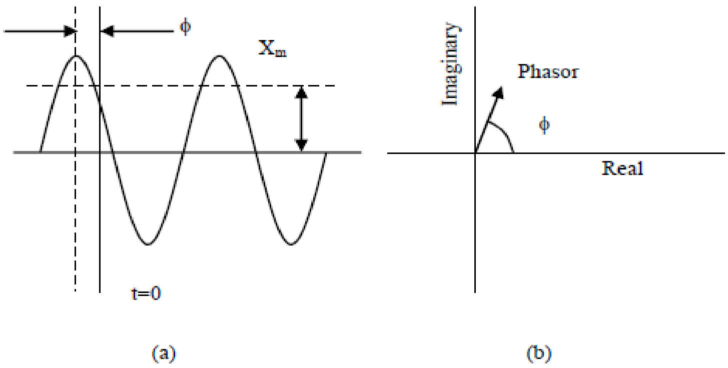

Fig. 1 – A sinusoid signal (*a*) and its phasor representation (*b*).

2. The Simulated Solar Energy Generation System

In this section a simulation of a simplified single stage single-phase grid connected PV System is proposed. In where the chopper stage is eliminated and the output voltage is maintained by the network to which the PV system is connected. Fig. 2 shows the main parts of the system:

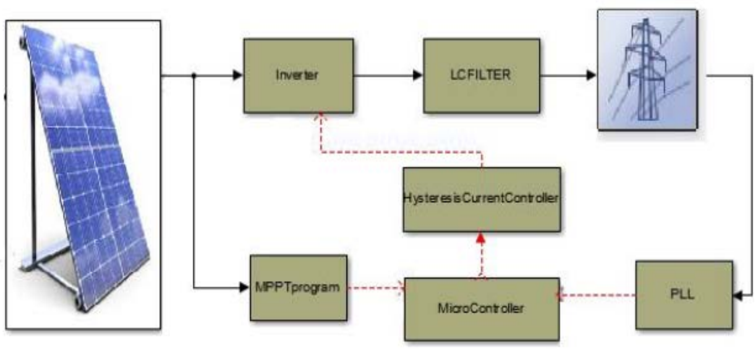

Fig. 2 – PV system’s main parts.

▪ The PV module; the heart of the system, it is a set of PV cells connected either in series or in parallel to constitute PV modules and PV arrays.

▪ single-phase full-bridge inverter with hysteresis current controller. The hysteresis control is used since feedback from the grid is required in the grid connected PV applications.

▪ LC Filter, As PV arrays are integrated into the grid system, power quality issues such as Total Harmonic Distortion (THD) became an increasingly serious concern since the switching devices used to convert power introduce harmonics in the system. In order to eliminate the switching ripples efficiently a low-pass filter at the output is required. The LC-filter is best suited to such configurations where the load impedance across the capacitor is relatively high at, and above the switching frequency. Furthermore, if a system is connected to the grid through an LC-filter, the resonance frequency varies over time as the inductance value of the grid varies.

▪ Microcontroller executing two tasks namely:

– P&O MPPT; The PV system has a non-linear current-voltage and power-voltage characteristics that continuously varies with irradiation and temperature. In order to track the continuously varying maximum power point of the solar array the maximum power point tracking (MPPT) control technique plays an important role. In this simulation the maximum power is obtained using the Perturb and Observe algorithm (P&O) in other words the output current is adjusted by P&O in the direction that increases the power at the output of the PV module.

– sine wave, matching grid voltage, generation to synchronize the inverter output with the grid utility.

2.1. Inverter to Grid Synchronization

The phase angle of the utility is a critical piece of information for the operation of power devices feeding power into the grid like PV inverters. There are many techniques to obtain the grid phase angle like the zero-crossing detection and the orthogonal phase locked loop (PLL) (Guo *et al*., 2011). Orthogonal PLL is a closed loop system in which an internal oscillator is controlled to keep the time and phase of an external periodical signal using a feedback loop. The zero-crossing detection is based on converting the feedback sinusoidal grid signal to an equivalent square wave signal, comparing it to the ground and generating a pulse each time a rising edge is detected; it generates an equivalent periodic pulse representing its frequency. Those pulses are used to generate an equivalent reference signal i_{ref} that will be used in the hysteresis controller. In this section a zero-crossing detection technique is used.

2.2. System Simulation and Results

MATLAB/Simulink software was used in all accomplished simulations. Fig. 3 shows the whole system simulated under 25°C and for different irradiances from 1000 to 800W/m^2. All results are presented below.

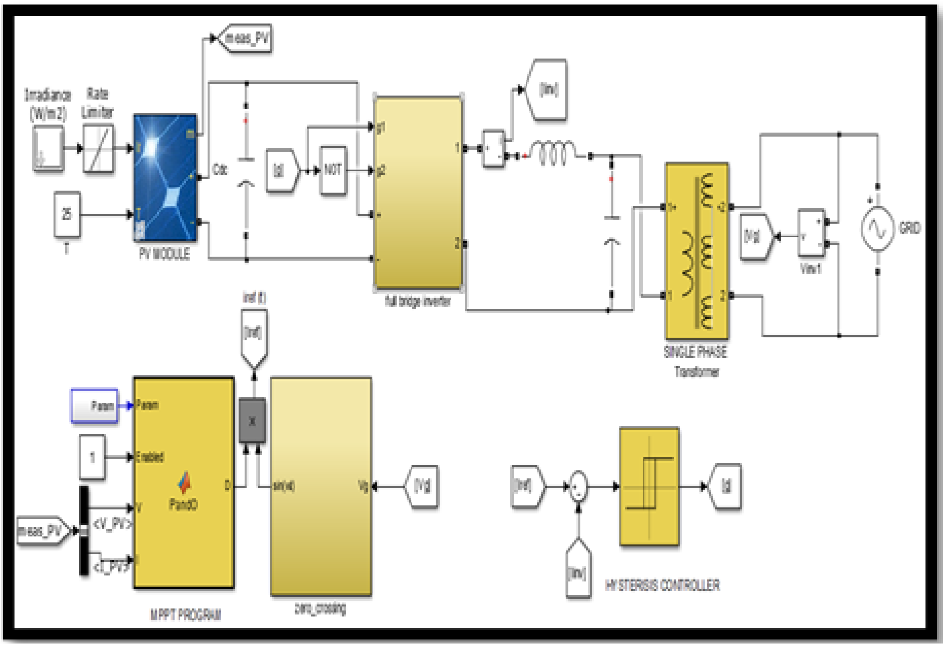

Fig. 3 – Simulation of single phase-single stage grid connected PV system.

▪ The output voltage must match the grid's voltage in phase and magnitude, regardless of the external conditions, however, the current can vary with irradiance and temperature variation.

▪ The desired functionality of this system is to generate power and inject it to the grid. So, the current must be controlled to be out of phase by 180 degrees; the system must be well synchronized. In other words, the frequency of generated current which is the key element that must match with that of the grid. Different techniques are available to detect this frequency, however in this work the zero-crossing technique is adopted.

Fig. 4 represents the inverter's output voltage and current.

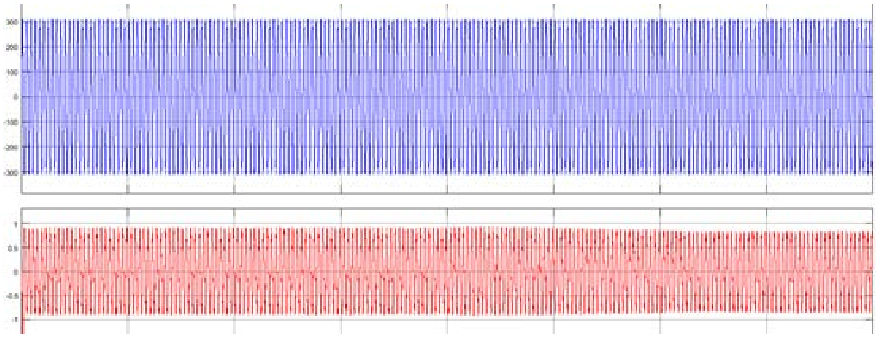

Fig. 4 – Inverters output voltage and current.

Fig. 5 shows the output voltage to the grid versus the injected current in the case of maximum current output from the MPPT algorithm. The output power quality is good; however, the amplitude is small. This small value is due to the use of only one panel, adding to it the system losses and the small reference current.

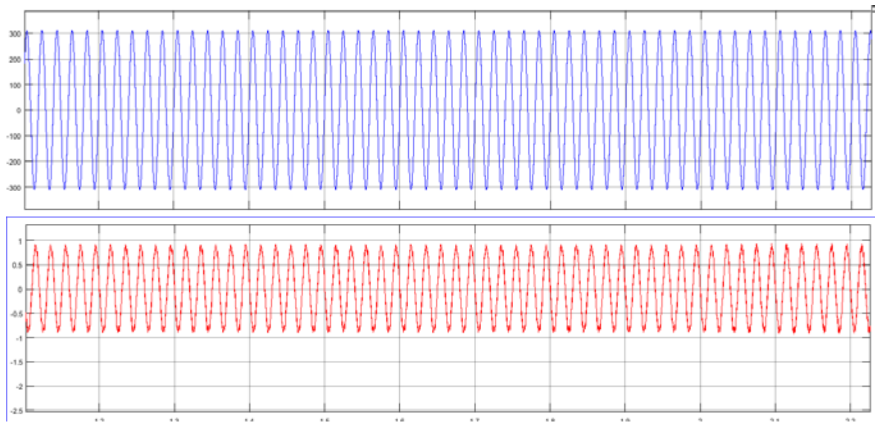

Fig. 5 – Voltage versus injected current controlled by MPPT.

3. PMU Application in Grid Connected PV System

Grid connected applications require an accurate estimate of the grid frequency to feed power synchronously to the grid. Similar to the conventional generating plants, outputs from the solar energy source have an impact on grid operation. Its rapid penetration in the grid requires real time monitoring of the system operating conditions for the secure operation of power system. This can be accomplished by using PMUs. PMU measures voltage and current at a precise time and outputs these quantities in phasor form. This makes the grid completely observable at any moment. Hence, utilities can drastically improve the ability to operate their system dynamics. In fact, PMUs are not only used for time monitoring, loss of mains protection is one of many real time applications that can benefit from PMU deployment. In the grid connected PV system loss-of-mains protection is an important requirement. The role of loss-of-mains protection is to disconnect the PV system from the utility grid to prevent power islands. This islanding scenario is shown in Fig. 6. It is formed when a section of the distribution network has become disconnected from utility supply, but utility customers continue to be energized by an embedded generator. This is undesirable from the point-of-view of power quality, and also poses serious hazards to personnel.

In this section a method of loss of mains protection using a recursive DFT PMU of authors' design is described. The role of the PMU is to continuously monitor the synchronization of the PV system with the grid using real time data from synchro-phasors.

There are two dominant forms of traditional loss-of-mains protection, rate-of-change-of-frequency (ROCOF) and vector shift (VS), as stated in (Laverty *et al.*, 2015), where both techniques are detailed.

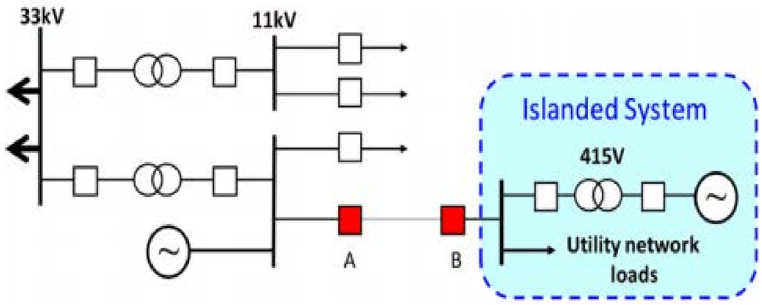

Fig. 6 – Example of islanding scenario.

When using the traditional loss-of-mains techniques it is impossible to distinguish between loss-of-mains events and other system disturbances. A case study on a system that contains distributed generations is detailed in the paper (Rajeev *et al.*, 2016) showing the limitations of traditional methods.

The synchrophasor data from PMU can be used to solve this problem. The proposed solution is shown in Fig. 7.

In this solution PMUs are used to compare the phasor of the PV system with a point on the grid synchronously. The used algorithm and its Simulink simulation are presented in Fig. 8 and Fig. 9 respectively.

If the two values are not the same, a loss of synchronism is probable. To confirm the islanding the data from the two PMUs are compared again after a threshold time. If the result is still different the islanding is confirmed, and the PV system is disconnected from the utility grid using a relay.

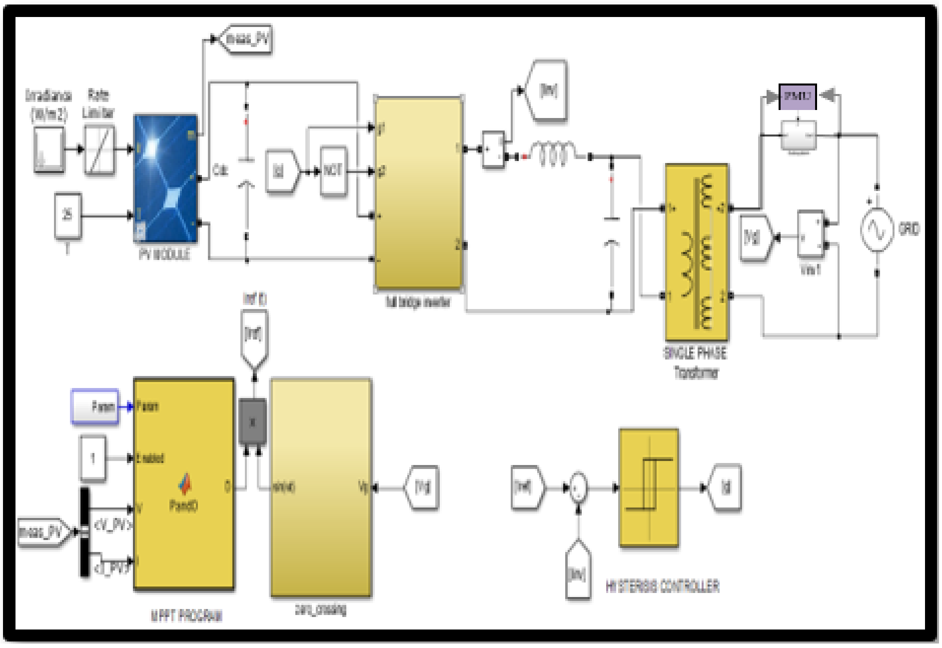

Fig. 7 – Simulation of GCPV system with islanding detection technique using PMUs.

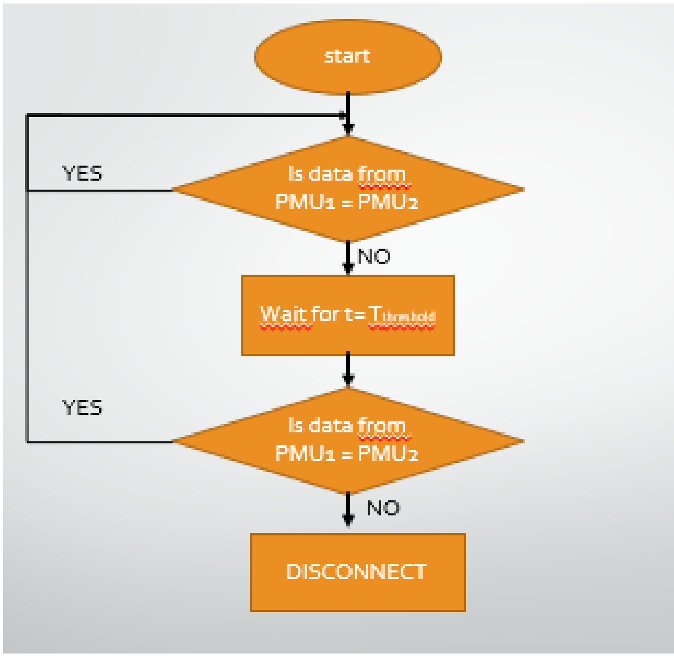

Fig. 8 – Algorithm of the proposed islanding detection technique using PMUs.

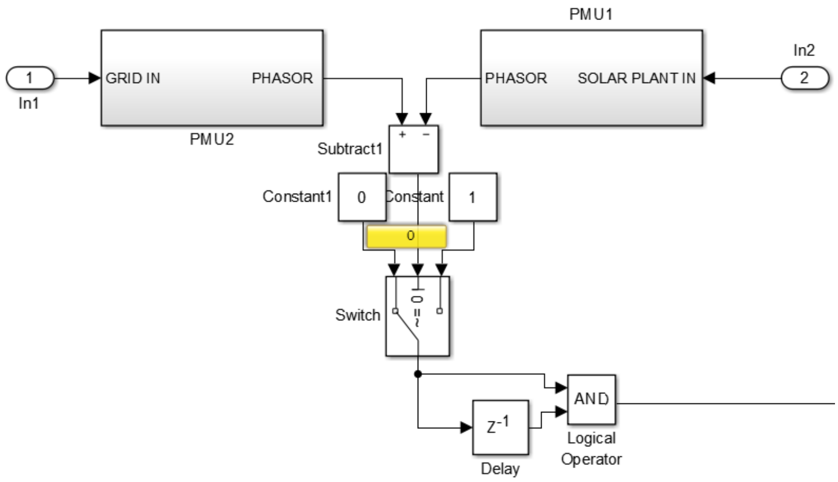

Fig. 9 – Simulation of the islanding detection technique using PMUs.

Using this method, the PV system synchronism is continuously monitored. Hence if synchronism is lost, loss-of-mains is identified. Then the PV system is disconnected from the grid to prevent it from damages.

4. Conclusion

This paper has presented an application of PMUs to solve islanding problems in a grid connected PV system featuring high penetrations. The principle of this solution is to continuously monitor the synchronism of the PV system generator with respect to a reference from the grid using synchrophasor measurements. Based on the phasor measurements the islanding can be determined and security measures such as disconnecting the islanded generator can be taken on time to prevent system damages. The next step in this work would be the implementation of a control system that could fix the causes of islanding.

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APLICAȚIE A DISPOZITIVULUI DE MĂSURARE FAZORICĂ PENTRU MONITORIZAREA UNUI SISTEM DE GENERARE A ENERGIEI SOLARE CONECTATE LA O REȚEA DE TIP GRID

(Rezumat)

În timp ce energiile regenerabile câștigă mai mult interes printre sursele de energie de astăzi, potențialului mare pe care îl au panourile solare fac ca acestea să își sporească de la zi la zi contribuția la energia electrică generată. Deși sursele de energie solară sunt similare celorlalte tipuri de sisteme de generare a energiei, integrarea acestora în rețea crește complexitatea acesteia și poate pune probleme la menținerea stabilității sistemului. În această lucrare, se propune o adaptare a unei soluții bazate pe un dispozitiv de măsurare fazorică (DMF) pentru integrarea centralelor solare în rețelele electrice obișnuite. DMF-urile pot măsura și înregistra în timp fazorii utilității, care sunt parametri critici pentru funcționarea dispozitivelor de alimentare care furnizează energia în rețea. Această lucrare discută utilizarea DMF-urilor pentru furnizarea unghiului de fază la sincronizarea sistemului în cazul pătrunderii unei cantități mari de energie solară în rețea, având în vedere că monitorizarea instantanee a tensiunii, curentului și puterii este o cerință importantă.