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Application of Synchro-Phasor Measurement Unit in Smart Grid Including Renewable Energy

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ABSTRACT

Renewable energy is one of the most abundant energies in our planet. In order to satisfy the world demand of electrical energy, solar and wind energy may be used. Identical to all other types of power generation plants, the integration of these renewable energy sources in smart power grid has an impact on its operation. Thus, when the electrical power is injected into the power grid by these energy sources, the system electrical parameters must be well monitored for synchronization purpose. This can be accomplished with the aid of synchro-phasors measurement units. The phase angle of the utility is a critical parameter for the operation of power devices feeding power into the grid such as PV and wind energy inverters. There are many techniques to obtain the grid phase angle such as the zero-crossing detection and the orthogonal phase locked loop. This research work discusses the use of Phasor Measurement Unit (PMU) for providing this important parameter to system synchronization in the case of high penetration of solar or wind energy in the power grid.

Keywords: Renewable Energy, PMU, Smart Power Grid, PV And Wind Energy, Zero-Crossing Detection, synchronization, Frequency estimation, Phasor estimation, Orthogonal Phase Locked Loop

INTRODUCTION

Renewable energy is being progressively integrated with ambitious targets of renewable energy integration set at national/regional levels. Solar PV and wind power are the front-runners among available renewable energy sources. However, as the penetration of renewable generation increases, the impact on power system dynamics is becoming increasingly apparent, and will become a more integral part of system planning and renewables integration studies. Historically, power systems have been based around large synchronous generators connected to a strongly meshed transmission network, with the dynamic characteristics of such systems being well understood. However, renewable generation, particularly in the form of wind and solar generation, is increasingly universally connected via power electronics interfaces, may well be connected to the distribution network, or weaker parts of the network, may offer new control capabilities, and, of course, is subject to the variability and uncertainty associated with local and regional weather patterns. The time variability and non-dispatchable nature of wind generation may pose substantial challenges, particularly at higher levels of penetration, including an increase in regulation costs and incremental operating reserves, but can also lead to increased opportunities for energy storage, demand side response, cross border interconnections, and other flexibility measures.

On the other hand, evolution of synchrophasor measurement technology, using Phasor Measurement Units (PMUs) for data measurement has opened a vast number of potential applications in the power system world, ranging from monitoring, protection, and control to enhance the smartness and efficiency of power systems. PMU-based Wide Area Monitoring Protection and Control (WAMPAC) can play a vital role in secure and stable integration of renewable energy, particularly in grid operation under high share of renewable (Phadke Arun G, 2008). PMUs make the power system Smarter and reliable has attracted many researchers to have further development in this area. 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 lead to the development of phasor measurement unit (PMU). PMU is a standalone, monitoring device, developed in mid 1980s. It measures the electrical waves at specific node 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) (A.G. Phadke ,2006). The objective of this chapter is to use synchrophasor measurements to solve islanding problem in a network including high penetrations of solar energy generation by performing a continuous monitoring in order to disconnect the islanded generator, and leave it connected if it is not islanded.

LITERATURE SURVEY

In the late seventies, the oil crisis caused a drastic increase in the demand of renewable energy sources. This increase was driven by the remarkable advantages offered by these kind of energy sources namely free resource, infinite reserve and clean conversion process. However, till today, the fuel is still the main source of energy in most power generating systems. While, global warming and energy policies have become a hot topic worldwide. Developed countries are trying to reduce their greenhouse gas emissions. For instance, the European union has committed to reduce their greenhouse gas to at least 20% below 1990 levels and to produce no less than 20% of its energy consumption from renewable sources by 2020 (EUROPEAN COMMISION, 2020). In fact, the secured and safe integration of renewable energy (RE) resources including wind and solar energy to the main grid is one of the biggest challenges for the world energy sector today (Tanveer Ahmada, 2020).

Among all renewable energy sources, the Solar energy is the fastest growing electricity source in the last decade. It is also considered as the cleanest source ever. It can be produced either off-grid or tied to the grid; grid-connected. As a matter of fact, most of the PV power generation comes from grid-connected installations, where the power is fed in the electricity network.

PV power generation is a growing business in developed countries, the first solar power concentrated commercial plant was established in 1980(M.S. Hossain,2016). lately, in 2016, as reported in (M.S. Hossain,2016) the top photovoltaic countries that produced energy from solar were Germany (40,988

MW), China (77,434 MW), Japan (41,600 MW), Italy (19,251 MW), United States (34,711 MW), France (6767 MW), Spain (7171 MW), UK (11,250 MW), Australia (5632 MW), Belgium (3292 MW), Thailand (2154 MW), Netherlands (1955 MW), Switzerland (1644 MW) (M.S. Hossain,2016). The same reference is revealing that the world largest concentrated solar panel installation with 354 MW is in Mojave Desert of California. The biggest solar power stations are located in Spain: Solnova and Andasol about 150 MW both. While, the world's largest photovoltaic power station is found in the United State, the Agua Caliente Solar project with more than 250 MW production, followed by the Charanka Solar Park in India (about 221 MW) (M.S. Hossain,2016). Further details of the solar energy use's statistical improvement throughout the world is presented in (M.S. Hossain,2016).

As the solar energy principle imposes, the power output of the photovoltaic panels is affected by daily and seasonal weather fluctuations, resulting in intermittent electricity generation or a rapid increasing penetration of solar power in the grid. For instance, in Germany, the high penetration of solar generation in the Electric Grid (Von Appen, 2013) has increased grid stability issues (e.g. "The 50.2 Hz Risk") which may endanger the operation of the entire interconnected grid. In order to avoid the risk of major power outages caused by events such as grid failures, the application of smart grid is a solution. It improves efficiency, reliability, cost, and sustainability of the production and distribution of electricity. A smart grid is an intelligent electrical grid that uses modern technologies, hardware, software and even practices for self-detection and self-healing. Yet, this task is complex since most utilities are facing the aging of existing infrastructure, in addition to the uncertainties and variability of the system (Mario Klari´c, 2018). Those problems combined can cause severe faults extending along the grid, to face this, and to ensure power grid stability, it becomes apparent that additional techniques of power system monitoring and control are required. the problems need to be identified and prepared in advance. In addition to the real time monitoring in order to prevent system instabilities at all voltage levels.

In conventional grids, the monitoring is done with a supervisory control and data acquisition (SCADA) system (Gunvant C. Patil ,2017) (D. Kato, 2014). Nevertheless, SCADA systems can only measure the magnitude of voltage and current but not the phase. Furthermore, it requires separate data acquired from oscilloscope devices installed in substations to measure information needed to analyze transient phenomena (D. Kato, 2014). A better technology to monitor the grid is Phasor measurement units (PMUs) (Gunvant C. Patil ,2017). PMUs are gaining attention as a technology that can provide operators with high-precision, time-synchronized measurements of the situation awareness they need. They have already been defined as suitable for many applications of larger renewable energy integration. Data gathered by PMUs have a short measurement cycle and are synchronized using absolute time. These advantages mean that even when an accident occurs, waveform information from multiple locations gathered at the time of the accident can be used in detailed accident analysis to create prevention measures for future accidents and to minimize the consequences. This chapter emphasizes on the application of PMUs in the Grid connected PV system for synchronization purpose and shows how it can be benefical in solving one of the most common problems that faces such systems; the islanding problem in a network including high penetrations of solar energy generation.

PHASOR MEASUREMENT UNIT: OVERVIEW

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:

$$x(t) = Xm\cos(\omega t + \varphi) \tag{1}$$

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

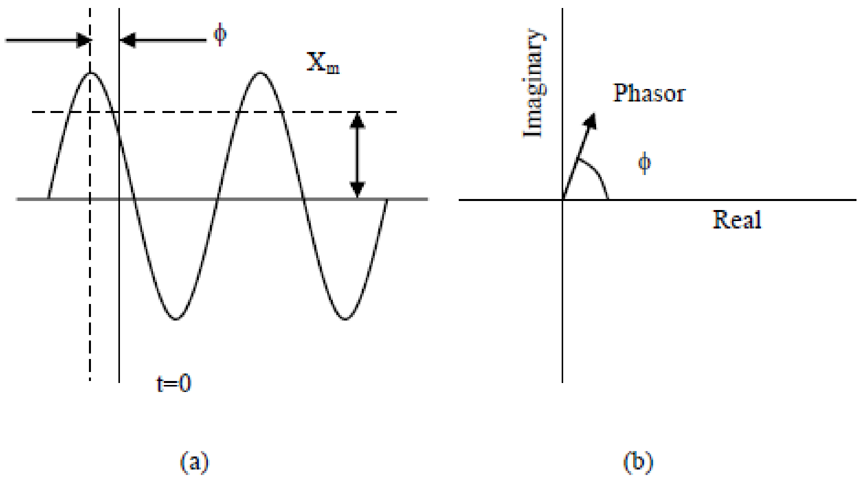
$$x(t) = Re\{ Xmej(\omega t+\varphi) \} = Re [\{ej(\omega t) \} Xmej\ \varphi] \quad (2)$$

$$x(t) \leftrightarrow X = (Xm/\sqrt{2})\ ej\ \varphi = (Xm/\sqrt{2})\ [\cos \varphi + j\sin\varphi] \quad (3)$$

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 Figure 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 (Phadke Arun G, 2008).

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 (Phadke Arun G, 2008).

Figure 1. (a) a sinusoid signal (b) and its phasor representation (Phadke Arun G, 2008)



This may delay the understanding and analysis of certain power system phenomena and hence the development of certain power system applications. To remove this barrier, phasors measured across the power grid should have a common timing reference such that direct comparison is feasible.

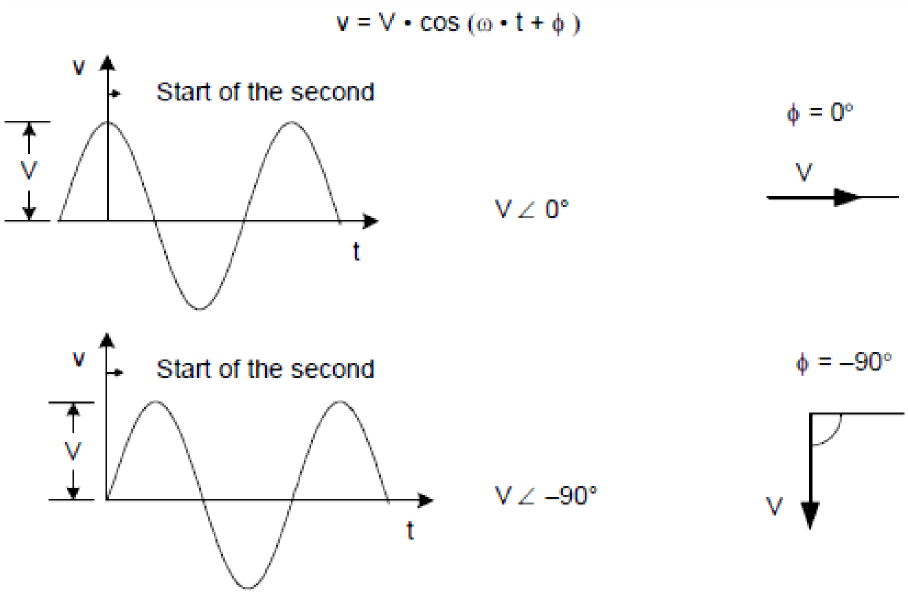
A synchrophasor is defined according the IEEE standard C37.118 as, A phasor calculated from data samples using a standard time signal as the reference for the measurement; however, synchronized phasors from remote sites have a defined common phase relationship (C37.118-2005, March 2006.). Thus, synchrophasors measured across an interconnected power grid will have a common timing reference and they can be compared directly as illustrated in Figure 2.

According to the same standard, a synchronizing source that provides the common timing reference may be local or global. The synchronizing signal may be distributed by broadcast or direct connection, and shall be referenced to Coordinated Universal Time (UTC). One commonly utilized synchronizing signal is the satellite signal broadcast from the Global Positioning System (GPS).

The definition of a real-time or synchronized Phasor provided in the IEEE Standard 1344-1995 (Phadke, A. G.,1993) (1344-1995, 2001) corresponds to the conventional definition described earlier, at least at rated frequency (50 Hz or 60 Hz). With real-time waveforms, it is necessary to define a time reference to measure phase angles synchronously (Power System Relaying Committee of The IEEE PES, 2006). The IEEE Standard 1344-1995 (Phadke, A. G.,1993) (1344-1995, 2001) defines the start of the second as the time reference for establishing the phasor phase angle value. The synchronized phasor measurement convention is shown in Figure 2.

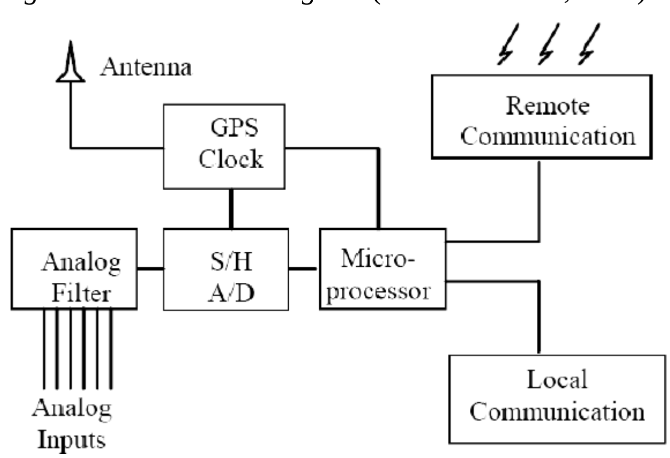
The instantaneous phase angle measurement remains constant at rated frequency when using the start of the second phase reference. If the signal is at off-nominal frequency, the instantaneous phase varies with time. It can be seen later that the choice of this reference has an impact on the phasor phase angle measurement at off-nominal frequency.

Figure 2. Synchrophasor measurement conventions with respect to time (C37.118-2005, March 2006.)



A PMU is a standalone device that measures 50/60 Hz AC voltage and current signals and provides them in phasor form with their frequency. The analog AC waveforms are digitized by an analog to digital converter for each phase and a phase-lock oscillator and a GPS reference time source, often called pulse per second (PPS) provides high-speed time synchronized sampling as illustrated in Figure 3. A PMU calculates line frequency, as well as voltage and current phasors at a high sampling rate and streams those data, along with the associated GPS time stamp, via networked communication lines. The synchrophasors can be phase or symmetrical component values.

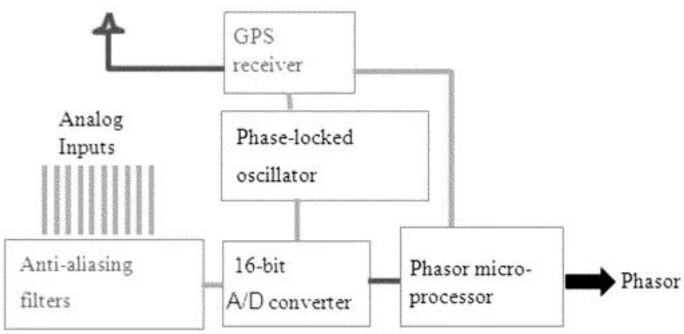
Figure 3. PMU block diagram (Phadke Arun G, 2008)



At present, phasor measurement units (PMUs) are the most accurate and advanced synchronized phasor measurement equipments. They measure 50/60 Hz sinusoidal waveforms of voltages and currents at a high sampling rate, up to 1200 samples per second and with high accuracy. From the voltage and current samples, the magnitudes and phase angles of the voltage and current signals are calculated in the phasor microprocessor of the PMU. As the PMU uses the clock signal of the Global Positioning System (GPS) to provide synchronized phase angles measurements at all the measurement points, the measured phasors are often referred to as synchrophasors. Thus, a Synchrophasor 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.

Figure 4 illustrates a functional block diagram of a typical PMU. The GPS receiver provides the 1 pulse-per-second (pps) signal, and a time tag consisting of the year, day, hour, minute, and second. The l-pps signal is usually divided by a phase-locked oscillator into the number of pulses per second required for the sampling of the analogue signals. The analog signals are derived from three-phase voltage and current transformers with appropriate anti-aliasing filtering. The microprocessor calculates the positive sequence voltage and current phasors, and determines the timing message from the GPS, along with the sample number at the beginning of a window.

Figure 4. Functional block diagram of a typical PMU (Phadke Arun G, 2008)



PV GENERATION SYSTEM

This section deals with the simulation of a simplified single stage single-phase grid connected Photovoltaic (PV) System. In the PV system the chopper stage is eliminated and the output voltage is maintained by the network to which the PV system is connected.

Figure 5 shows the main parts of the PV system, which are:

1. **PV module:** This is the heart of the system, which is a set of PV cells connected either in series or in parallel to constitute PV modules and PV arrays.a numbered term.
2. **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.
3. **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

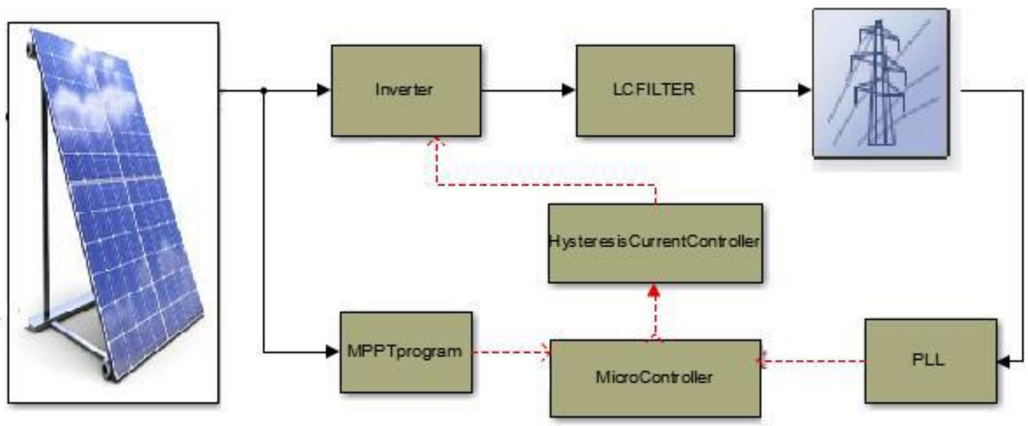
ripples efficiently a low-pass filter at the output is required. The LC-filter is best suited to such configurations where the load impedance across the capacitor is relatively high at, and above the switching frequency. Furthermore, if a system is connected to the grid through an LC-filter, the resonance frequency varies over time as the inductance value of the grid varies (Xiao-Qiang GUO, 2011).

4. **Controller or Microcontroller:** it may execute two tasks namely:

   a. 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.

   b. Sine wave, matching grid voltage, generation to synchronize the inverter output with the grid utility.

Figure 5. PV system's main parts (Mahboubi M, 2019)



Thus, Maximum Power Point Tracking (MPPT), Grid synchronization, Islanding, DC-link voltage control and Current control are the major factors which are required for a grid-tied photovoltaic system to work efficiently and effectively. Phase, amplitude and frequency of the utility voltage are critical information for the operation of the grid-connected inverter system. For grid synchronization scheme may need phase, amplitude and frequency of utility voltage that is used to generate reference signal. Actuate and fast detection of these parameters are essential in order to keep grid parameters within range as mentioned in standards. This research work shows how PMU can provide these parameters and they can be used for different grid synchronization in power grid including a connected photovoltaic system.

INVERTER TO GRID SYNCHRONIZATION

The phase angle of the utility is a critical 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 (Xiao-Qiang GUO, 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.

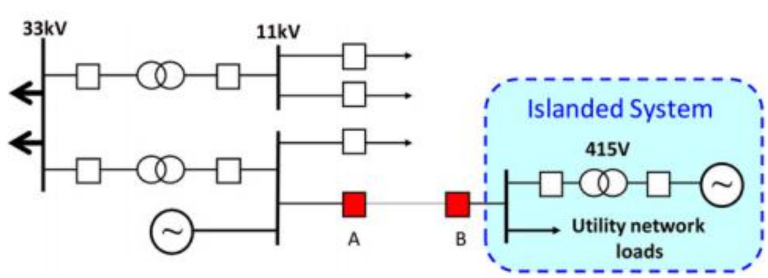
- **The zero-crossing detection** is based on converting the feedback sinusoidal grid signal to an equivalent square wave signal, compare it to the ground and generate a pulse each time a rising edge is detected; it generates an equivalent periodic pulse representing its frequency.

However, when a PMU is used, it provides the phase, the amplitude and the frequency of the utility voltage. These provided data can be used to generate pulses which in turn are used to generate an equivalent reference signal iref. Then, the generated reference signal will be used in the hysteresis controller.

PMU APPLICATION IN GRID CONNECTED PV SYSTEM

Grid connected PV system requires an accurate estimate of the grid frequency to feed power synchronously to the power grid. Similar to the conventional generating plants, outputs from the solar energy source have 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 output 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 figure 5. It is formed when a section of 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 (Rajeev A, 2016).

Figure 5. Example of islanding scenario (Rajeev A, 2016)



This section describes a method of loss of mains protection based on PMU technology, specifically using a PMU device of authors' design, which continuously monitors the synchronization of the PV system with the grid by means of 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). Both techniques operate on the principle that at the moment of island formation there will be an imbalance between islanded load and islanded generation. Islanding is inferred from a change in the pattern of zero-crossings of the voltage waveform (Rajeev A, 2016).

It is not possible to adequately differentiate loss-of-mains events from widespread system disturbances using traditional loss-of-mains techniques which rely only on the measurement at the point of connection of the embedded generator to the grid. A case study realized on a system that contains distributed generations is detailed in (David M. Laverty, 2015). It shows that ROCOF method is prone to undesired operation, or nuisance tripping.

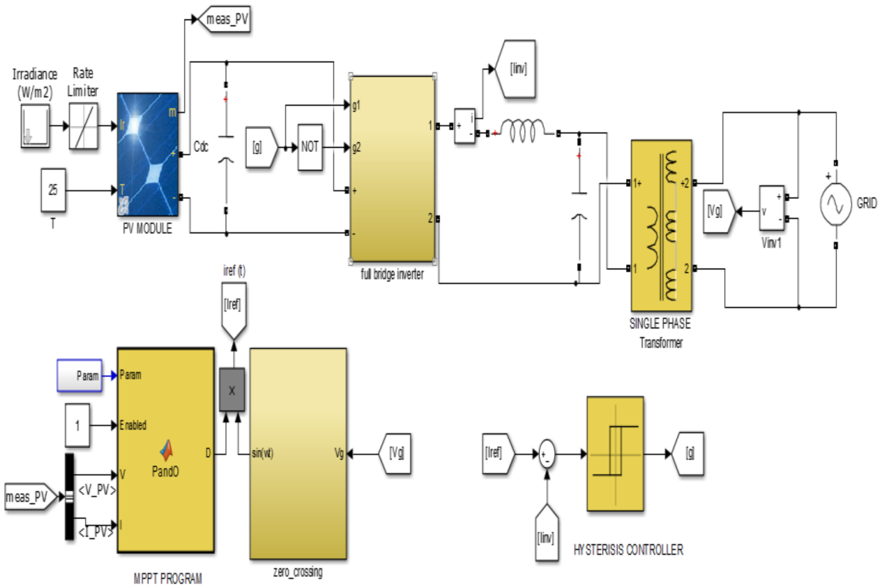
The synchrophasor data from PMU can be used to solve this problem. The proposed solution is discussed in the next section.

SYSTEM SIMULATION AND RESULTS

Case 1: Grid connected PV system synchronization using PMUs

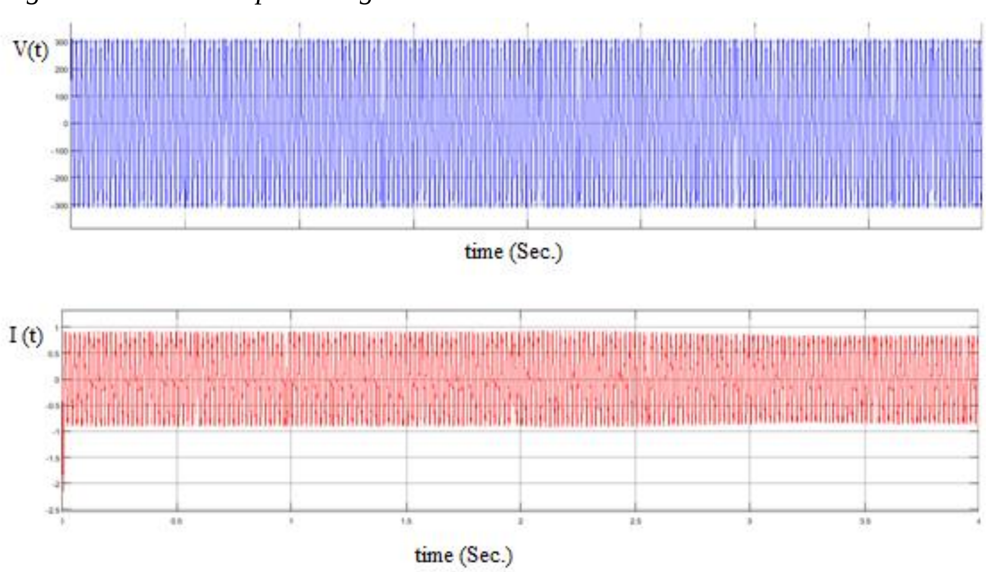
In this research work, the last technique for synchronization is used. MATLAB/Simulink software has developed in all accomplished simulations. Figure 6 shows the Simulink model of whole system that is simulated under 25°C and for different irradiances from 1000 to 800W/m2. All results are presented here.

Figure 6. Simulink Model of a connected PV system



The output voltage must match the power grid voltage in phase and magnitude, regardless of the external conditions, while, the current can vary with irradiance and temperature variation as illustrated in Figure 7.

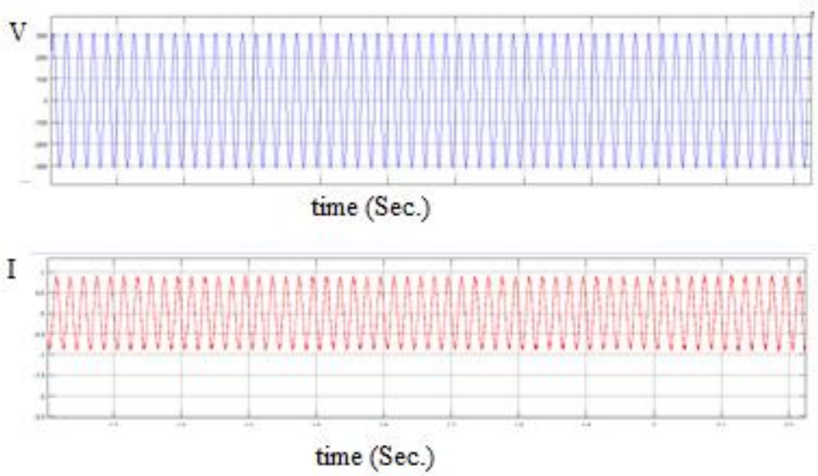
Figure 7. Inverter output voltage and current



The output voltage must match the grid voltage in phase and magnitude, regardless of the external conditions, however, the current can vary with irradiance and temperature variation. When the current is in phase with the voltage, the power is positive and the inverter receive power from the grid. Since the desired functionality of this system is to generate power the current must be controlled to be out of phase by 180 degrees, resulting in negative power which means that the system supplies or injects power to the grid. To send power into grid, the system must be well synchronized. In other words, the frequency of generated current which is the key element must match with that of the grid. Different techniques are available to detect this frequency; however, in this work the PMU based frequency technique is adopted.

Figure 8 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.

Figure 8. Inverter output voltage and current using MPPT controller.



Case 2: Grid connected PV system with an islanding detection technique using PMUs

Grid connected PV system requires an accurate estimate of the grid frequency that may be used to feed power synchronously to the power grid. The synchrophasor data from PMU can be used to provide this accurate frequency. In this solution PMUs are used to compare the frequency and phase angle of the PV system with a secure point on the grid synchronously. The used algorithm and its Simulink subsystem are presented in figures 9 and 10 respectively. If the two values are different, 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 circuit breaker.

With this method a continuous monitoring of the PV system synchronism is the principle of operation. If synchronism is lost, then loss-of-mains is identified. Hence, the PV system is disconnected from the grid.

Figure 9. Algorithm of the proposed islanding detection technique using PMUs

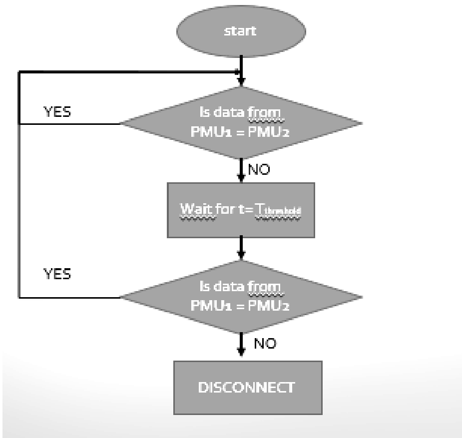
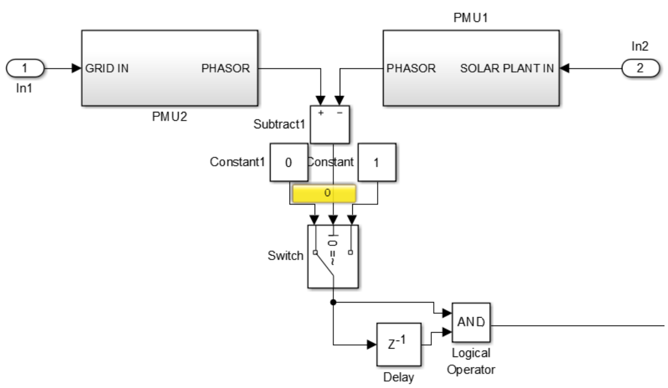


Figure 10. Islanding detection technique Simulink Subsystem using PMUs



CONCLUSION

In this study, the output of a solar PV power generation system is controlled via a hysteresis current controller and used to inject a power into the utility grid. However due to the use of only one panel the inverter's output is small. Yet, for a series and parallel PV panels connection this proposed configuration can greatly satisfy the power demand, limit the use of conventional power generation techniques and also it is the only mean to tackle the future power requirements. Using solar PV power generation system saves the fossil fuels from depletion, limits global warming and keeps the environment clean and green.

This chapter presents the application of PMUs to Grid connected PV system for synchronization purpose. Then it investigates the use of PMUs to solve islanding problem in a network including high penetrations of solar energy generation. In the first application, a PMU is used to provide the necessary data to generate pulses which in turn generate an equivalent reference signal iref. this last will be the reference signal in the hysteresis controller. While, the second application shows how the use of synchrophasor measurements makes the islanding detection easier. This is done by comparing the phasor of the PV system generator with respect to a reference from the grid. Using this method means performing a continuous monitoring of the tied system in order to disconnect the generator if islanded, and leave it connected if it is not. .

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