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Synchronous reference frame phase locked loop in grid tied solar photovoltaic system

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Abstract: The role of solar photovoltaic system in the production of electricity is steadily growing. A grid tied solar photovoltaic system is becoming more and more common because of the plentiful sunshine and advanced power technologies. The synchronization process or how to synchronize an inverter with the grid is a significant issue in the integration of a solar photovoltaic system and the grid. Using a proper synchronization method improves the power transfer between the inverter and the grid. The major factors that need to be measured and synced are frequency, phase and voltage magnitude. In this synchronization process, a Synchronous Reference Frame Phase Locked Loop (SRF PLL) is employed to identify the phase angle of the grid under normal and abnormal grid situations. Anti-islanding protection, a frequently demanded safety feature which will disconnects the inverter from the grid and limits the power flow from the inverter to loads when the grid enters a fault condition. It is important to ensure this protection when using a grid tied solar photovoltaic system, is presented in this paper.

Keywords: Synchronization, anti-islanding, SRF PLL, grid, solar.

I. INTRODUCTION

Distributed generation (DG) systems are being encouraged by government policies worldwide to lower greenhouse gas emissions due to the rising concern about the quick depletion and rising cost of fossil resources[1]. Particularly, those DGs that rely on renewable energy sources like hydro power, windmills, and solar photovoltaic (PV) plants are taken into account. Renewable energy, sometimes known as clean energy which is derived from naturally replenishing sources or processes. It has a number of benefits, including the need for less maintenance, financial savings, lack of pollution, multiple advantages for the environment and human health and storage capacity. Due to its many benefits including its cheap operating cost, lack of noise or mechanical moving parts, lack of CO_2 or other harmful gas emissions, flexibility in size, and usefulness in arid locations, one of most environmental friendly energy sources is solar, that is rapidly expanding. The growth and committed to offering clean, dependable electricity to individuals in rural locations is also making sure that communities have access to safe and dependable electricity. In solar PV system, there are off grid and on grid solar system. In off grid system, grid is not presented and instead of that it requires battery system for backup. So, it makes the system bulky and costly and also it requires frequent maintenance operations. Whereas in on grid system otherwise called as grid connected system where solar is connected to grid and it doesn't require any battery system. So it makes the system less expensive, less bulky, reliable and easy to install[4].

When operating in grid connected mode, photovoltaic (PV) systems are matched with the grid according to IEEE standards for voltage, phase, and frequency. Synchronization is the process of integrating a PV system with the grid to share load while using a power converter. In point of common coupling (PCC), a power electronics converter interface connects the PV system to the primary utility. Grid synchronization [9] or how to synchronize the grid with the inverter, is one of the issues that grid connected systems encounter. The synchronization technique goal is to provide data on the grid amplitude, frequency, and phase in order to generate a voltage or current reference that is in phase with the utility voltage, matches the output of the inverter, and also delivers real power into the utility to meet load requirements. Grid connected PV needs to be properly synced with the grid. Grid synchronization may result in significant transient currents at the time of connection if it is not properly constructed, which could damage equipment and result in frequency variations, waveform distortions, and phase shifts.

Solar PV systems that are connected to the grid will operate with several power quality and safety issues. Voltage and frequency regulation, flickering, waveform distortion, etc. are a few of the power quality issues. Protection from islanding, responding to abnormal utility circumstances as voltage and frequency disturbances, being able to reconnect after a utility disturbance, grounding, etc. are a few of the issues related to safety. Unintentional islanding is a significant safety issues with grid connected solar systems among all the other issues. A circumstance in which a segment of the power system that comprises both load and distributed energy resources (DER) stays electrified while isolated from the rest of the power system is known as islanding, also known as loss of grid or loss of mains[13]. Additionally, an island denotes a situation in which a segment of an area electric power system (EPS) is electrically isolated from the rest of the EPS and is only powered by one or more local DER through the associated point of common coupling (PCC)[3]. When

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a section of the utility grid loses contact with the rest of the system, islanding occurs. Both intentional and unintentional islanding are possible. An unintentional island is one that wasn't planned, whereas an intentional island is one that was. When a section of the area EPS is unintentionally split off from the rest of the area EPS and the DER still supplying power, an island may unintentionally arise. Unintentional islanding in DGs grid interconnection is still a significant challenge for grid connected systems since the system could fail to activate the safety mechanisms when the system is islanded. This causes problems with the power supply, protection, reverse power flow, and system stability. Utility personnel may also die as a result, as they may not realize the region is still powered and suffer a fatal electric shock. Because of this, a grid tied solar PV system must be able to detect islanding and instantly cut itself off from the grid (this is known as anti-islanding)[11]. Since a grid tied solar PV system disconnects from the grid when there is a grid fault, restricting the supply of power to the loads, anti-islanding with quick response time is crucial. The system then reconnects with the grid when the grid is restored.

The paper aims to synchronize solar PV system with the grid and also ensuring anti-islanding protection for improving the power quality and safety issues.

II. GRID TIED SOLAR PHOTOVOLTAIC SYSTEM USING SRF PLL

The figure 1 below shows the single phase solar grid tied system circuit diagram.It consist of PV array, single phase inverter, grid, load then SRF PLL for synchronization and a circuit breaker.

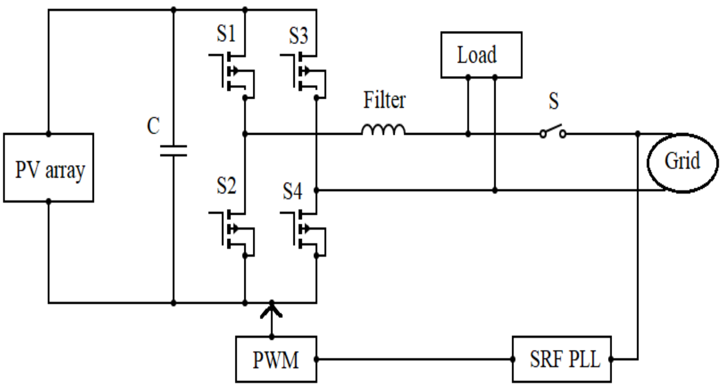

Fig 1: Circuit diagram of single phase grid connected solar system using SRF PLL.

PV array is directly connected to the inverter and the inverter is connected to the grid. The basic operation of grid tied is same as explained in the three phase system that is grid poses bidirectional power flow. If there is no supply from grid then automatically the inverter will shut down and does not generate any power. For injecting power from inverter to grid with high power quality, a proper synchronization technique is needed that will match phase, frequency and voltage of grid with the inverter phase, frequency and voltage. For this SRF PLL is used which will properly synchronize with fast, accurate and less computation. A circuit breaker is placed between inverter and grid for ensuring anti-islanding protection and to improve the safety and power quality.

A. COMPONENTS

- PV panel: Solar energy is converted into DC electrical energy using a solar PV array. A number of solar PV modules are connected in series and/or parallel to form the array. A parallel connection is utilized to boost current output, whereas a series connection increases voltage output. A series-parallel coupled solar PV array is created by connecting several series strings in parallel with a number of series strings connected in series. Modules may also be linked together in a parallel string.
- Inverter: The inverter is used to convert PV array DC output to AC voltage and current. For single phase, inverter with four switches are used. The output of inverter is tied to mains AC grid as well as loads. Therefore, the power flow is unidirectional. The inverter injects AC current into the mains AC grid.In a solar grid tied system, the inverter output voltage, frequency, phase angle must be matched with the grid voltage, frequency, phase angle. By using a proper synchronization method, the matching can be done.
- Grid: Grid is used as electrical supply. The grid power flow is bidirectional, acting as both a source and a sink depending on the electricity generated by the sun.
- Load: A load is connected which receives power from inverter as well as grid according to the solar power generation.

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- SRF PLL: The block diagram of single phase SRF PLL is shown in figure below.

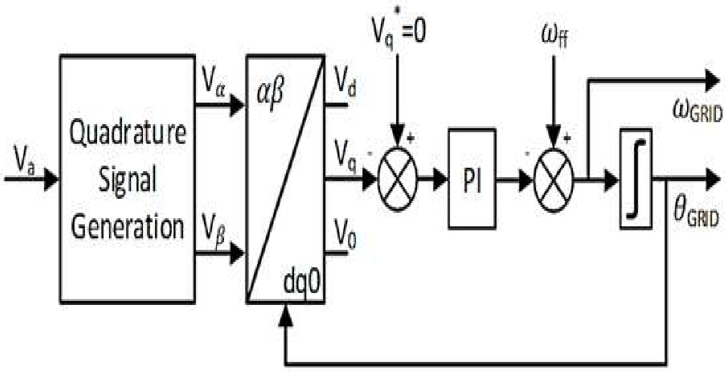

Fig 2: Basic block diagram of single phase SRF PLL.

Here, single phase voltage is converted to alpha and beta voltages by Clarke's transformation. V_α and V_β are transformed to direct axis and quadrature axis voltages. By setting V_q as zero is controlled by the PI controller. The output of PI controller is the frequency of grid and by integrating the frequency, phase angle of grid is obtained.
1) Stationary reference frame (αβ): Single phase voltage is transformed to V_α and V_β which are 90 degree apart.

$$\begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix} = V_m \begin{vmatrix} \cos\theta \\ \sin\theta \end{vmatrix}$$

2) Rotating reference frame (dq): Here, V_α and V_β is transformed into V_d and V_q .

$$\begin{vmatrix} V_d \\ V_q \end{vmatrix} = \begin{vmatrix} \cos\theta' & \sin\theta' \\ -\sin\theta' & \cos\theta' \end{vmatrix} \begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix}$$

- Anti-islanding protection: PV inverters are turned off by anti-islanding protection, a frequently demanded safety feature, when the grid experiences an islanded condition. UL1741 or IEEE 1547 require anti-islanding protection [12]. An Area EPS must be de-energized within two seconds of the establishment of an island, as per IEEE 1547. In other words, the PV plant interconnection system must identify an unintentional island and stop energizing the grid within two seconds of its generation if the PV Plant energizes a portion of the grid through the interconnection point. When there is a grid outage, PV systems that are in anti-islanding mode continue to send power to loads, which can sometimes cause damage to the loads and can have an impact on technician safety during maintenance operations. Anti-islanding features must be used to prevent these problems since they become active when there is a grid fault and a solar system disconnects from the grid, never supplies electricity to loads, and then reconnects when the grid is restored. To achieve anti-islanding protection, over current relay is used here. A protection relay known as an over current relay activates when the current exceeds a preset value. The electrical power supply is protected from excessive currents caused on by short circuits, ground faults, etc. by over current protection.

III. SIMULATION AND RESULTS

To evaluate the performance of synchronization of solar PV system with grid, simulation is done using MATLAB / Simulink. To ensure that the inverter is synchronized with grid using SRF PLL and also ensure anti-islanding protection.

A. SINGLE PHASE SRF PLL

Simulation parameters and its values for SRF PLL using single phase are summarized in Table 1 below.

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Table 1: Simulation parameters for SRF PLL.

Parameters	Values
Grid	230V, 50Hz
Proportional constant, K_p	10
Integral constant, K_i	50000

Figure below shows the simulation results of single phase SRF PLL under normal grid condition. The figure 3 below shows the balanced single phase supply from grid with peak voltage amplitude 325V.

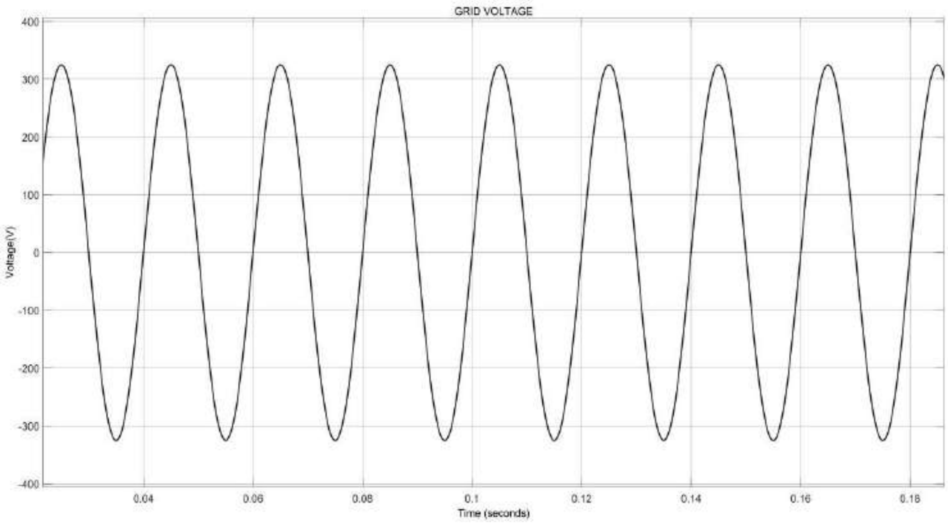

Fig 3: Waveform of single phase grid voltage.

The single phase voltage of grid is converted to alpha and beta components of voltage using Clarke transformation. Figure 4 are the alpha and beta components of voltage, both having same magnitude of grid voltage of 325V. From this waveform, it is understood that V_α and V_β are displaced by 90 degree .

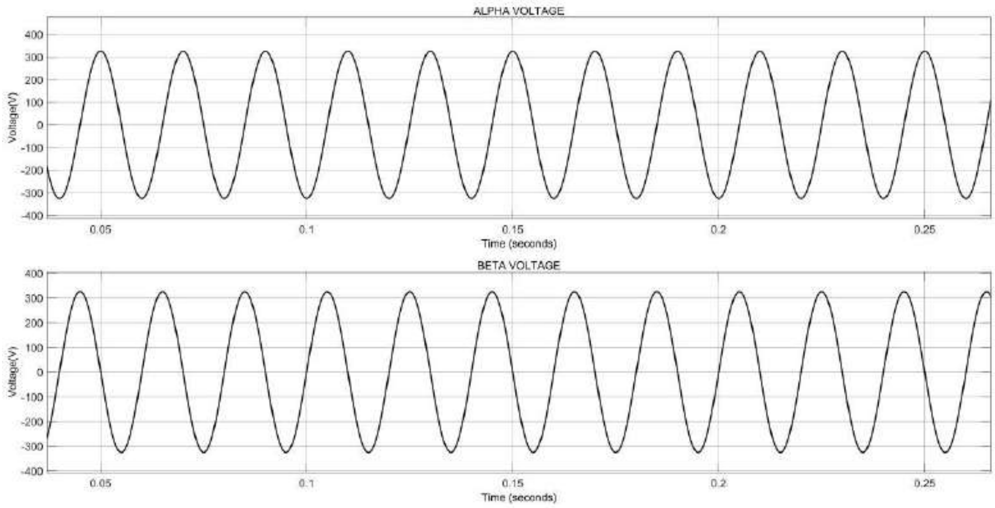

Fig 4: Waveform of alpha and beta voltage.

Figure 5 represents quadrature axis voltage V_q and direct axis voltage V_d. V_d having same amplitude of the grid voltage which is 325 and V_q is setting to zero by the control loop. The output of PI controller is the frequency of grid of 315 rad/sec which is shown in figure 6 and by integrating this frequency, phase angle of 30 degree is obtained shown in figure 7.

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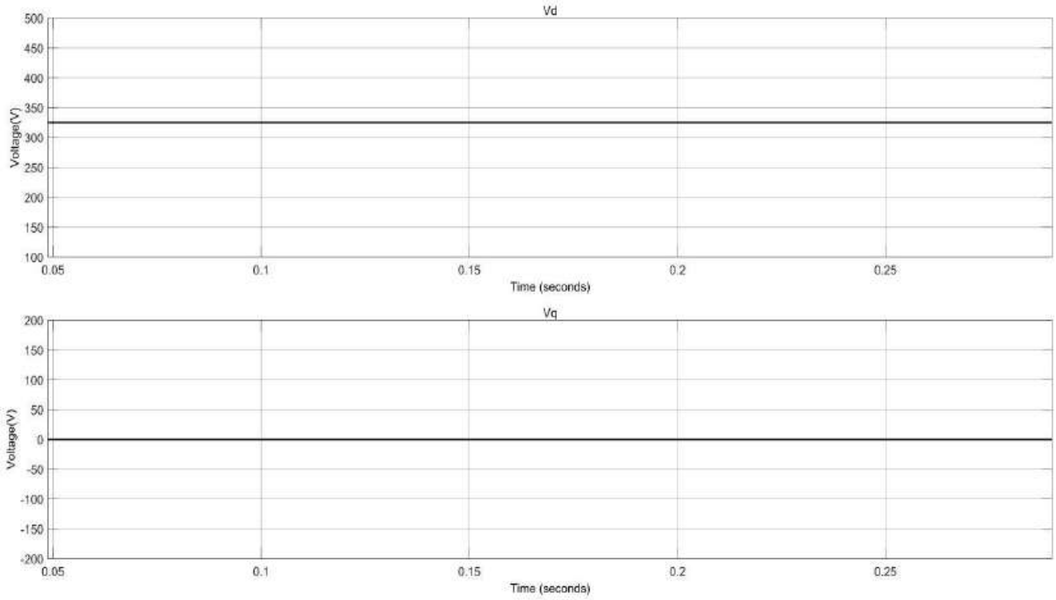

Fig 5: Waveform of d and q axis voltage.

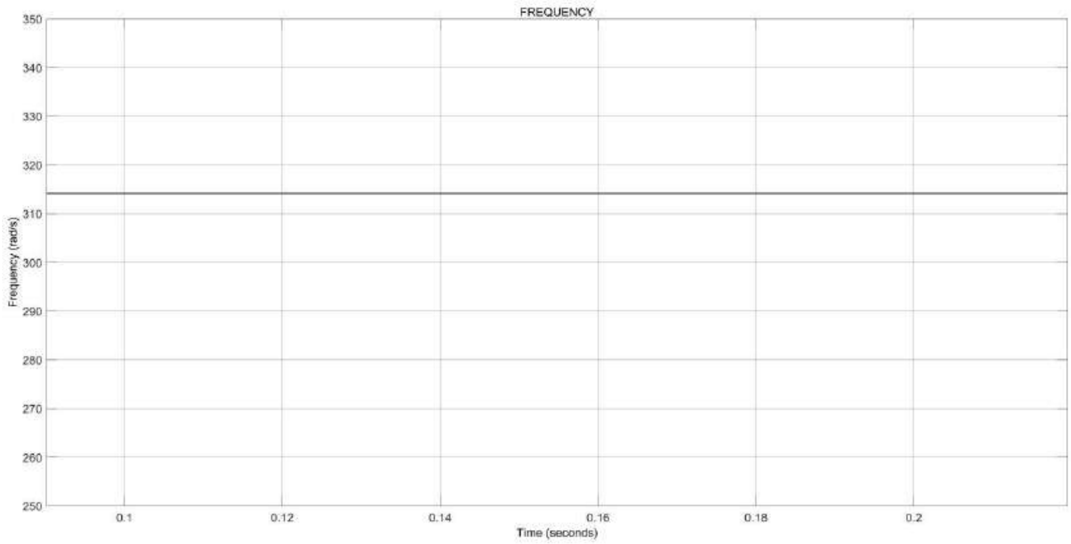

Fig 6: Waveform of frequency of grid.

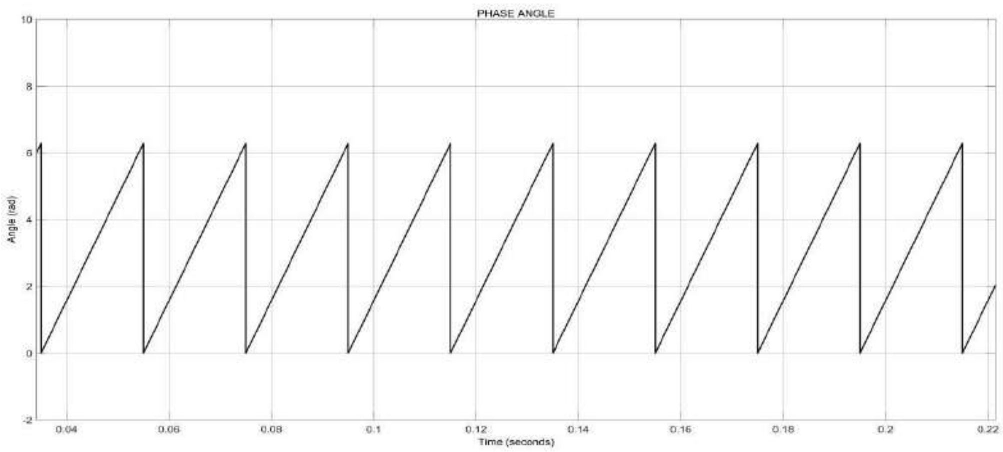

Fig 7: Waveform of phase angle of grid.

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From these results, it is clear that SRF PLL can detect and measure phase angle fastly and accurately.

B. SINGLE PHASE SOLAR GRID TIED SYSTEM

Solar grid tied is simulated using SRF PLL under normal grid condition in MATLAB/ simulink. Simulation parameters and its values are summarized in Table 2 below.

Table 2: Simulation parameters

Parameters	Values
Grid	12V, 50Hz
Load	50W, 12V
Inductor filter	4.06mH, 4.35mH
Capacitor filter	6.23µF
Switching frequency	50KHz

Figure 8 is the voltage and current from panel is 35 and 1.42A .

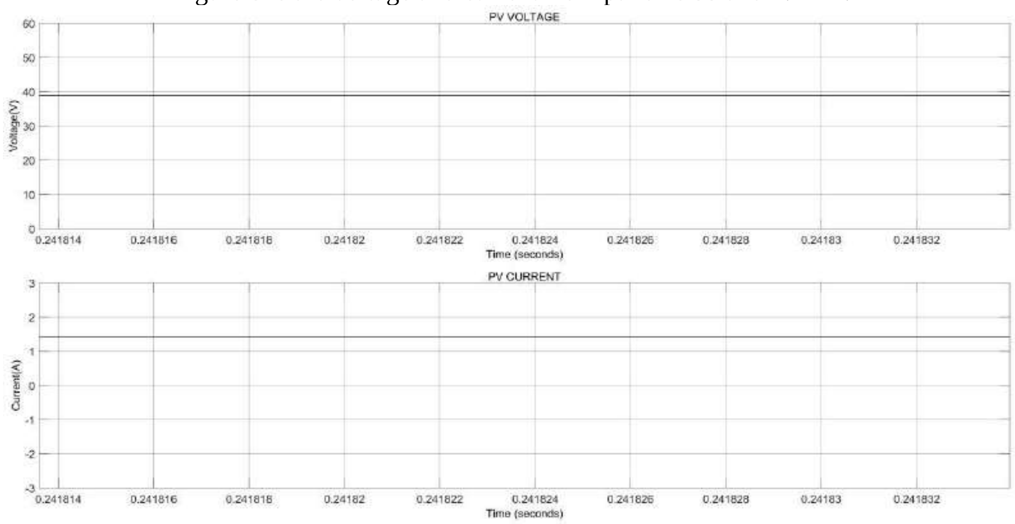

Fig 8: Waveform of voltage and current from panel.

The voltage and current from the inverter is shown below in 9. Voltage of peak amplitude 17V and current obtained as 6A.Voltage and current of load is shown in figure 10.Voltage obtained as 17V peak and current is 5.4A. This represents that the inverter current is flow to the load and the load will consumed it according to their power demand.

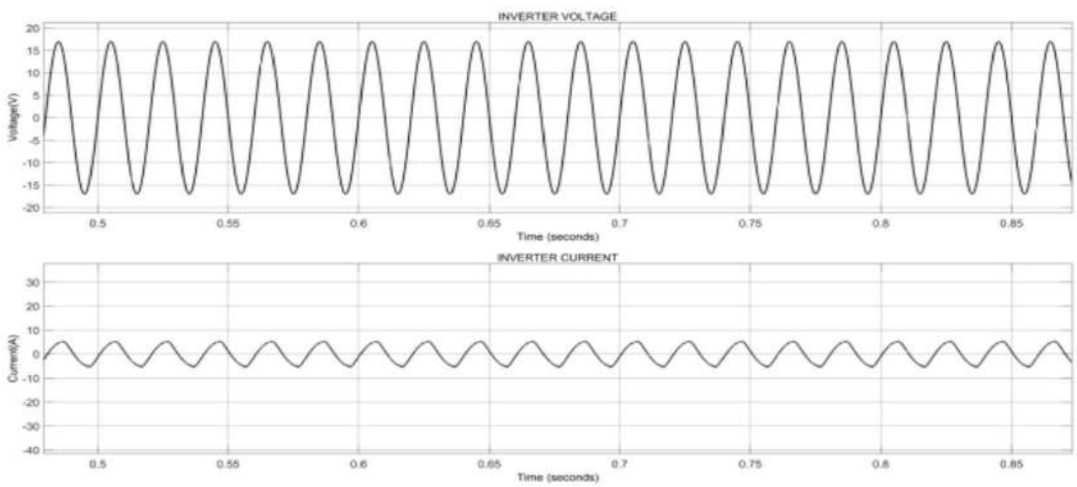

Fig 9: Waveform of inverter voltage and current.

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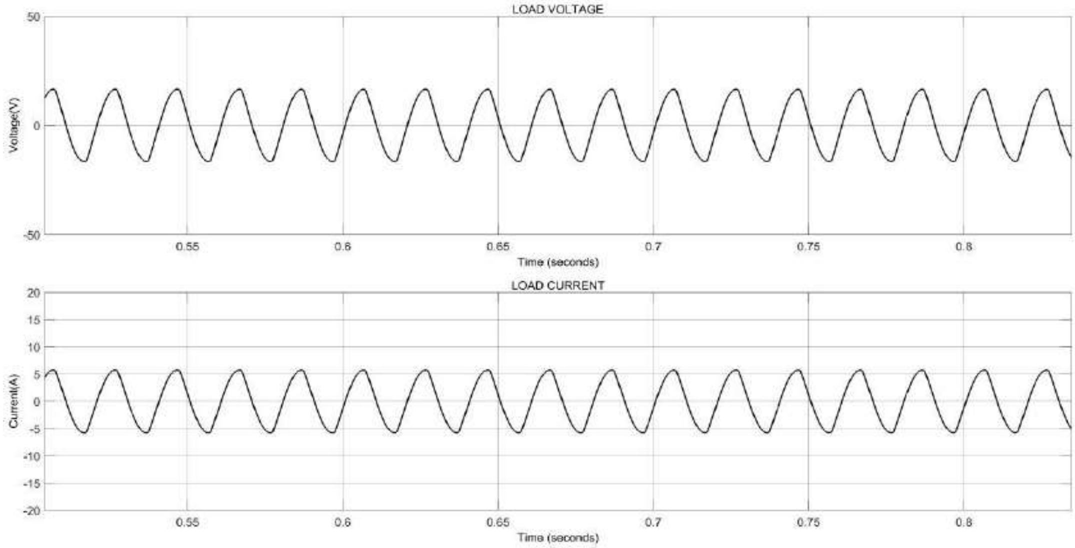

Fig 10: Waveform of load voltage and current.

Grid voltage and current waveform are shown in figure 11. Peak voltage of grid is 17V and current is 0.6A. It implies the excess current from the solar system is fed to the grid. From these results, we can understand that the grid voltage is matched with inverter output voltage using proper synchronization method. SRF PLL accurately measure the phase angle and frequency of the grid.

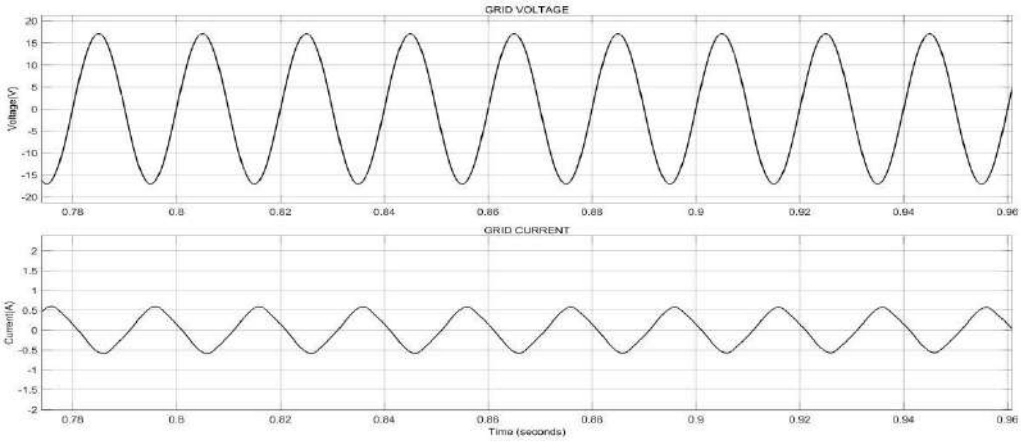

Fig 11: Waveform of grid voltage and current.

When a fault is applied at the grid during the period of 0.1s to 0.25s. By using an over current relay, it senses the faulty interval and a trip signal is given to the circuit breaker which is placed in between grid and inverter. The circuit breaker will open so that the inverter will disconnect from the grid. Hence anti-islanding protection is achieved. Figure 12 is the voltage and current from the load. Here also voltage and current is zero during the faulty interval. This implies that there is no power is flowing to the load.From these results, anti-islanding protection is achieved. All these simulation results in three phase and single phase implies that the inverter is synchronized with the grid with the help of SRF PLL and also anti-islanding protection is achieved that will disconnect inverter from grid when there is power outage in grid.

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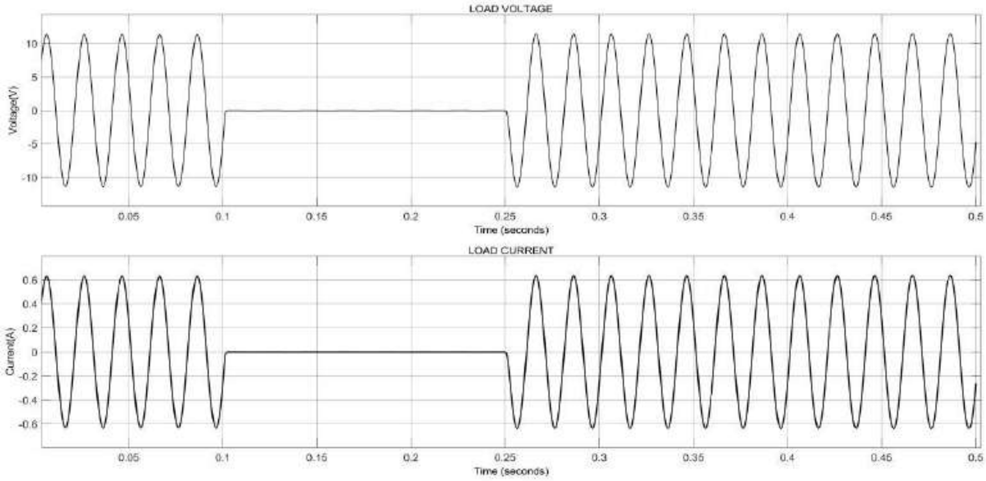

Fig 12: Waveform of load voltage and current.

IV. HARDWARE AND RESULTS

Prototype of solar grid tied system with anti-islanding property is implemented using single phase. The aim is to match single phase inverter output voltage, frequency and phase with single phase source (transformer is used as source) voltage, frequency and phase and also ensure anti-islanding property that is to show inverter output voltage as zero when there is no supply from the single phase source.

The figure 13 shows the hardware setup in the laboratory. It consists of DC source, single phase inverter with four switches, then a resistive load, a microcontroller for synchronization programming and a step down transformer of 9V is connected instead of the grid.

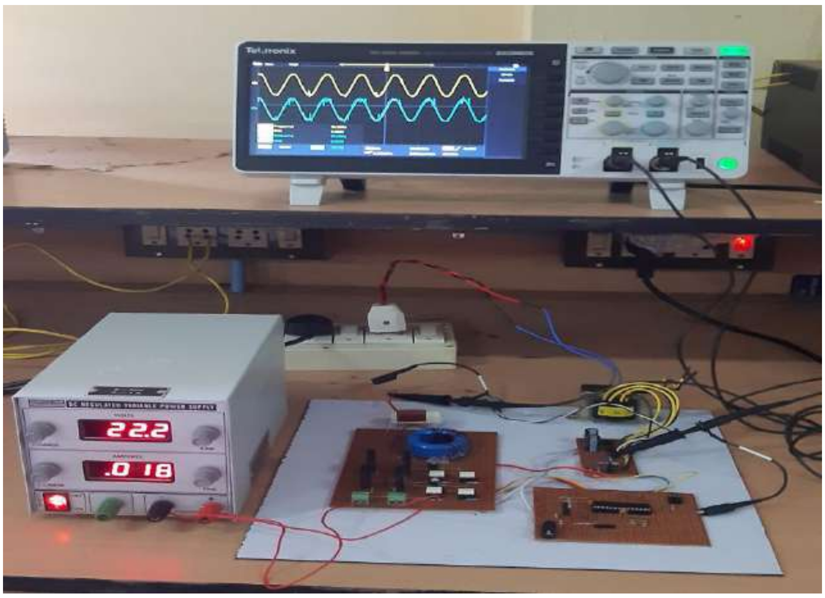

Fig 13: Hardware setup.

To synchronize the inverter with the transformer, it is necessary to match the transformer parameters with the inverter parameters. So the synchronization process is done using a microcontroller. DSPIC30F2010 is used as microcontroller. Based on this transformer voltage, frequency, phase angle which is read by the microcontroller, PWM signals are generated and is given to the driver circuit TLP250 which will drive the MOSFET of inverter. So inverter output is same as transformer output. The feedback is provided from the output of inverter like voltage, frequency and phase angle to microcontroller. So the microcontroller synchronize inverter parameter to transformer parameter and generates PWM pulses for inverter. Continuous comparison and matching is done using microcontroller. A switch is connected between transformer and inverter to ensure that when supply from transformer is turned off by using the switch, then automatically

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the inverter also turned off. Hence there is no power flow is possible.

The waveform obtained from the prototype is shown below.The figure 14 shows the output RMS voltage of inverter It is seen that the RMS voltage obtained is 9.544V and frequency as 50.05Hz for 22V DC supply. The figure 15 shows the RMS voltage of transformer.It is found that the RMS voltage of transformer is 9.548V and frequency as 49.80Hz for 22V DC supply.

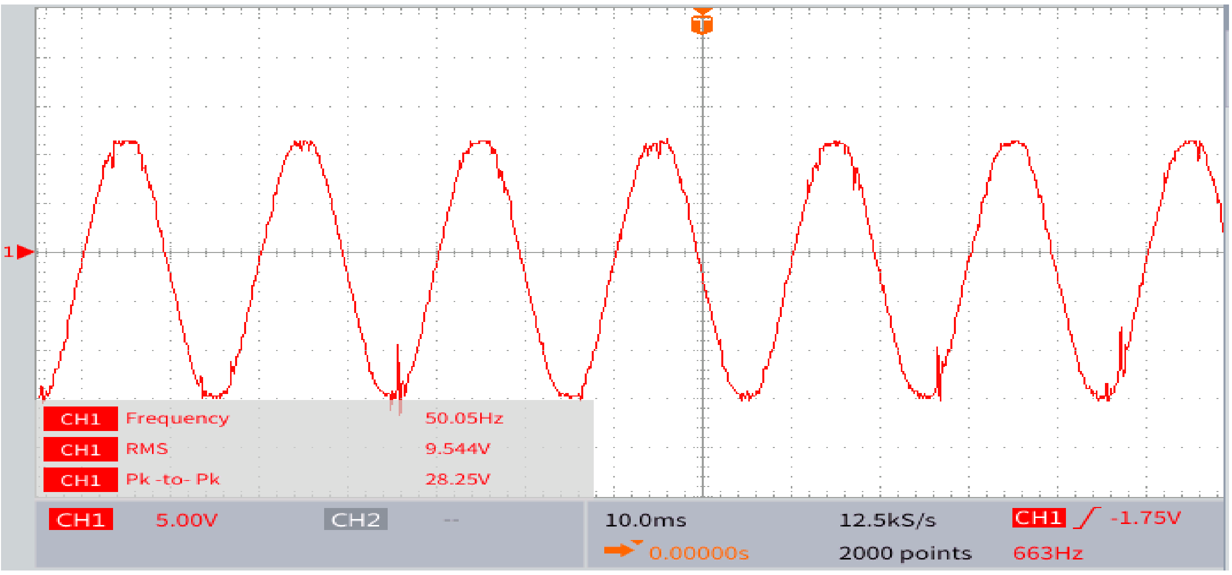

Fig 14: Waveform of voltage of inverter.

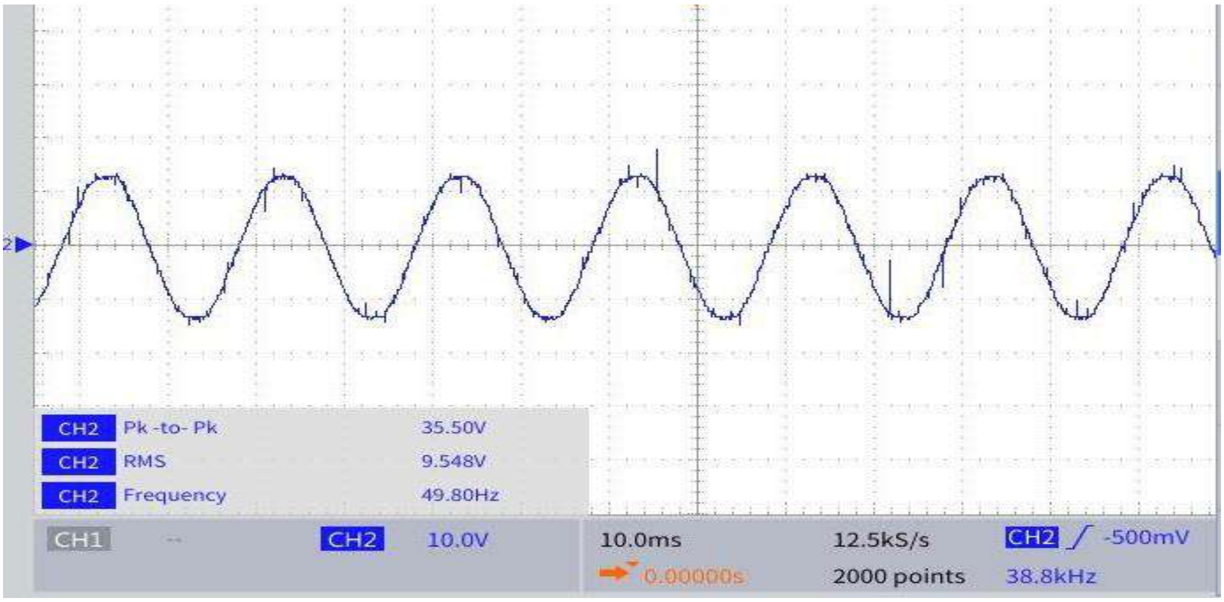

Fig 15: Waveform of voltage of transformer.

The figure 16 shows both inverter and transformer waveform.From this results, it is understood that both inverter and transformer are in same phase and have same phase angle. The voltage of inverter which is shown in red color is 9.476V and frequency 49.60Hz. While the voltage of transformer which is shown in blue color is 9.534V and frequency 49.80Hz. Here, the frequency of inverter and transformer are differ by 0.2Hz and the RMS voltage of inverter and transformer are differ by 0.058V. Hence, the inverter is synchronized with the transformer by their voltage, frequency and phase. When the supply from transformer is turned off by turning off the switch which is placed between transformer and inverter. Then there is no voltage at the inverter output. The waveform for the same is shown in 17 below. Here, red color

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represents the inverter voltage which is equal to zero and blue shows the transformer voltage which is also equal to zero. From these results, it is understood that transformer is synchronized with the inverter and power outage in transformer causes automatically power outage in inverter.

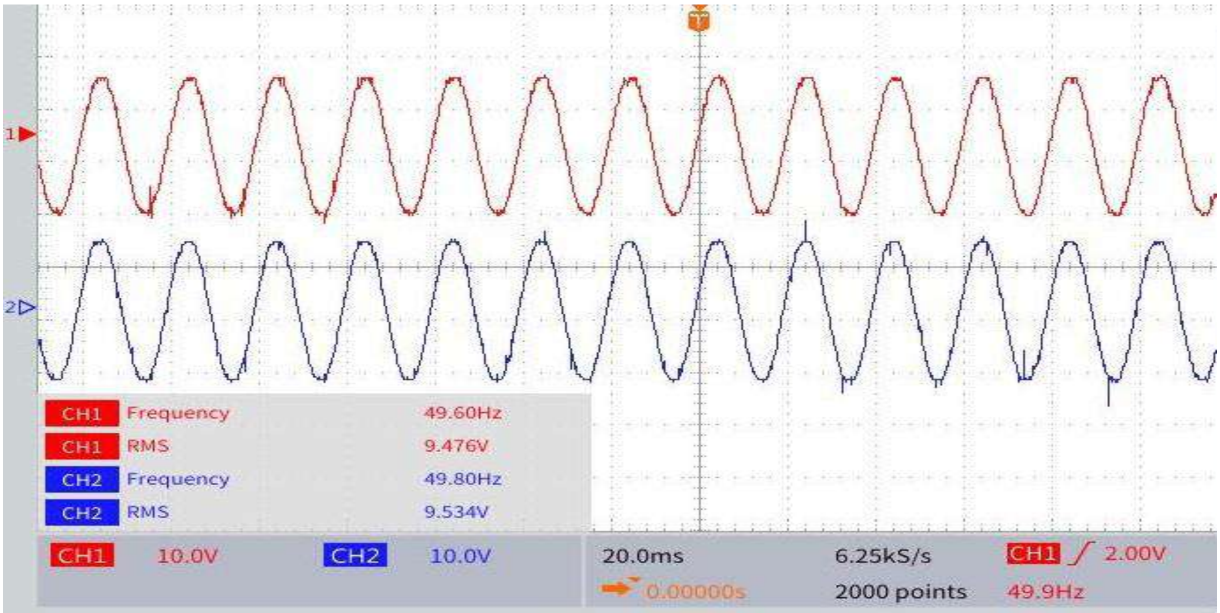

Fig 16: Waveform of voltage of both inverter and transformer.

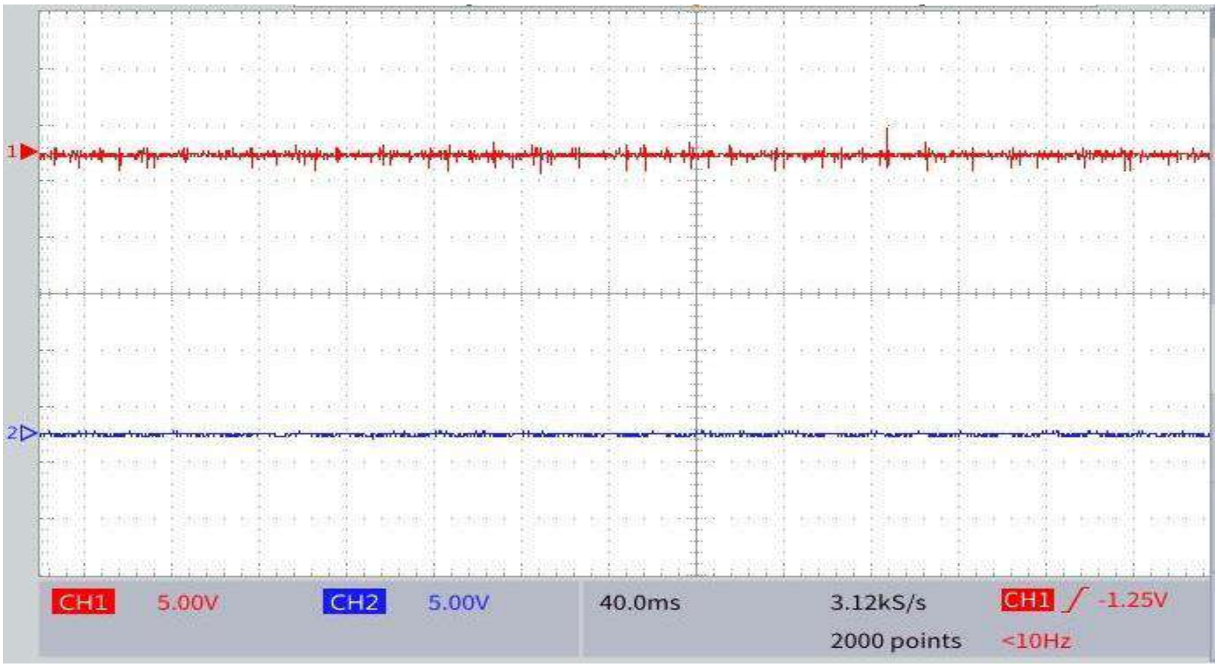

Fig 17: Waveform of voltage of inverter and transformer when switch in off state.

V. CONCLUSION

Synchronous reference frame phase locked loop in grid tied solar PV system with anti-islanding protection was developed. By using MATLAB/simulink , SRF PLL for grid synchronization was analyzed under normal and faulty grid conditions and verified that it can detect the phase angle of grid under any conditions, its measurement is fast and accurate. Then,the inverter is synchronized with grid by their voltage magnitude, phase, frequency using SRF PLL. Also an anti-islanding property is implemented using over current relay in the solar grid tied system for improving safety by

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disconnecting the inverter from the grid due to any fault conditions. Before islanding happens due to the circuit breaker opening in response to a fault, the PV system protections should identify the issue and trip.In order to minimize these effects and to perform according to the international standards, the anti-islanding relays have to be inserted in between inverter and grid. Hence improve the power quality. From the prototype, it is verified that the inverter output voltage, frequency and phase is matched with the voltage, frequency and phase of the grid. Also, when there is no power in grid then inverter also does not generate any power was implemented using a switch. From these simulation and hardware results, it can conclude that in a grid tied solar system will ensure power quality, reliability,
stability and safety.

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