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Passive Anti-islanding Protection for Grid Connected Solar Photovoltaic Power Plant: A Case Study

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***Abstract*—Islanding detection and protection is an important aspect in grid connected solar photovoltaic power generation system. This paper presents the analysis, design, implementation and evaluation of passive anti-islanding methods in solar PV plants. Over/Under Voltage Protection (OVP/UVP) and Over/Under Frequency Protection (OFP/UFP) are basic passive islanding detection method (IDM) for detecting an islanding condition by monitoring parameters at Point of Common Coupling (PCC) such as voltage amplitude and frequency and then cause the inverter to shut down when there is sufficient transition from normal specified threshold range. The performance of the proposed method has been studied by using simulations in MATLAB/SIMULINK.**

***Keywords*— PV System, Islanding, Anti-islanding protection, Passive anti-islanding protection, NDZ .**

I. INTRODUCTION

In the last few years, distributed generation systems (DGSs) have acquired popularity amongst industry and utilities because of many potential benefits, such as improved power quality and reliability, and increased efficiency. The recent development on power electronic converters and the high performance of modern control schemes have led to the effective integration of different types of energy sources to the power system [1]. The photovoltaic-based generation has gained prominence in DG systems due to its clean, affordable, and available technology. However, power transfer from photovoltaic (PV) DG system to the network requires a normal operation condition, and disturbances in the power grid may characterize the need to disconnect the PV system, especially in islanding condition.

Islanding is a potentially dangerous mode of operation of a grid-connected PV inverter. It is defined as a continued operation of a grid-connected inverter when the utility grid has been switched off or the distribution lines have been damaged so that no electric energy is delivered by the utility to the load. The IEEE standard 1547 recommend that the islanding detection technique should be capable of functioning properly under all operating conditions, and considering all types of quality issues [2]. There are two types of islanding modes, namely the intentional and the unintentional islanding. The uncontrolled island operation is a serious problem that should be avoided whenever possible. Whereas the intentional islanding is a common scenario especially for maintenance purposes [3]. The islanding detection techniques are divided into two groups: passive and active methods.

The passive methods usually monitor system parameters of grid-connected inverters such as variations in voltage, frequency, and harmonic distortion etc., based upon the thresholds set for these parameters [4]-[6]. When one or more of these parameters deviate from the permitted threshold range, an islanding event is considered to have occurred. If there is no change in the parameters, the monitoring of the parameters at PCC continues. This method is fast to detect the islanding. But it has large non detection zone [7]-[8] and it need special care to set the thresholds for it is parameters.

The active methods are based in positive feedback in the inverter control and injection of harmonics via the PV inverter [9]. Grid connected PV inverters are required to have passive islanding detection and protection methods that cause the PV inverter to stop supplying power to the utility grid if the voltage amplitude or the frequency of the point of common coupling (PCC) between the local customer load and the utility grid strays outside of prescribed limits.

II. ISLANDING STANDARDS

As per IEEE 1547.4 [10], "Guide for Design, Operation and Integration of Distributed ResourceIsland Systems with Electric Power Systems"set for grid connected solar photovoltaic system, table I and II specifies the threshold range specifications for voltage and frequency and the clearing time to allow the DG to stay connected to the utility grid without any disconnection of DG during over/under voltage and frequency protection.

TABLE I.CLEARING TIME WITH RESPECT TO ABNORMAL VOLTAGE RANGES

Voltage (at PCC)	Maximum trip time (s)
V < 50%	0.16
50% < V < 88%	2.00
88% ≤ V ≤ 110%	Continuous operation
110% ≤ V ≤ 120%	1.00

TABLE II. CLEARING TIME WITH RESPECT TO ABNORMAL FREQUENCY RANGES

Frequency Range (50 Hz = Normal Operation)	Clearing time(s)
< 49Hz	0.16
49 Hz ≤ Freq ≤ 51 Hz	Continuous operation
> 51 Hz	0.16

III. SYSTEM TOPOLOGY

The system topology consists of a grid connected solar photovoltaic power plant, three phase full bridge inverter, digital controller hardware and islanding test set up.

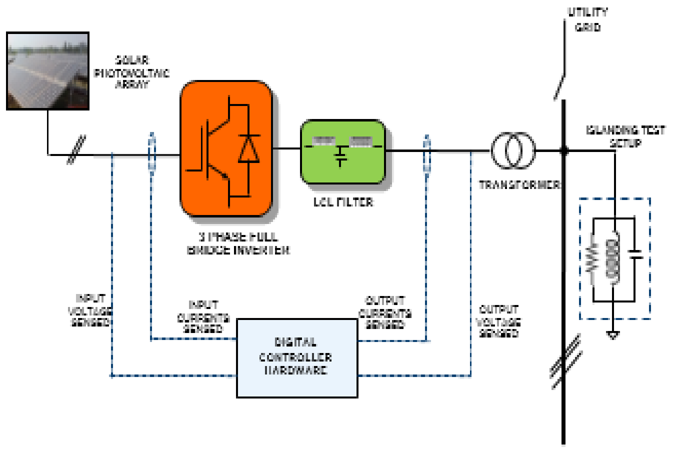

Fig. 1. System Topology

Grid interconnection of photovoltaic power generation system has the advantage of more effective utilization of generated power. Grid interconnection of PV system is accomplished through the inverter, which converts DC power generated by PV module to AC power used for ordinary power supply for electrical equipments.Inverter technology is very important to have reliable and safety grid interconnection operation of PV system.

A filter is required between a VSI and the grid to reduce harmonics of the output current. A simple series inductor can be used, but the harmonic attenuation is not very pronounced. In addition, a high voltage drop is produced and the inductor required in the design is very bulky. Commonly a high-order LCL filter has been used in place of the conventional L-filter for smoothing the output currents from a VSI. The LCL filter achieves a higher attenuation along with cost savings, given the overall weight and size reduction of the components. LCL filters have been used in grid-connected inverters and pulse-width modulated active rectifiers, because they minimize the amount of current distortion injected into the utility grid. The higher harmonic attenuation of the LCL filter allows the use of lower switching frequencies to meet harmonic constraints as defined by standard such as IEEE-1547.

IV. PASSIVE ANTI-ISLANDING METHOD

A. *Proposed Algorithm*

The principle of the passive methods is based on the fact that an islanding will cause variation in the system parameters. The passive methods usually monitor system parameters of grid-connected inverters such as variations in voltage, frequency, harmonic distortion etc. based upon the thresholds set for these parameters and doesnot perturb the system.

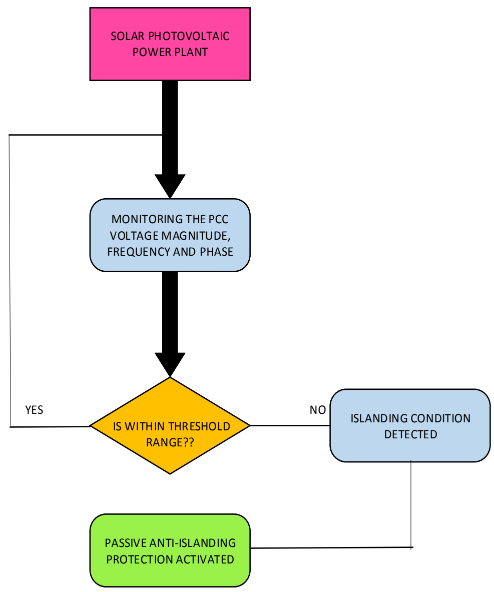

Fig. 2. Proposed Algorithm

When one or more of these parameters deviate from the permitted threshold range, an islanding event is considered to have occurred. If there is no change in the parameters, the monitoring of the parameters at PCC continues. This method is fast to detect the islanding. But it has large non detection zone and it need special care to set the thresholds for it is parameters. The simplest passive techniques are under/over voltage(UVP/OVP) and frequency(UFP/OFP), rate of change of frequency, phase jump detection and harmonic based methods.

According to the IEEE standard 1547, the voltage threshold given is 85% to 110% of normal value and the allowable frequency is set between 49.5 and 50.5 Hz for a 50-Hz system. If there is any deviation from this range, it is considered as an island.

B. *Non-Detection Zone*

Despite its simplicity and easiness to implement, passive methods suffer from large nondetection zones (NDZs). NDZs could be defined as the loading conditions for which an islanding detection method would fail to operate in a timely manner. However, if the DG generation active and reactive power (P_G, Q_G) matches the power requirements of the local load active and reactive power (P_L, Q_L), no electric parameter changes occur at the DG connection point. Moreover, with an increasing penetration of DG in the power system, new grid codes require not to disconnect the DG during voltage and frequency excursions that may occur during normal operation. Thus, protection thresholds for these variables must be consistently widened, resulting in larger non detection zones(NDZ). Therefore, more sophisticated detection methods can be needed to detect the island situation.

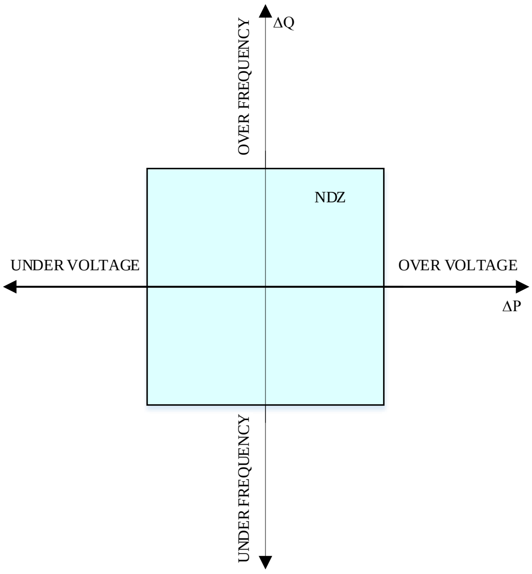

Fig. 3. NDZ Representation

Usually there is always some power mismatch $\Delta P+j\Delta Q$ between the PV inverter output and the RLC load. Beforethe grid is disconnected, this power mismatch $\Delta P+j\Delta Q$ aresupplied by the grid. Passive islanding detection methods are based on the power mismatch$\Delta P+j\Delta Q$ and the thresholds of OVP/UVP (V_{max}, V_{min}) and OFP/UFP (f_{max}, f_{min}). Once the change of the voltage frequency of PCC exceeds outside of the prescribed limits, the OFP/UFP, OVP/UVP are triggered to prevent islanding. If the change doesn't exceeds outside of prescribed limits, the islanding will occur and the corresponding scope of ΔP and$\Delta Q$is defined as the Non-Detection Zone (NDZ).

The relationship between the power mismatch and the thresholds of OVP/UVP, OFP/UFP was given in the equations below and it was shown in Fig.3.

The NDZ for active power was given by,

$$\left(\frac{V}{V_{max}}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{V\Delta}{V_{min}}\right)^2 - 1 \qquad (1)$$

The NDZ for reactive power was given by,

$$Q_f\left(1-\left(\frac{f}{f_{max}}\right)^2\right) \leq \frac{\Delta Q}{P} \leq Q_f\left(1-\left(\frac{f}{f_{min}}\right)^2\right) \qquad (2)$$

V. MATHEMATICAL MODELLING

A. Modelling of Grid connected Solar Photovoltaic Power System and Controller design

The block diagram of the grid connected solar photovoltaic system shown in Fig. 4 and Fig.5 consists of a dc source, dc link capacitor, PWM inverter, filter, three-phase ac source, and its controller. The system was modelled in unity power factor. IGBT switches are used for grid connected inverters as 10 kHz switching frequency was used.

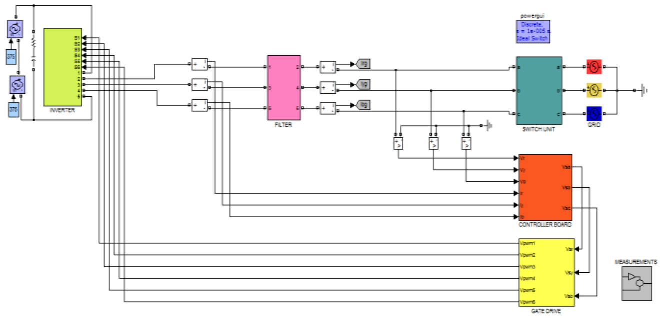

Fig. 4. Simulation Block Diagram of Grid connected Solar Photovoltaic System

The controller is used for generating switching signals for the PWM modulator. The equations given below was used for the modelling of the controller,

$$V_{sd} = i_{sd}R_s + L\frac{di_{sd}}{dt} - \omega_s L i_{sq} + V_g \qquad (3)$$

$$V_{sq} = i_{sq}R_s + L\frac{di_{sq}}{dt} + \omega_s L i_{sd} \qquad (4)$$

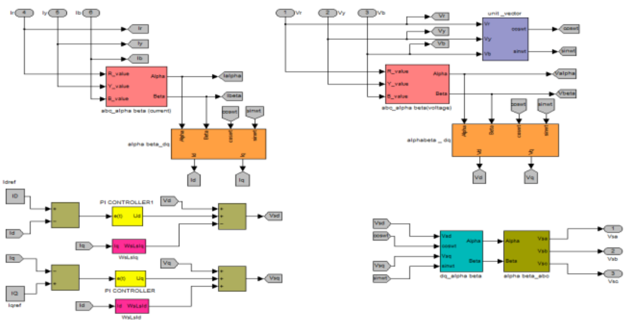

Fig. 5. Controller Board

The Fig. 6 shows the simulation model of grid connected solar photovoltaic power plant with islanding with a three-phase parallel R-L-C load.

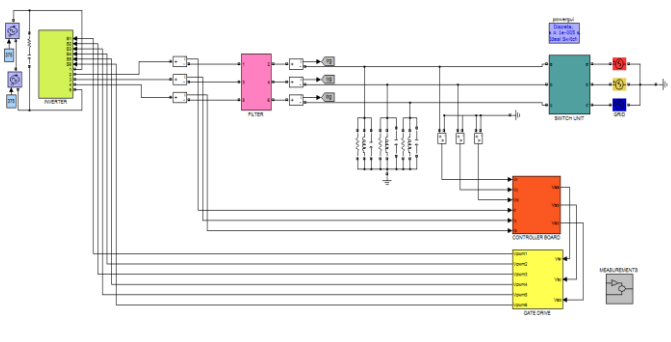

Fig. 6. Simulation Block Diagram of Grid connected Solar Photovoltaic System under load condition

B. Unit Vector Generation

In order to do the transformations, we require cosθ and sinθ which are generally referred to as cos and sin unit vectors respectively. These unit vectors help us to get the projection of vectors along particular directions. The Fig. 7 shows the phasor diagram showing the unit vectors.

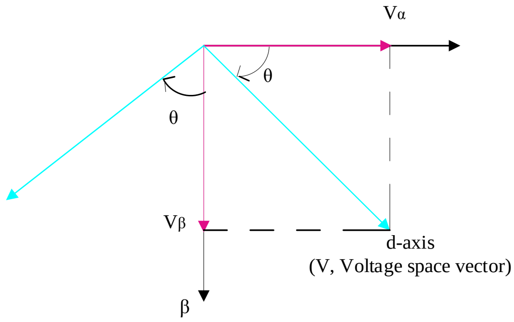

Fig. 7: Unit Vector

From the Fig. 4, we have,

$$\cos\theta = \frac{|V_\alpha|}{|V|} = \frac{\frac{3}{2}V_m \sin(\omega t)}{\frac{3}{2}V_m} = \sin(\omega t) \quad (5)$$

$$\sin\theta = \frac{|V_\beta|}{|V|} = \frac{-\frac{3}{2}V_m \cos(\omega t)}{\frac{3}{2}V_m} = -\cos(\omega t) \quad (6)$$

From the above derivation, it is evident that the unit vectors can be generated by transforming the gird voltage to α-β plane and then dividing the α- component and β-component by the magnitude of the space vector $\left[\sqrt{|V_\alpha|^2 + |V_\beta|^2}\right]$. The unit vector implemented using the MATLAB software was shown in Fig. 8 below.

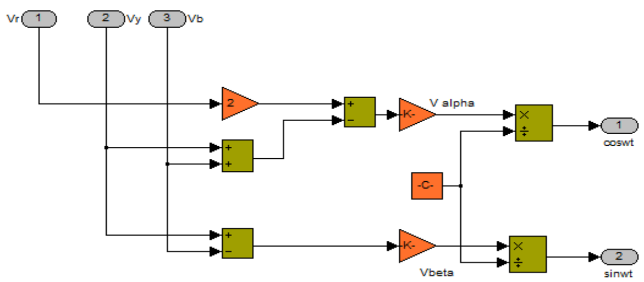

Fig. 8. Unit Vector Generation

C. Load Calculation

Islanding can occur at any section of the grid i.e., in transmission line, substations etc. To represent various power levels different load conditions have been considered and the islanding condition was evaluated. Taking base voltage as grid side voltage, i.e.$V_{baseline\ rms}$ as 415 V and rated output power of inverter as 10kW, Table III represents resistance values corresponding to different power levels.

TABLE III. R LOAD VALUES

Power (kW)	**Resistance (Ω)**
1	5.9658
5	29.828
10	59.658
15	89.484

In order to find R-L load and R-L-C load consider the Quality Factor. Quality factor for a parallel R-L-C load is given by,

$$Q_f = \frac{R}{X_L} = \frac{R}{L\omega} \quad (7)$$

$$Q_f = \frac{R}{X_c} = RC\omega \quad (8)$$

The tabulation of R-L load for selected Q-factors keeping R constant using above equation is given in Table IV and for R-L-C load keeping R and L constant using equation is given in Table V.

TABLE IV. R-L LOAD VALUES FOR SELECTED Q FACTORS

Qf	Resistance 29.828Ω	Resistance 59.658Ω	Resistance 89.484Ω
	Inductance(mH)	*Inductance(mH)*	*Inductance(mH)*
1	94.94	189.897	284.836
2	47.473	94.949	142.418
2.5	37.978	75.959	113.935
4	23.736	47.474	71.209

TABLE V. R-L-C LOAD VALUES FOR SELECTED Q FACTORS

Qf	Resistance 29.828Ω	Resistance 59.658Ω	Resistance 89.484Ω
	Capacitance(μF)	*Capacitance(μF)*	*Capacitance(μF)*
1	106.72	53.36	35.57
2	213.43	106.71	71.14
2.5	266.79	133.39	88.929
4	426.86	213.42	142.29

VI. SIMULATION RESULT

The simulation block diagram of the grid connected solar photovoltaic system and the controllers with associated sensors are shown in Fig.5 and the controller board in detail in Fig. 6. Under grid connected mode of operation, the voltage and current waveform will be sinusoidal as shown in Fig. 9 and the voltage and current profile remain unchanged throughout the grid connected mode of operation. However when islanding occur there will be a corresponding change in voltage and current as represented in Fig. 10.

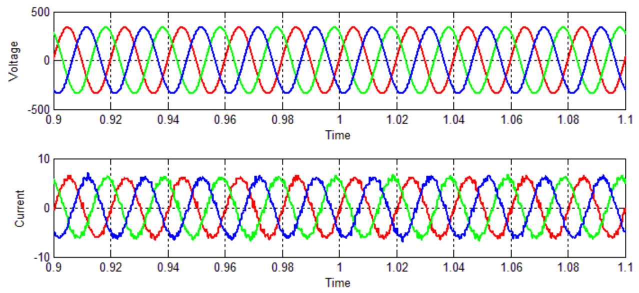

Fig. 9.Without Islanding

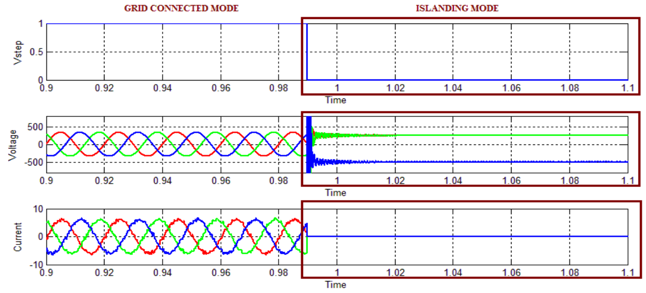

Fig. 10. With Islanding

Islanding can occur at any section of the grid i.e., in transmission line, substations etc. To represent various power levels different load conditions have been considered and the islanding condition was evaluated. Table III specifies the considered load values.

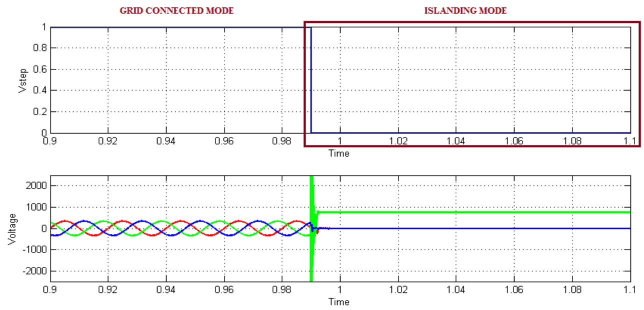

Fig. 11. Islanding mode with R-Load

In passive islanding detection methods, the PCC parameters, voltage and frequency, are continuously monitored and the analysed. The response of the system with purely resistive load under islanding condition is represented in Fig.11. Here, when islanding occur, the PCC voltage profile undergoes a damping. The change in voltage profile during islanding condition is different for different load conditions.

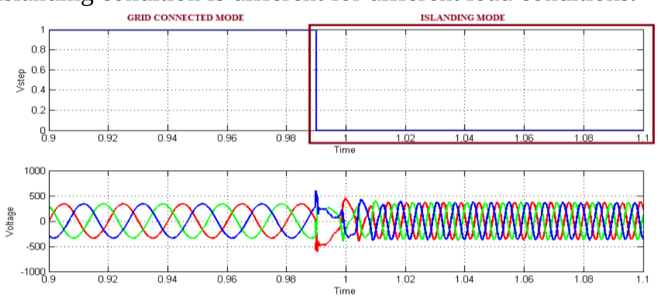

Fig. 12. Islanding mode with R-L –Load with R=59.658Ω and L=189.897mH and Q_f =1

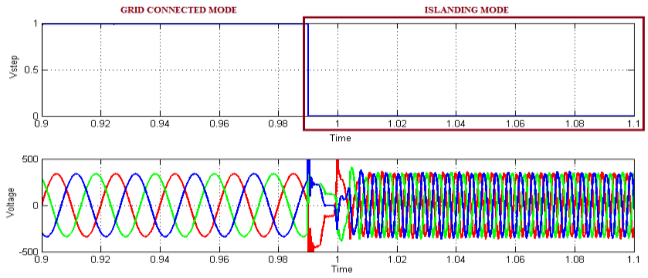

Fig. 13. Islanding mode with R-L –Load with R=59.658Ω and L=75.959mH and Q_f =2.5

From Fig. 12 and Fig.13 it can be seen that as quality factor of the system increases the frequency of the system under islanding condition also increases. So over frequency method can be ued to easily detect the islanding condition.

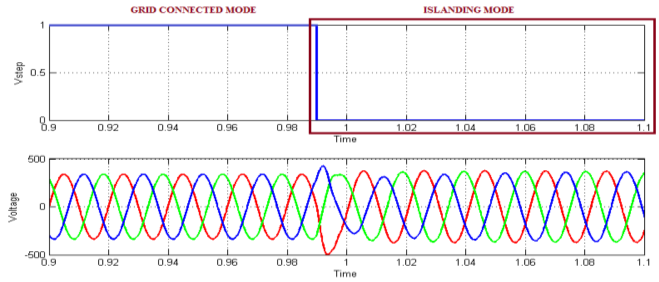

Fig. 14. Islanding mode with R-L-C Load with R=59.658Ω ,L=75.959mH and C= 133.39μF and Q_f=2.5

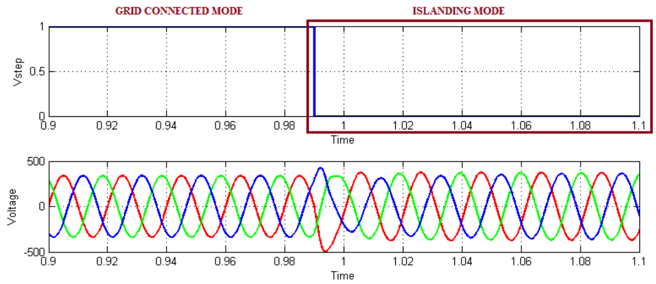

Fig. 15. Islanding mode with R-L-C Load with R=59.658Ω ,L=47.474mH and C= 213.42μF and Q_f=4

The response of the system with R-L-C load under islanding condition is represented in Fig. 14 and Fig. 15 wih quality factors 2.5 and 4 respectively.

Despite its simplicity and easiness to implement, passive methods suffer from large nondetection zones (NDZs).NDZs could be defined as the loading conditions for which an islanding detection method would fail to operate in a timely manner. From Fig. 15, it can be seen that, the magnitude and frequency of the voltage waveform during islanded mode is almost same as that of grid connected mode and hence detection of islanding condition is difficult. Hence this indicates a case of non detection zone. From analysis of simulation results for different load conditions it was concluded that, for an RLC load, for quality factor of above 2.5, the islanding detection is difficult.

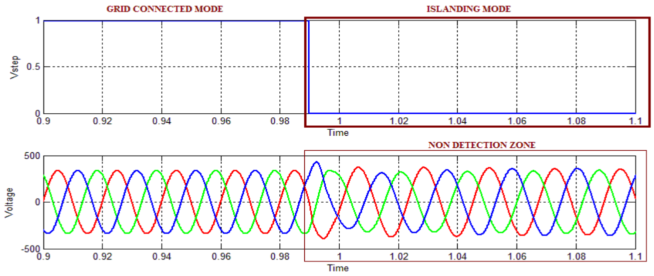

Fig. 16. Non Detection Zone

In worst conditions loading, passive methods cannot detect the islanding condition. Since the voltage at PCC continues as same as non- islanding condition during islanding condition also, the over/under voltage and over/under frequency protections are not effective.

VII. CONCLUSION

In the last few years, distributed generation systems (DGSs) have acquired popularity amongst which the photovoltaic-based generation has gained prominence. In this paper, analysis, design, implementation and evaluation of passive anti-islanding methods for grid connected solar photovoltaic power plant was done. The developed algorithm comprises of system components and an appropriate controller. The model has been implemented using the MATLAB/SIMULINK software package. The dynamic behavior of the proposed model was examined under different operating conditions. The developed system and its control strategy exhibit excellent performance in the simulation.

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