A Novel Active Anti-Islanding Protection Scheme for Grid-Interactive Roof-Top Solar PV System

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***Abstract*—This paper proposes a novel active anti-islanding scheme for inverter fed roof-top solar PV generation connected to LT distribution grid with unbalanced non-linear loads. The method is based on creating a perturbation in the system using positive feedback and d-q implementation algorithm. The conventional passive anti-islanding schemes fail to detect islanding during power balancing conditions, but the novel active anti-islanding controller ensures that the voltage (or frequency) at the point of common coupling (PCC) is automatically driven beyond the threshold preset values. This proposed scheme has been tested in the presence of non-linear loads and development has found faster islanding detection compared to the existing methods. Further, the islanding conditions are simulated and accurately verified on real time.**

Keywords— anti-islanding; positive feedback; d-q implementation; distributed generation; solar PV; non detection zone

I. INTRODUCTION

Distributed Generation (DG), unlike centralized generating power plants, generate electricity from small scale renewable energy sources like solar PV, wind energy, fuel cell, micro-turbine etc. The main advantages of using DG are that it can be installed near the load, economy in maintenance, reduction in transmission line losses, reduced congestion in transmission and distribution network, reduced environmental impacts in global warming and other forms of pollution. Unlike centralized generation (power stations), the power generated by DG is readily available on-site for both grid-connected and autonomous systems. The most popular scheme which has become a significant area of research is the grid connected DG systems where the renewable resources are integrated into the distribution systems at the LT level. The rising popularity of renewable resources has resulted in the increased penetration levels of DG's into the utility grid. According to IEEE Standard 929-2000 [1], "*IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) systems*", the operation of grid connected roof-top solar PV systems will give rise to many problems in power quality and safety. Some of the power quality problems are voltage regulation, frequency regulation, flickering, harmonics, waveform distortion etc. Some of the problems associated with safety are islanding protection, response to abnormal utility conditions like voltage and frequency disturbances, ability to reconnect after a utility disturbance, grounding etc. Among all the associated problems, unintentional islanding is one of the most important safety concerns associated with grid connected roof-top solar PV systems. According to IEEE Standard 1547 [2], islanding is defined as "A condition in which a portion of an Area Electric Power System (EPS) is energized solely by one or more Local EPS's through the associated Point of Common Coupling (PCC) while that portion of the Area EPS is electrically separated from the rest of the Area EPS". The occurrence of islanding can be fatal to utility workers who may not realize that the local area is still powered and encounter severe electric shock. For this reason, DG must be equipped to detect islanding and isolate itself from the grid immediately, which is commonly referred to as anti-islanding.

There are many anti-islanding schemes reported in the literature [3]-[5] which can be broadly classified as active and passive schemes. Passive anti-islanding schemes [3], [6] are used in the detection of islanding with the help of protective devices which monitors the changes in system parameters like voltage, frequency, phase shift etc. These methods are traditionally economical and simple in technology. But there exists a scenario in which exact balance of PV generation and load would result in negligible change in voltage and frequency at PCC, thus making it difficult to detect absence of electric utility and hence resulting in failure of passive schemes. This problem if rectified by changing the upper and lower threshold limit of overvoltage (OV)/undervoltage (UV) relay and overfrequency (OF)/ underfrequency (UF) relay, would result in nuisance tripping which causes further malfunction of the protection system. Thus, there is a need to explore the shortcomings of standard passive anti-islanding schemes by implementing novel active anti-islanding schemes. Active anti-islanding schemes [3]-[6] such as Impedance Measurement, Active Frequency Drift, Slip Mode Frequency Shift etc. are used in the detection of islanding by creating perturbation in the same system parameters which otherwise fail to get detected by the traditional passive schemes.

The main contribution of this paper is to devise an efficient algorithm which combines multiple measurable parameters at PCC like voltage, frequency, active power and reactive power and modifies them using phase transformations to result in instant detection of islanding. This is in contrast to the active anti-islanding schemes reported in the past which considers only single parameter like voltage (or frequency) which could sometimes still result in the Non-Detection Zone (NDZ) [7], a concept which will be explained in detail in Section II, especially whenever there is no significant change in the PCC voltage (or frequency), and the corresponding OV/UV and OF/UF relay will malfunction under those circumstances. Additionally, the detection time has been maintained accurately for unbalanced non-linear loads with minimum distortion in waveforms. The remaining of this paper is organized as follows. Section II briefly describes about the shortcomings of existing protection systems due to the presence of NDZ and the

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motivation towards the need to explore islanding detection schemes in Indian conditions. Section III includes the design configuration and anti-islanding control strategy of the grid connected roof-top solar PV system. The system is developed using MATLAB Simulink and also built on real time digital simulator test bed to verify the real time performance. The simulation results and inferences under various possible conditions of islanding are presented in section IV. Finally, the conclusion is given in section V.

II. NEED FOR ISLANDING DETECTION SCHEMES

The presence of NDZ primarily makes detection of islanding difficult with traditional passive schemes. Grid connected roof-top solar PV systems are connected with OV/UV and OF/UF relays which, under most circumstances, will disconnect the solar PV panel from the utility grid in the event of violation of threshold limits of voltage and frequency. The relays will sense the abnormalities in the system and provide the trip signal to the circuit breaker.

From Fig. 1, it is observed that

$\Delta P = P_{load} - P_{PV}$ and $\Delta Q = Q_{load} - Q_{PV}$ (1)

Since the solar PV typically operates at unity power factor, the reactive power $Q_{PV} = 0$ and hence $\Delta Q = Q_{load}$. Assuming that the load is represented as a 3-∅ RLC loads,

$$P = \frac{V^2}{R} \quad (2)$$

$$Q = V^2\left(\omega C - \frac{1}{\omega L}\right) \quad (3)$$

A. The phenomena of islanding

The schematic diagram, as shown in Fig. 1, is used to explain the process of islanding. During a fault, the circuit breaker automatically opens and the system gets isolated. Under these circumstances, ΔP and ΔQ both tends to zero. Now the present state of the islanded system depends on the values of ΔP and ΔQ just before the utility grid has been disconnected to form the island, which is denoted by ΔP^- and ΔQ^-. Depending on the nature of ΔP^- and ΔQ^-, the corresponding relay will become operational to protect the system. Let $t=0^+$ be the time at which the CB has been opened, then the following four cases of safe detection of islanding and isolation of system is explained in Table I with reference to the equations (1), (2) and (3). As seen in the four mentioned cases, the OV/UV relays and OF/UF relays of the system will automatically detect islanding and isolate it immediately. But unfortunately, there is a worst case scenario, in which $\Delta P^- = 0$ and $\Delta Q^- = 0$.

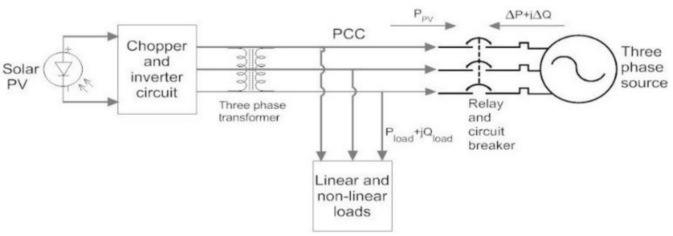

Fig. 1: Schematic diagram of grid connected roof-top solar PV system

In this case, the power generation and load demand is exactly matched and hence there won't be any change in voltage and frequency at PCC. This will result in the failure of relays to operate.

Table I: Conditions for safe detection of islanding

Conditions just before islanding	**Reason for isolation of system just after islanding occurred**
$\Delta P^- > 0$	Decrease in V_{PCC} is detected by UV relay
$\Delta P^- < 0$	Increase in V_{PCC} is detected by OV relay
$\Delta Q^- > 0$	Increase in ω is detected by OF relay
$\Delta Q^- < 0$	Decrease in ω is detected by UF relay

B. Drawbacks in standard protection system due to NDZ

In reality, ΔP^- and ΔQ^- do not have to be exactly zero for malfunction of protection systems to occur because the magnitude and frequency of the utility voltage can be expected to deviate slightly from nominal values, and therefore the thresholds for the four relays cannot be set arbitrarily small or else the PV system will be subject to nuisance trips. This limitation leads to the formation of NDZ [7] which is graphically shown in Fig. 2.

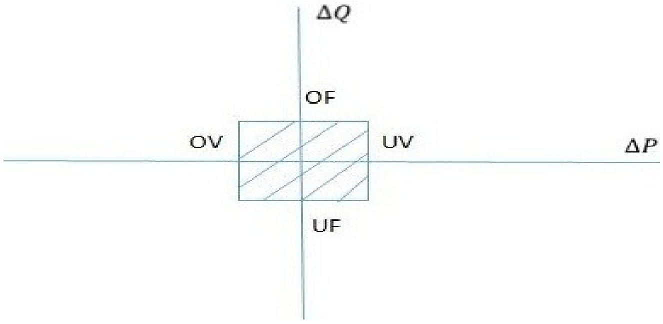

Fig. 2: Graphical representation of NDZ

Studies have shown that the probability of ΔP^- and ΔQ^- falling into the NDZ of the OV/UV relays and OF/UF relays can be significant. It is therefore important that PV systems incorporate methods to detect islanding in the case in which $\Delta P^- = \Delta Q^- = 0$. A case study in risk assessment of unintentional islanding in the distribution network at IIT Gandhinagar campus [8] has revealed that the highest number of instances of load balancing occurs in non-working days during winter and off-peak seasons. Mathematically, the power mismatch equations in NDZ are reproduced below from [7]:

$$\left(\frac{V}{V_{max}}\right)^2 - 1 \leq \frac{\Delta P}{P} \leq \left(\frac{V}{V_{min}}\right)^2 - 1 \quad (4)$$

$$Q.F.\left(1 - \left(\frac{f}{f_{min}}\right)^2\right) \leq \frac{\Delta Q}{P} \leq Q.F.\left(1 - \left(\frac{f}{f_{max}}\right)^2\right) \quad (5)$$

Quality factor (Q.F.) is defined as:

$$Q.F. = 2\pi \times \frac{maximum\ energy\ stored}{energy\ dissipated\ per\ cycle}$$

Mathematically, Q.F. can be represented as:

$$Q.F. = \frac{\sqrt{Q_C \times Q_L}}{P}$$

where Q_C is the capacitive reactive power of loads and Q_L is the inductive reactive power of loads. Applying the equations (4) and (5) for islanding conditions in Indian scenario according to clause 12(6) of CEA regulations [12], the mismatch in NDZ is calculated and formulated as shown in Table II.

Table II: Power mismatches conditions in NDZ in Indian scenario

Quality factor	1.6 to 2.5
Voltage threshold	80 % < V < 110%
Frequency threshold	47.5 Hz < f < 50.5 Hz
Active power threshold	-17.36 %< $\frac{\Delta P}{P}$ < 56.25 %
Reactive power threshold	-27 % < $\frac{\Delta Q}{P}$ < 4.925 %
Total harmonic distortion	THD < 4.92 %

According to IEEE 929-2000 standards, the islanding detection time is a very important consideration for the design of any system whose details are summarized in Table III.

Table III: Threshold for islanding detection time

10 cycles (0.2 sec) or less	• 50 % mismatch in P • Load p.f. < 0.95 (lead/ lag)
2 sec	• Q.F. < 2.5 • Load p.f. > 0.95 (lead/ lag)

III. SYSTEM CONFIGURATION AND CONTROL STRATEGY

As shown in Fig. 3, the proposed system consists of the DG (consisting of solar PV, PWM inverter and filter circuit) on the left side, three phase utility distribution grid on the right side, and three phase loads (linear and non-linear) connected at PCC. The system parameters of various blocks which are used for simulation are given in table IV. These parameters are the typical values which were used for case study at IIT Gandhinagar campus in [8].

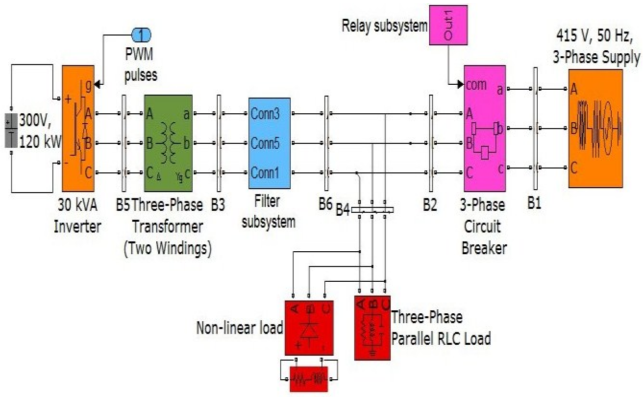

Fig. 3: Master Simulink block of grid connected solar PV system

Table IV: Block diagram parameters of grid connected roof-top solar PV system

Solar PV	300 V (D.C), 120 kW
PWM inverter	30 kVA × 4
Filter circuit	20 mH, 200 µF
3-phase utility grid	415 V, 50 Hz
3-phase linear loads	120kW(minimum demand)

The anti-islanding controller to the PWM inverter is constructed using the positive feedback and d-q implementation algorithm. As shown in Fig 4, the anti-islanding controller is the heart of all operations occurring in the system. The voltage and current at PCC are extracted and given as input to both the active and passive subsystem. After execution of various processes in both the subsystems, the modified values of PWM signals are generated and this output is given to the PWM inverter. These modified PWM signals gives a direct evidence of occurrence of islanding in the system which needs to be isolated. The trip signal is given by the designed relays to the circuit breaker. The passive subsystem consists of voltage and frequency relays with the preset values as mentioned in the clause 12(6) of CEA regulations [12].

Fig. 5 shows the various blocks associated with the passive subsystem. The frequency relays, both OF and UF, are constructed using 3-phase PLL block in Simulink. The voltage relays, both OV and UV, are constructed using the 3-phase sequence analyzer block in Simulink. In addition, the THD of the active and reactive power is also built to maintain the threshold limits as mentioned in IEEE 929-2000 standards. All the operations are compared with the standard reference values using the algebraic Boolean operator. The comparisons are held onto a switch before the final output signal is sent to the sample and hold circuit.

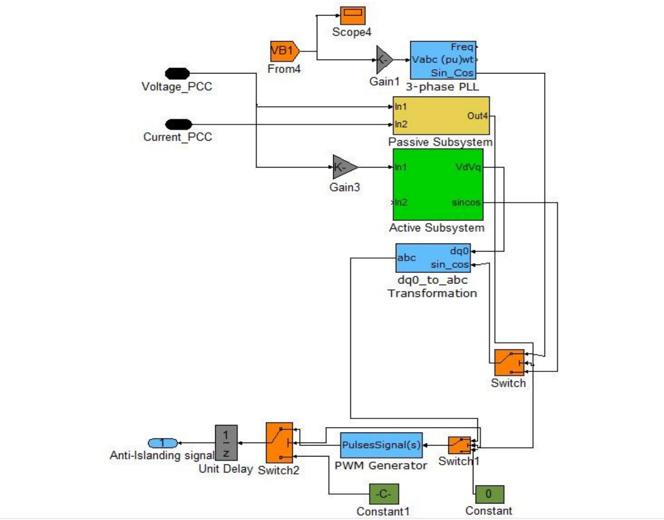

Fig. 4: Anti-islanding controller

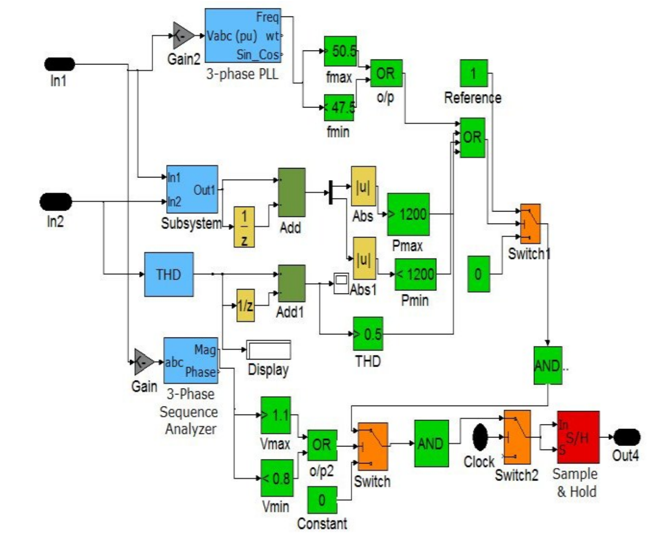

Fig. 5: Passive subsystem

Fig. 6 describes about the active subsystem which consists of a-b-c to d-q implementation blocks and current regulator. The voltage and current at PCC are transformed into d-q frame to get a direct correlation with active and reactive power. The current regulator has an inbuilt PID controller which compares the PCC values in d-q frame with reference values. The outputs from the current regulator are modified values of V_d and V_q which is further used by the anti-islanding controller to generate modified values of PWM signals.

The MATLAB model is built on real time system which consists of master, slave and console subsystems. The master subsystem is the combination of DG, utility grid and three phase loads. The slave subsystem consists of anti-islanding controller with both passive and active anti-islanding schemes. The simulation results are verified on the digital scope which is compiled inside the console subsystem. The OpComm block is inserted ahead of all input signals which is basically used to synchronize all the incoming signals and implement the algorithm in real time mode. All subsystems must go through the OpComm block before any operations can be done on the signals.

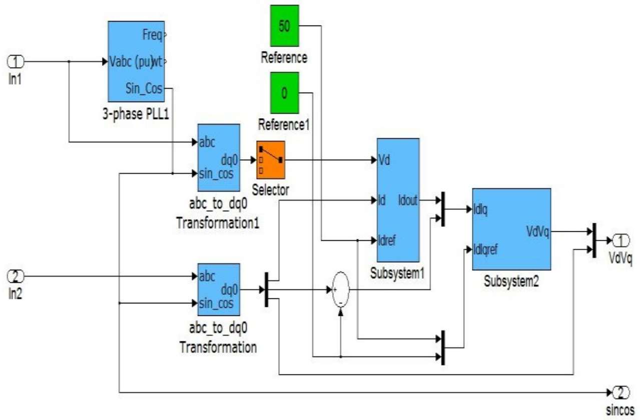

Fig. 6: Active subsystem

A. Positive feedback

The basic principle of positive feedback [9]-[11] is to drive away the values of magnitude of voltage and frequency during islanding. In voltage feedback scheme, when the PCC voltage is increasing, the anti-islanding feedback will command the active power output to be increased. This will cause an increase in the output voltage and will further drive up the active power. This process continues and eventually drives the voltage out of nominal ranges. As per clause 12(6) in CEA regulations [12], the upper and lower ranges in voltage are set as 1.1 p.u. and 0.8 p.u. respectively. In frequency feedback scheme, when the PCC frequency is increasing, the anti-islanding feedback will command the reactive power output to be increased. This will cause an increase in the output frequency and will further drive up the reactive power. This process continues and eventually drives the frequency out of the nominal ranges. As per clause 12(6) in CEA regulations [12], the upper and lower ranges in frequency are set as 50.5 Hz and 47.5 Hz. Similarly the converse occurs if the above mentioned voltage and frequency are decreasing in magnitude.

B. d-q implementation

The basic principle of d-q implementation [9], [11] is to transform the 3-phase quantities into 2-phase quantities which simplifies the system from its transient nature to steady state variables. The active power is proportional to d-axis and the reactive power is proportional to q-axis components respectively. The voltage at PCC is decoupled into d-axis and q-axis components using Park's a-b-c to d-q transformation. The frequency components are obtained from d-q to PLL transformation. The reference current I_{dref} is obtained by d-q transformation of the PCC currents. The V_d component of voltage is passed into Band pass filter, gain and limiter and finally becomes a current variation ΔI. The current regulator, as shown in Fig. 7, uses a PID controller compares the ΔI with I_{dref} and converts into modified PWM pulses in d-q frame. These modified pulses are transformed back using d-q to a-b-c inverse transformation and fed into the PWM inverter. The modified PWM pulses to the inverter imply the changes in the threshold values of voltage and frequency and the relay sends the trip signal to the circuit breaker. The circuit breaker opens within 0.1 seconds to isolate the system during islanding.

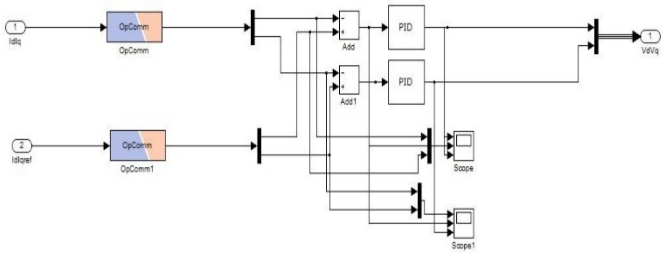

Fig. 7: Current regulator

IV. SIMULATION RESULTS AND INFERENCES

The MATLAB model is constructed and simulation is carried out for various possible conditions of islanding which can occur at the PCC. The simulation is run for 1 second, and the condition for islanding is preset at 0.4 seconds. At t=0.4 s, the relay gives the trip signal to the circuit breaker to disconnect the inverter from the system. From Fig. 8, it is verified that during islanding, the utility current from the grid, current at PCC and load current becomes zero instantly. The presence of zero current indicates that the anti-islanding algorithm has successfully isolated the system automatically when islanding has been detected. The speed of detection is less than 0.1 seconds which falls in stipulated thresholds according to IEEE 929-2000 standards.

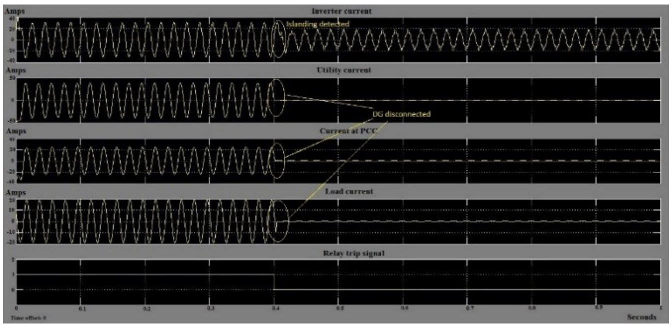

Fig. 8: Detection of islanding with zero current at PCC

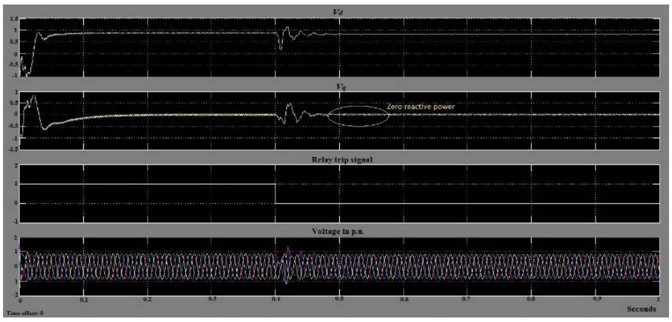

Fig. 9: Zero reactive power by inverter

The q-component of voltage is directly proportional to the reactive power. According to IEEE 929-2000 standards, the solar PV inverters need to operate at unity power factor so that maximum active power can be extracted out of the system. This means that zero reactive power is required to be maintained which is confirmed by simulation as shown in Fig.9. Additionally, to verify the effectiveness of the proposed algorithm during the presence of non-linear loads, four different cases were simulated under various conditions of islanding.

Fig. 10 represents the condition of overvoltage immediately after the occurrence of islanding. The voltage instantly shoots to 330 V which is exactly 1.1 times the rated voltage 300 V. The condition of undervoltage immediately after the occurrence of islanding is also verified accordingly. As shown in Fig. 11, the voltage dips down to 240 V which is exactly 0.8 times the rated voltage 300 V. The conditions of voltage disturbances in the system indicate the ability of the controller to detect islanding instantly. Further, the threshold limits are satisfied according to the standards given in clause 12(6) of CEA regulations [12]. The presence of NDZ could result in the failure to detect islanding due to power balancing. Under such circumstances, there would be negligible changes in voltage conditions. The biggest advantage of the algorithm over existing methods is the ability to detect islanding even if there were no significant voltage disturbances. This is possible by analyzing the frequency component at PCC.

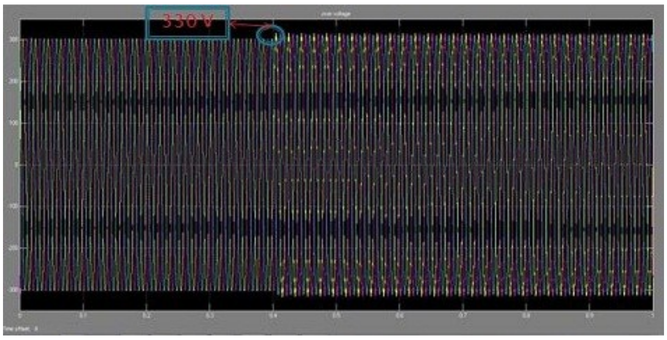

Fig. 10: Overvoltage during islanding

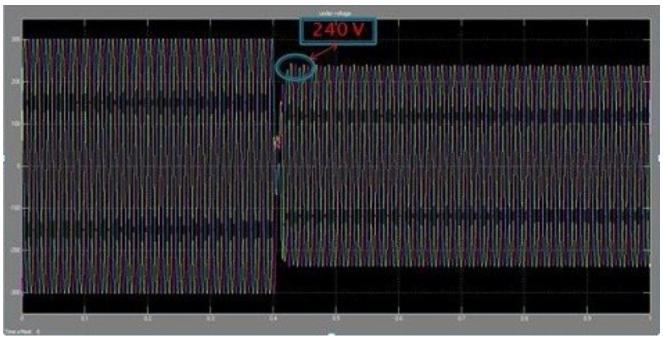

Fig. 11: Undervoltage during islanding

As shown in Fig. 12 and Fig. 13, even though there is no change in voltage after the occurrence of islanding, the controller ensures that there are significant changes in frequency such that it is driven beyond the threshold levels, i.e., UF/OF relay will help in the isolation of the system after the occurrence of islanding. Further, the threshold limits in frequency are also satisfied according to the standards given in clause 12(6) of CEA regulations [12].

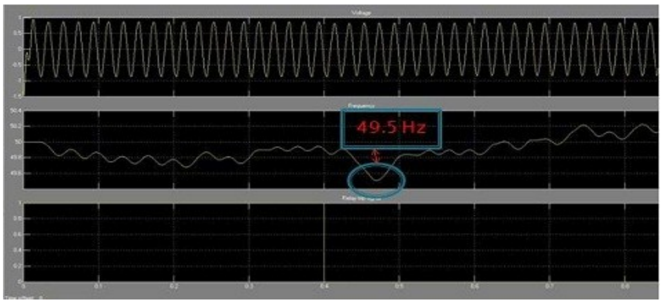

Fig. 12: Underfrequency during islanding

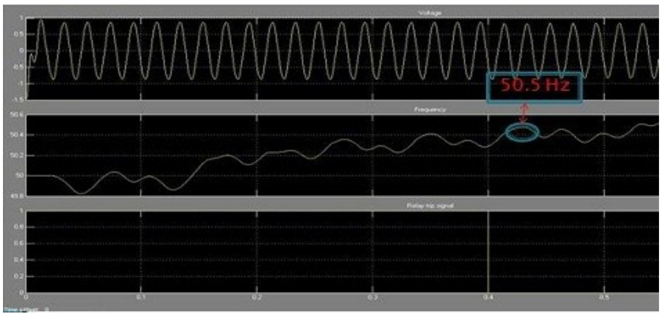

Fig. 13: Overfrequency during islanding

The offline version of the MATLAB model is implemented using real time simulator test bed consisting of master and slave control as shown in Fig. 14. The online real time simulation is run on the host computer which is also the main server interconnecting the real time simulators in the power system laboratory.

Fig. 14: Real time digital simulator test bed with master and slave control, Power systems laboratory, IIT Gandhinagar

V. CONCLUSION

Modern distribution systems have increased usage of renewable resources Islanding protection has been a major concern for grid connected solar PV systems. Modern industrial inverters have been restricted with passive anti-islanding schemes owing to the limitation of diversity of loads which prevents it from predefining the various load conditions required in active anti-islanding schemes. This paper has developed a novel anti-islanding scheme with faster detection over existing methods. The algorithm has been implemented with minimal distortion in waveforms even in the presence of various types of loads. The main advantage of using real time simulators was the ability to validate the algorithm in real time which produced precise results over the MATLAB model.

ACKNOWLEDGMENT

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