Maximize-M Kalman Filter and Self-tuned P&O Algorithm Based Integration of Solar PV with Low-Voltage Weak Grid System

Shubham Narendra Patil [1], Prof.S.S.Hadpe[2]

[1]Student, Dept. of Electrical (Power system) Engineerin, Matoshree college of engineering, Maharashta, India
[2]Professor, Dept. of Electrical (Power system)Engineering, Matoshree college of engineering, Maharashta, India

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Abstract *- With the ever increasing electricity demand, fast depletion of fossil fuel and the growing trend towards renewable energy resources, the integration of green distributed energy resources (DERs) such as solar photovoltaic (PhV) generation and wind power in the utility grid is gaining high popularity in the present years. The capability of these modular generators needs to be harnessed properly in order to achieve the maximum benefit out of such integrated systems. Most DERs are connected to the utility grid or microgrids with the help of power electronics interface. They are capable of producing both active and reactive power with the proper control of the inverter interface. A new method of Maximum Power Point Tracking (MPPT) of solar array including the MPPT at solar PhV array side and a new control method of transferring this MPPT power to the inverter side insuring the DC voltage stability by using the concept of power balance at various conversion stages is proposed and studied.*

Key Words: *Photovoltaic PV, Active Power, Reactive Power, Islanded Microgrid, Microgrid, Optimization, MPPT*.

I. INTRODUCTION

With the ever increasing demand of electricity that has been raising important power system operational issues like voltage and frequency instability, the integration of distributed energy resources into the modern power systems have become very popular. Since last few decades. The fast depletion of fossil fuel reserves and environmental concerns have provided greater incentive to integrate renewable energy based DERs like solar, wind and biomass in modern power systems.

solar photovoltaic (PV) energy systems are becoming popular and frequently used on commercial as well as residential level. Moreover, technology related to the PV array is also growing and trying to extract maximum power from the PV panel [1]. Since the characteristic of the PV panel is nonlinear in nature so, PV characteristic consists of a single point where the PV power is maximum, that is known as maximum power point (MPP)[2][3]. Therefore, to operate at MPP, it needs MPPT ((Maximum Power Point Tracking)) algorithm. The 'perturb and observe (P&O)'[4], 'incremental conductance (InC)'[5], Hill Climbing' and beta factor, based MPPTs are few techniques, which are highly popular to find the MPP of PV characteristic. However, steady-state oscillation, slow dynamic responses and fixed step change, are the major issues with these techniques. A literature review on MPPT, shows that many authors have tried to solve these problems through some modifications in classical algorithms namely, modified P&O[6], improved InC[7], fuzzy logic based MPPT[8], artificial intelligence based MPPT[9] approach, etc. However, still, a reliable optimum solution has not come. Because, if few improved techniques are performing well in the steady state then lagging in a dynamic condition, vice versa. Use of solar PV (Photovoltaic) generation for rural electrification, is growing very rapidly. The popularity of solar PV generation in the rural area, is due to its static nature, easy installation, low maintenance, and zero fuel cost. Therefore, government, as well as nongovernmental organizations, are installing or supporting the installation of rooftop PV system in rural areas for continuous electricity. These schemes are also popular in the urban areas.[10]

Microgrid can work in two modes that include interconnected mode and Islanded mode. In grid connected mode microgrid is connected with the public grid and in islanded mode microgrid works autonomously providing electrical power to local load. Since renewable energy sources are intermittent in nature, due to this fact Microgrid needs control strategy for its reliable operation while maintaining power quality.

Electronic interfaced inverters are the major components of Microgrid in Islanded or grid connected mode.These inverters are responsible for the control of active and reactive power to maintain reliable power sharing between renewable energy generators. In islanded operation Distributed Generators are responsible for frequency and voltage control of the microgrid. Similar to traditional power systems, the power/frequency (P/f) droop control is implemented for the microgrid controllers [11].

A microgrid (MG) is an energy system that consists of distributed generators, energy storage units and loads that can operate in either islanded or in grid-connected mode. Grid connected MGs are commonly used due to consistent configurations for variable/dynamic loads that should be fed without interruption. However, these resources introduce new challenges for power management, control and economical operation of the system when several energy sources are available to feed the load and meet demand requirements. Power management and control schemes are systematised into lower level and upper level controls.

Lower level control is known as primary control and is responsible for stabilising voltage and frequency.[12]

Photovoltaic (PV) power systems have become one of the most promising renewable generation technologies because of their attractive characteristics such as abundance of solar and clean energy. Rapid PV technology development and declining installation costs are also stimulating the increasing deployment of PV in power systems. However, due to the nature of solar energy and PV panels, instantaneous power output of a PV system depends largely on its operating environment, such as solar irradiance and surrounding temperature, resulting in constant fluctuations in the output power.[13]

II. MICRO-GRID CONNECTED /ISLANDING OPERATION

A. Micro-grid connected /islanding operation methods

Micro-grid could operate in grid-connected mode and islanding mode. Grid-connected mode means that there is a connection between micro-grid and utility system, loads flow between them. Islanding operation means that when faults happen in grid, micro-grid is isolated from the remainder of the utility system and DGs supply power energy to load. Islanding operation improves reliability of power supply.

Islanding has great harmfulness: firstly, due to the islanding areas is out of grid's control, the voltage and frequency may be unstable and it will threaten safety operation of electric equipments; secondly, workers couldn't judge if equipment is power down or not when islanding happened, so the worker's life is threatened; thirdly, main grid would be impacted when micro-grid reconnected with main grid.

B. The grid code about islanding operation

Due to the great harmfulness of islanding, the require DG to be disconnected from the grid once it is islanded. Anti-islanding protection could ensure grid running normally, but with the increase of distributed generation's capacity, the current anti-islanding protection exist some defects. For example, the DG couldn't be made full use; reliability of distributed network power supply is reduced, etc. As we know, faults cannot be avoided in power system. If DGs are isolated from the utility system whenever a fault occurs, then reliability of power supply is hard to be ensured and superiority of DG can't be reflected. Based on the analysis above, practices of disconnecting the DG when faults happen will no longer be a practical or reliable solution.is a new standard proposed intentional islanding and unintentional islanding, intentional islanding means that a micro-grid or a portion of the power grid, which consists of loads and a distributed generation system, is isolated from the remainder of the utility system according to foregone planning Intentional islanding could keep micro-grid operation stable and improve reliability of power supply. Unintentional islanding is an operation state that DGs supply power to loads independently. This operation state is incidental and unstable. This code approves intentional islanding operation and prohibits unintentional islanding. Stable micro-grid operation depends on the smooth switching of operation mode. The key is to choose an appropriate control strategy.

III. CONTROL STRATEGY OF MICRO-GRID CONNECTED/ISLANDING OPERATION

A. Traditional Control Strategy of Micro-Grid connected /islanding Operation

Nowadays, master-slave and peer-to-peer control strategy are used in micro-grid. Master-slave control means that all the DGs in micro-grid adopt P-Q control in grid-connected mode, but in islanding mode, in order to keep voltage and frequency stable, one or several DGs are changed to V-f control. Peer-to-peer control means that all of DGs in micro-grid adopt droop control, which could ensure reasonable power assignment among DGs. P-Q control means that DG is controlled to output maximum power or specified power according to actual condition. The principle of P-Q control when micro-grid frequency is 50Hz and connected bus voltage is rated, DG operates at point B and power output is Pref, Qref; if connected bus voltage and micro-grid frequency rising or reduced, then operating point moves from B to A or C to keep power output at Pref, Qref. P-Q control is designed to maximize the utilization of renewable energy, it is suitable for intermitted resources. P-Q control is easy relatively, but it can't keep voltage and frequency stable.

IV. INTEGRATION OF DERs TO THE GRID

The high penetration of DERs in the modern electricity grid can provide many potential positive benefits through their integration but they can have many negative impacts on the network if power output and voltage at the Point of common coupling (PCC) is not properly regulated through controls. The challenge mainly lies in the integration of varying renewable sources like Solar PhV and Wind Energy Conversion systems. DERs can provide a technical relief to the grid in the form of reduced losses, reduced network flows and voltage drops, however, there are several negative impacts due to high penetration of these variable resources which include voltage swell, voltage fluctuations, reverse power flow, changes in power factor, injection of unwanted harmonics, frequency regulation issues, fault currents and grounding issues and unintentional islanding[14]

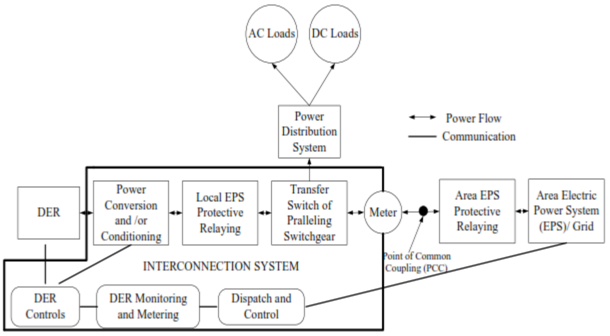

Fig-1 Interconnection System Schematic

Below Figure gives an overall picture of all the interconnection interfaces.

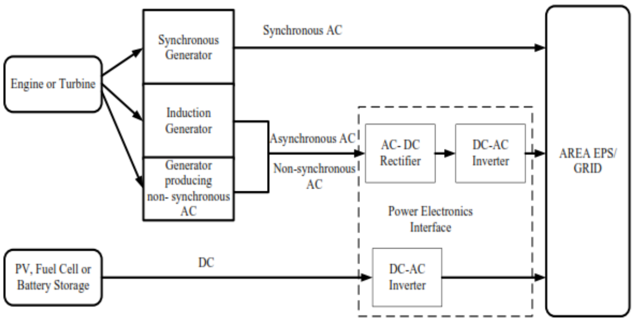

Fig-2 Interconnection interfaces of DERs to the grid.

The Institute of Electrical and Electronics Engineers (IEEE) has set a standard for the interconnection of DERs to the utility grid. The standard is termed as IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems[16]. This standard has set uniform criteria for the interconnected DERs in terms of safety, operation, performance, testing and maintenance. The main focus of this standard is DERs connected to the radial distribution feeder. IEEE 1547 provides technical requirements for the safety and reliability of DER interconnection which includes voltage regulation, power monitoring, grounding, synchronization, connection to network distribution systems, back-feeds, coordinating equipment ratings, disconnecting means, abnormal operating conditions, power quality and islanding.

MICROGRIDS

Microgrid is a collection of distributed generatorsm or micro-resources, energy storage devices and loads which operate as a single and independent controllable system capable of providing both power and heat to the area of service [17]. The micro-resources that are incorporated in micro-grids comprise of small units, less than 100 kW provided with power electronics (PE) interface. Most common resources are Solar Photovoltaic (PhV), Fuel Cell (FC) or microturbines which are located close to the load centers and integrated together to produce power at the distribution voltage level. The PE interface and controls of the micro resources ensure that desired power quality and energy output is maintained independently during operation. Hence, from the utility grid perspective, the microgrid is viewed as a single controllable unit capable of meeting local energy needs helping in reliability and security of the system. Dispite all the potential benefits the microgrid offers with its development, there are many challenges which need to be addressed for the successful operation of the micro grid. The most important one is the technical difficulty in managing large numbers of plug and play micro-resources and it requires a very robust communication infrastructure. High costs of DERs and absence of operational standards also impose some challenges to its successful operation.

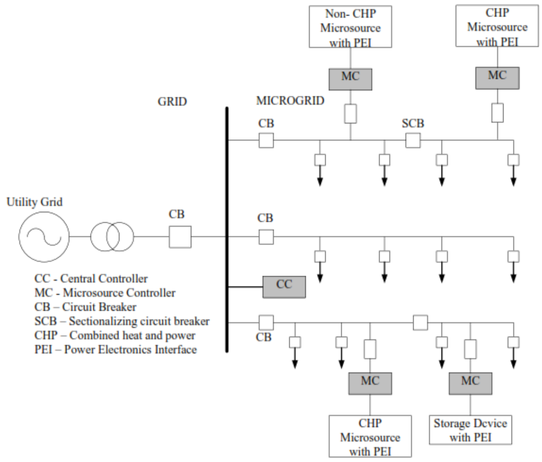

Fig- 3 Typical Microgrid Configuration

A. Self-Tuned Perturb and Observe (SPO) Algorithm

The utilization factor and efficiency of PV array are improved by using an MPPT algorithm for maximum power extraction. The most popular MPPT techniques are P&O, Inc and HC. However, the problems with these techniques are steady-state oscillations, slow dynamic responses and fixed step size issues. Therefore, for mitigating all above problems, a novel SPO algorithm has been proposed. The working strategy of SPO is divided into two parts. 1 section deals with the steady state situation after that mitigates oscillation, by reducing the size of the step change. Moreover, the 2nd section deals with the dynamic change condition after that quickly jumps on required reference DC link voltage, by increasing the size of the step change the dynamic and steady-state behaviours of the SPO MPPT algorithm are shown in Fig.4, which shows the oscillation reduction in steady state condition and sudden jump in dynamic conditions. The block model of SPO is given in Fig.5 and flowchart is given in Fig.6.

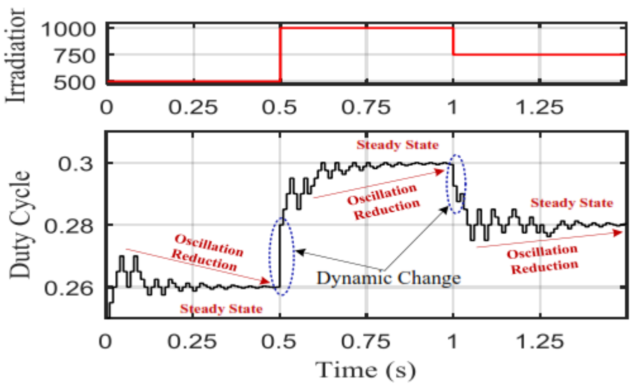

Fig- 4 Steady-state and dynamic behaviour of SPO algorithm.

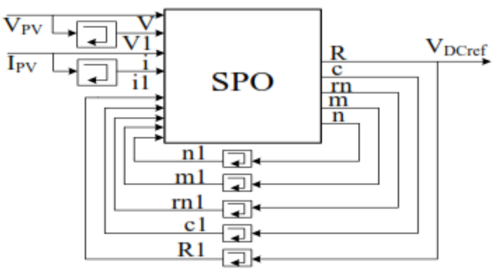

Fig- 5 Block model of SPO algorithm.

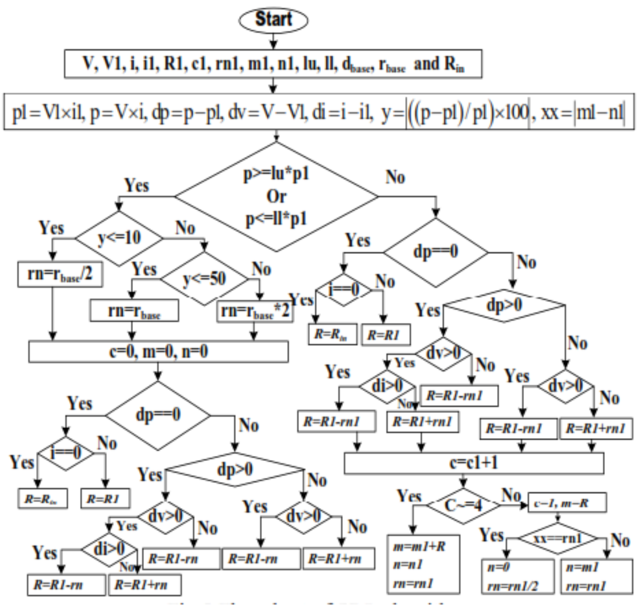

Fig- 6 Flowchart of SPO algorithm

B. Maximize-M Kalman Filter (MMKF)

MMKF is the hybrid of Kalman filter and maximize-M data dependent, iterative partial update technique, which is shown in Fig.7 In this work, MMKF, through filtering, smoothing and learning process estimates fundamental component from *iL* and *v*, which consists of huge amount of harmonic components.

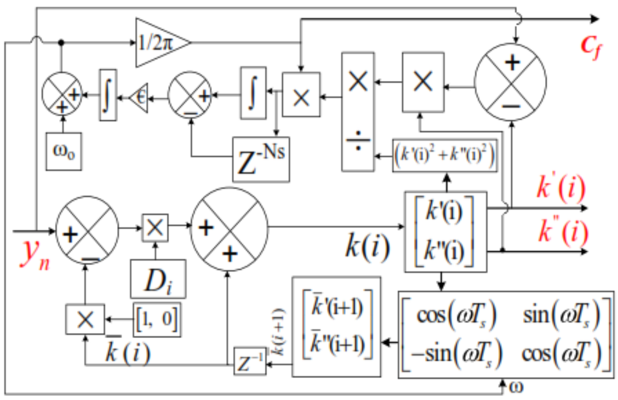

Fig- 7 Block Diagram of MMKF

1) Kalman Filter (KF)

KF is a well-established recursive technique of estimation in the discrete time domain, from the derived state space model of any system. For the derivation of KF, the considered state space model is described as,

$k(i+1)=g_i k(i)+Q_i$

$y(i)=h_i^T k i+Q_i$

here, *k* is state vector, *i* is sampling instant, *y* is input signal, *gi* is state transition matrix, *Qi* is process noise, *O* is measured noise, *hi* is measurement matrix.

2) Maximize-M Kalman Filter

Maximize-M is a data dependent, iterative partial update technique, which generates the largest magnitude of entries update vector. It means, a coefficient matrix (C_m) which is used for maximizing the weight coefficients (*Wf*) during error (*Fn(i)*) minimisation.

$W_f(i+1)=W_f i1+C_M(i)*F_n(i)$,....i=1,2,3....

3) Tuning of MMKF

The close estimation and tracking capability of MMKF, are based on *Qi* and *q* parameters. Therefore, the online adaptive tuning process is used here, which is based on the estimated parameters of the previous iteration. The estimated value of *Qi* is derived as,

$Q_i = K(i)-K(i-1)=D_i[y(i)-h_i k(i)]$

4) Comparative Analysis of Proposed MMKF Algorithm

The comparative analysis of the proposed MMKF control algorithm with most popular algorithms, such as SOGI, ANF (Adaptive Notch Filter), and KF, is shown in fig.8

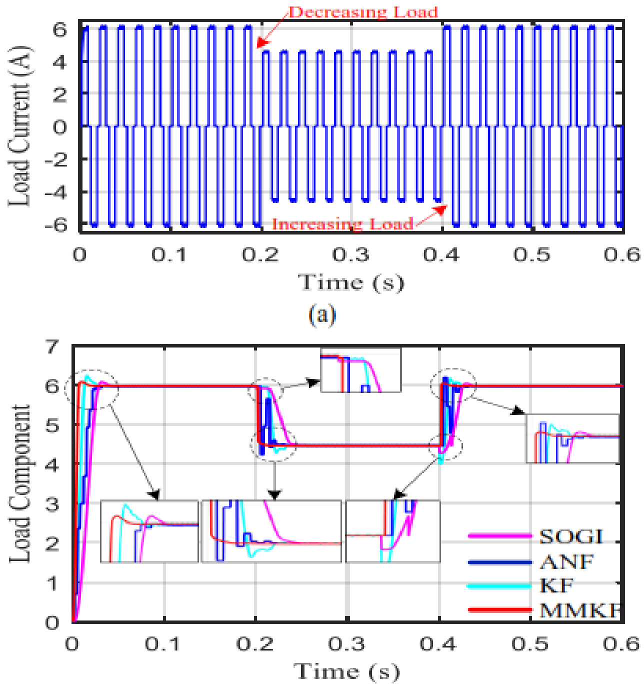

Fig- 8 Responses of different algorithms, (a) load current and (b) extracted load component.

For comparative analysis, the variable loading condition, for the highly nonlinear load is considered, where the load is reduced for the period of 0.2s to 0.4s is considered, which is shown in Fig.8(a). Fig.8(b) shows a comparison in the response of fundamental load component extraction from the load current, which is the resultant active load component (ξ).

The fundamental load component means, the peak value of the fundamental component of the load current. In term of oscillations, Fig.8(b) shows that during load change the highest oscillations are in ANF and lowest in MMKF. Similarly, regarding settling time and accuracy, Fig.8(b) depicts that higher settling time and lower accuracy are in SOGI, while lower settling time and higher accuracy are in MMKF, which shows a very good fundamental load component extraction ability of MMKF control Algorithem.

V. RESULTS

A prototype is developed for performance evaluation of MMKF based control technique, as shown in Fig.9 Torealize the PV characteristic, a solar PV simulator (AMETEK, ETS600x17DPVF) is used, and it is integrated with the actual grid. During integration, for DC PV power to conversion in AC form, load feeding, and for synchronization a single-phase voltage source converter (VSC) is used. Moreover, for MPPT operation, a boost converter is used. The RC filter and interfacing inductors are used for harmonics and switching ripples mitigation.

A. Case-1: Operation at Nonlinear Loads

Here, generated solar PV power is higher than the load demand. Therefore, after fulfill the load demand, excess power is supplied to the grid, which performances are shown in Figs.10-12 In Fig.10 the waveforms of *ig* and *v* are out of phase, which depicts that the power is supplied to the grid. This is also shown in Fig.10 (a). Moreover, in Fig.10 and Fig.10 (e), the waveforms of *iL* and *vs s* are in-phase, which depicts that power is feeding to the load. The amounts of supply power into the load and grid, are shown in Figs.10 (f) nd 10(b), respectively, which reveal that 1.62 kW and 1.83kW power are transfered to the load and the grid, respectively. The harmonic spectra of *ig*, *v* are shown in Fig.10(c)-(d) and Fig.10(g), which shows that THDs of *Ig*, *vs* and *iLs* are only 1.8%, 2.1%, and 18.9%. Moreover, the waveform of *iL* and *V* are shown in fig.10

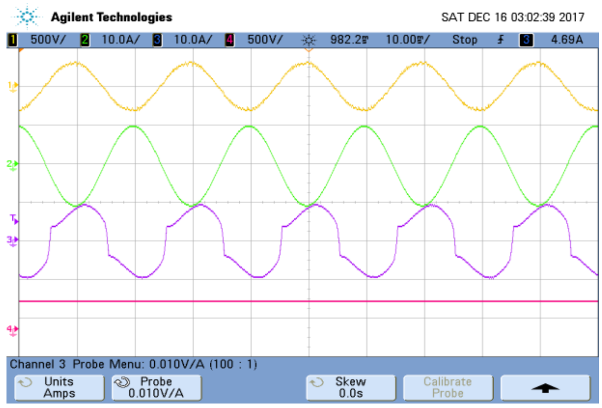

Fig- 9 Waveforms in normal condition.

The waveforms of *IPV* and *VPV* at 1000W/m and *i*2 solar insolation, are shown in Fig. Moreover, it also shows the waveform of the extracted *ki'* and *i*, which reveals a very good filtering capability of MMKF.

B. Case-2: Operation during grid overvoltage condition

In the case of an overvoltage condition, a 13.5% of the rise in *Vs* is considered, which waveforms are shown in Fig.12-13.

The waveforms of overvoltage depict that, the voltage at PCC is increased, so due to constant supply power, the *I* is decreased. Moreover, since *P* is directly propositional to the square of *vs* at PCC, so *PLL*, as well as *iLL*, is increased. However,the e *V* is maintained constant, which is shown in Fig.12 The THDs of *iDC g* and *vs* are still less, which are shown in Fig.13.

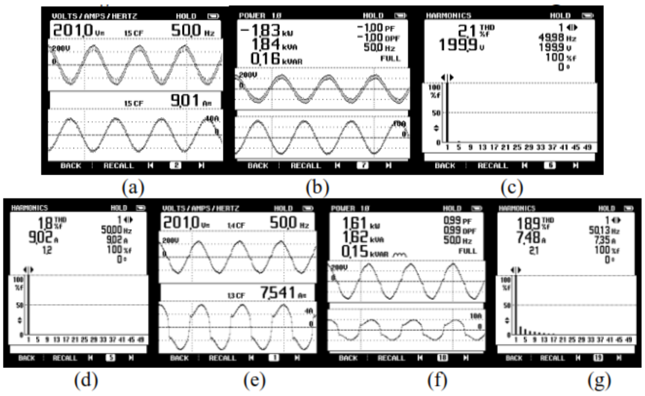

Fig- 10 Waveforms of (a) *vs* ***Ig*** and *ig*, (b) *pg* (grid power), (c)THD of *vs*, (d) THD of the ***ig*** V_L And iL, (f) *pL* (load Power), and (g) THD of i_L

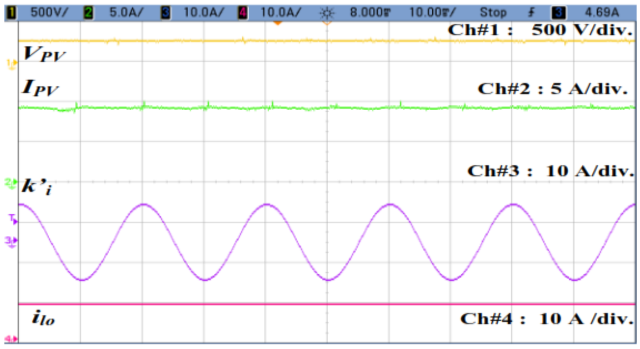

Fig- 11 Waveforms of PV and load components.

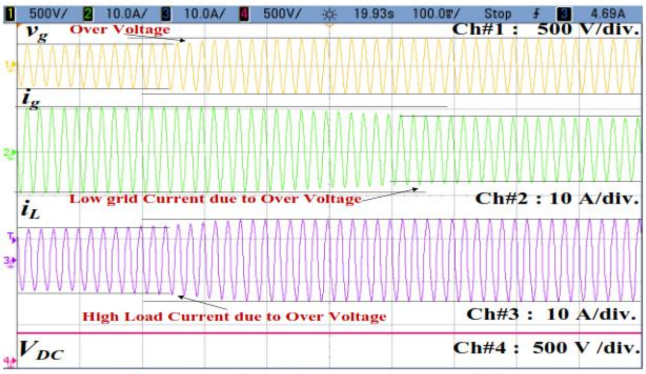

Fig- 12 Waveforms for overvoltage conditions.

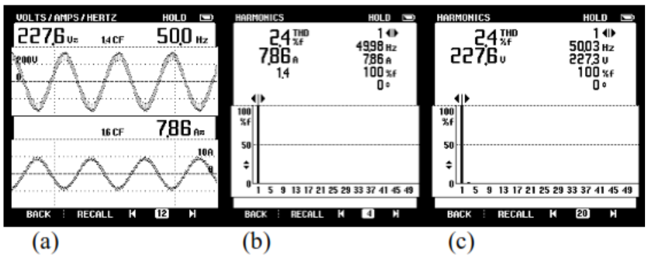

Fig- 13 Waveform of, (a) *vs* and *ig*, (b) harmonic spectrum of *ig* and (c) *v*, during grid overvoltage condition.

C. Case-3: Operation during Grid Under-Voltage Condition.

In case of under-voltage, a 12% fall in *v* is considered, which waveforms are shown in Fig.14 and Fig.15 Fig.14-15 depict that during undervoltage, the *v* at PCC is decreased, so the *ig* is decreased. Moreover, since the *P* is directly propositional to the square of *vs*, so *PLs,* as well as *i*, is decreased. However, the *V* is maintained constant, which is shown in Fig.14 The THDs of *I DCg* and *v* are still low, which are shown in Fig.15.

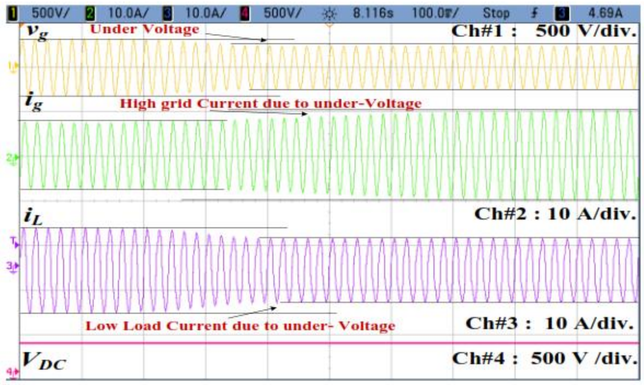

Fig- 14 Waveforms for under-voltage condition.

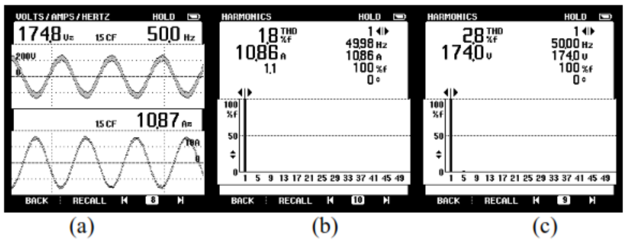

Fig- 15 Waveforms of, (a) *vs* and *ig*, (b) harmonic spectrum of *i* and (c) harmonic spectrum of *vs*, during grid under voltage condition.

VI. CONCLUSION

In the control strategies, the solar PhV generator is operated at MPP, and the battery storage acts as a buffer in order to inject and absorb deficit or surplus power by using the charge/discharge cycle of the battery. Thus, the control strategies demonstrate effective coordination between inverter V-f (or P-Q) control, MPPT control, and energy storage control. The proposed control methods are entirely developed in the abc reference frame, so it avoids the transformation to the dq0 reference frame and vice versa. Therefore, the proposed control is not sensitive to measurement noise as it is dependent on the measurements of the past cycle rather than at a particular time instant. similarly, the integrated and coordinated P-Q control algorithm can be effectively used in supplying some critical loads of a microgrid with solar PhV and battery.

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