An Assessment of RAD Based Control Algorithm for Single-Stage Multitasking Grid Tied SECS

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***Abstract*— This paper deals with a three phase single-stage multitasking grid tied SECS (Solar Energy Conversion system). A single three leg VSC (voltage Source Converter) topology is used in this work. The SECS not only feeds solar PV (Photo-Voltaic) energy into the grid but also serves the purpose of grid currents balancing, reactive power compensation, harmonics elimination and MPPT (Maximum Power Point Tracking). A feed-forward term for the solar contribution is used to improve the dynamic response for climatic changes. The PV array voltage and hence the dc link voltage is continuously adjusted to achieve MPPT. A RAD (Round Adaptive Detection) based algorithm is proposed for the control of three phase VSC. The system is modeled and simulated on MATLAB based platform. A wide range of simulation results are shown to demonstrate all features of proposed system. Moreover, all salient intermediate control signals are provided for assessment of control algorithm. The THD (Total Harmonics Distortion) of grid current has been found well under IEEE-519 standard.**

Keywords*— *Solar PV; Single-stage; 3P3W; MPPT; RAD, Power Quality.

I. Introduction

The consumption of electrical energy by a country is has become a development index in last one century. Conventionally petroleum, coal etc are used as fuel to generate the electricity. However, the rapid depletion of these conventional energy sources has put an energy crisis situation in front of the world. Moreover, these conventional energy sources are prime cause of increasing pollution and green house effect causing global warming. Considering these facts the green energy sources are expected to be prime future energy sources. The solar energy is becoming natural choice for carbon free energy source because of its abundance. However, the cost considerations of solar PV has always been an issue with installations in practice but recent trends show that solar PV is reaching the grid parity [1]-[2].

The two subcategories of solar PV energy based system standalone and grid interfaced SPV system. Several standalone PV systems are proposed by researchers [3]-[5]. Multilevel inverter circuit technology for standalone PV system is proposed in [3], wherein the robustness and efficiency of the system has been improved with the help of multilevel inverter technology. A storage size selection criteria for energy storage system considering the economic aspect is given in [4]. Limitation of battery storage system and use connection to grid when threshold is reached is proposed in [5]. Considering these points the grid interfaced SPV systems are more preferable for the places where grid is available.

The characteristics solar PV array is nonlinear and because of that there exists a unique operating point for which peak power can be extracted from a given PV array. This operating point changes with climatic condition which evolves the necessity of continuous tracking of MPP (Maximum Power Point). Several MPPT (Maximum Power Point Tracking) techniques are proposed to track the maximum power point. A review of MPPT techniques is shown in [6]. However, perturb and observe (P&O) based MPPT algorithms are widely used because of their simplicity in implementation. An analysis of P&O based MPPT algorithm is shown in [7]. This work also uses P&O based MPPT algorithm.

The use of power electronics converters in distribution system is increasing day by day. The power electronics equipments are more efficient then may conventional alternatives. However, power electronics converters such as rectifiers, SMPS (Switched Mode Power Supplies), electronic blasts are nonlinear loads. This nonlinear load presents their ill effects in terms of increase losses in the distribution system along with poor voltage power quality at PCC (Point of Common Coupling). However, because of efficiency constraint the power electronics based equipment cannot be avoided which raises the need for some retrofit solution to compensate for these problems. The D-STATCOM (Distribution Static synchronous Compensator) presents is one such retrofit solution for these power quality problems. The VSC based active power filters and D-STATCOMs are proposed by researchers. In these applications the VSC is used as a shunt grid interfaced device. Several control algorithms are proposed for D-STATCOM. A back propagation algorithm based control algorithm for power quality improvement is shown in [8]. A control algorithm which uses neural network based conductance estimation is shown in [9].

Grid interfaced solar PV systems are proposed by several researchers. However, the PV inverters are underutilized as solar energy is not available all the time. Considering this researchers have proposed multifunctional SPV systems which not only feed solar energy into the grid but also help in power quality improvement. A two stage SRF theory based control for SPV system is shown in [10]-[12]. However, two stage system includes one extra power conversion stage which increases cost and losses in the system. A single stage dual functional ILST theory based SECS (Solar Energy Conversion System) is shown in [13]. However, the proposed algorithm in [13] uses fixed central frequency and performance may deteriorate under frequency deviation.

This paper uses an RAD (Round adaptive Detection) based control algorithm for control of grid tied SECS. The RAD acts as a filter in which central frequency is always locked with grid frequency by virtue of its structure. The adaptive detection of harmonics is shown in [14]-[16]. The discrete adaptive detection of harmonics is shown in [14]. An analysis of adaptive detection based algorithm is shown in [15]. An active power filter based on using adaptive technique is shown in [16]. However, in this paper RAD based control algorithm is proposed for control of multitasking grid tied SECS. A single stage- stage SECS is used in the proposed work. The single VSC serves the purpose of MPPT, harmonics mitigation, compensation of reactive power, grid currents balancing along with feeding extracted energy into the distribution system. An assessment of proposed RAD based control algorithm is presented along with its intermediate signals. The MATLAB simulations are used to verify the performance of the proposed system. A wide variety of simulation results are shown to demonstrate all the features of proposed system. The proposed system follows IEEE-519 standard [17].

II. SYSTEM CONFIGURATION

The system configuration is shown in Fig. 1. A three-phase, distribution system is the system under consideration. The proposed system consists of a solar PV array, a 3-leg VSC, interfacing inductors (L_{VSC}), ripple filter (C, R), three-phase loads, and the 3P3W (3-phase 3-wire) distribution system. The solar PV array is a series parallel combination of small power solar panels to match the required rating. The SPV array is connected at the dc link of VSC. The dc link voltage is so controlled that the SPV array operates at MPP. The power extracted from the PV array is fed to the dc link of the VSC, which is then transferred to the 3-phase grid. The dc link capapcitor of the VSC acts as a small energy buffer. The VSC consists of three IGBT (Insulated Gate Bipolar Transistor) legs. This VSC is connected to 3P3W distribution system at PCC via interfacing inductors. A three-phase load (linear/nonlinear) is connected at PCC. A small ripple filter is connected in shunt at PCC to suppress switching ripple. The rating of all components is given in Appendix.

III. SYSTEM CONTROL

The basic control strategy for the proposed system is shown in Fig. 2. The two main subsections of the control algorithm are MPPT and control for grid interface part of VSC. The MPPT algorithm adjusts the dc link reference to a value which corresponds to peak power output from PV array at a given climatic condition, whereas the dc link voltage control loop keeps the average dc link voltage to set reference value in steady state condition. The VSC feeds the extracted energy into the 3P3W distribution system along with grid currents balancing, reactive power compensation, harmonics elimination. An P&O based MPPT algorithm is used for control of boost converter whereas a RAD based control algorithm is proposed for control of VSC. The RAD based control is used to extract fundamental active power consuming component of load current. Finally these estimated load active power consuming component of load currents is then used to estimate the reference grid currents. An indirect current control strategy is used to generate the switching pulses for the VSC. The complete control algorithm is described in detail in the following section.

A. Maximum Power Point Tracking

A perturb and observe (P&O) based MPPT technique is used in the proposed work. The P&O based MPPT algorithms are widely used and offer benefit of simplicity in implementation. The operating point is perturbed and the rate change of PV array power with respect to change in direction is observed. In case the rate of change is positive the reference PV array voltage is increased otherwise the reference PV array power is decreased. The governing equations are,

$$V_{dcref}(k)= V_{dcref}(k-1)+\Delta V \text{ if } dP_{PV}>0 \text{ and } dV_{PV}>0 \text{ or } dP_{PV}<0 \text{ and } dV_{PV}<0 \quad (1a)$$

$$V_{dcref}(k)= V_{dcref}(k-1)-\Delta V \text{ if } dP_{PV}>0 \text{ and } dV_{PV}<0 \text{ or } dP_{PV}<0 \text{ and } dV_{PV}>0 \quad (1b)$$

where ΔV is the size of perturbation and V_{dcref} is the reference dc link voltage. The output of this MPPT algorithm is saturated at suitable upper and lower limits for proper operation of the SECS.

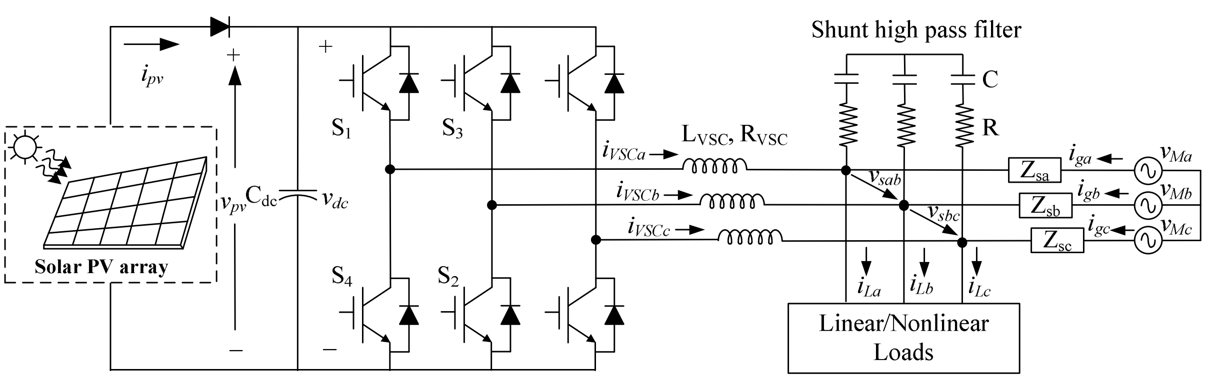

Fig. 1 System Configuration.

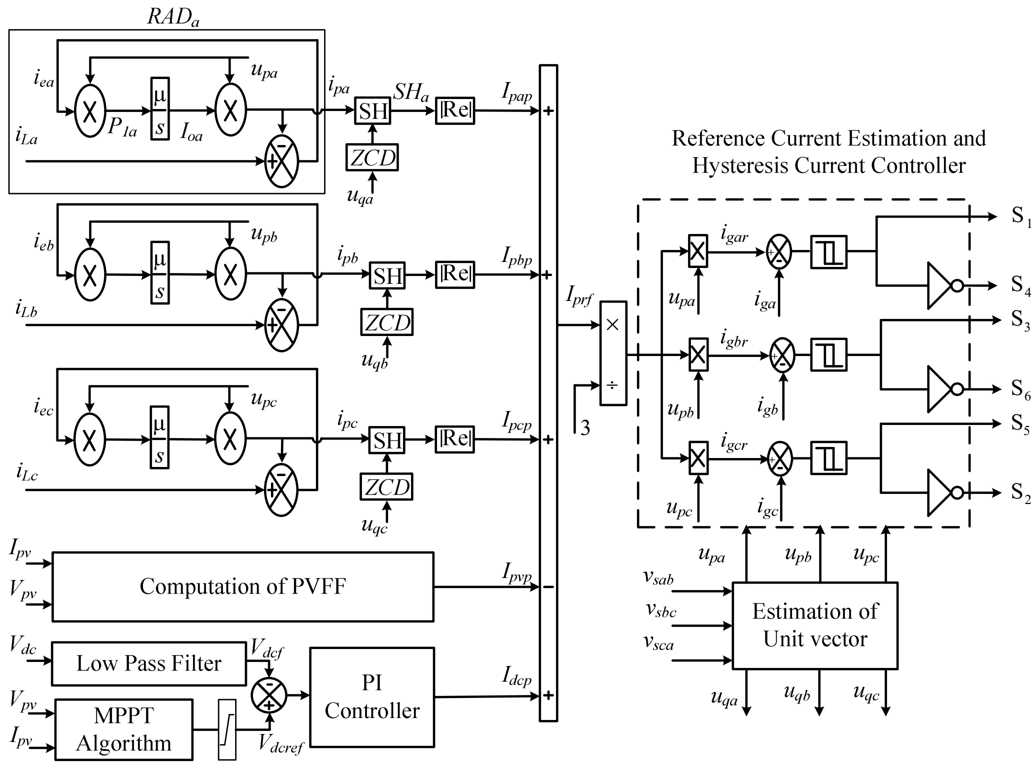

Fig2 Block diagram of control algorithm.

B. Control Algorithm for VSC

The basic block diagram of the proposed control algorithm is presented in Fig. 2. For the control of the VSC several quantities are sensed. These sensed quantities are then processed according to control algorithm to generate the appropriate switching pattern. The sensed quantities are, grid currents (i_{ga}, i_{gb}), PCC voltages (v_{ab}, v_{bc}), load currents (i_{La}, i_{Lb}), dc bus voltage (v_{dc}/v_{pv}) and PV array current (i_{pv}). Only two load and grid currents are sensed instead of three as the out of three anyone can be easily estimated inside the DSP by applying basic KCL equation. The phases to neutral voltages are estimated from sensed line voltages. The estimated phase to neutral voltages for phases a, b, c is designated as v_{sa}, v_{sb}, v_{sc} respectively. To estimate the unit vectors or synchronizing signals at first the amplitude of three-phase voltage is estimated as,

$$V_u = \sqrt{\frac{2(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}{3}} \tag{2}$$

This amplitude is used to determine the unit vector of PCC voltage which contains the phasor information of all phase voltages. The unit vectors are estimated as,

$$u_{pa} = \frac{v_{sa}}{V_u}, u_{pb} = \frac{v_{sb}}{V_u}, u_{pc} = \frac{v_{sc}}{V_u} \tag{3}$$

From these unit vectors the quadrature unit vectors are estimated as,

$$\begin{aligned} u_{qa} &= -u_{pb} / \sqrt{3} + u_{pc} / \sqrt{3} \\ u_{qb} &= \sqrt{3}u_{pa} / 2 + (u_{pb} - u_{pc}) / 2\sqrt{3} \\ u_{qc} &= -\sqrt{3}u_{pa} / 2 + (u_{pb} - u_{pc}) / 2\sqrt{3} \end{aligned} \tag{4}$$

The in-phase and quadrature unit vectors are used in control algorithm.

The total PV array power is used to estimate its contribution to grid currents. Since at first step the total active power component for all three phases are estimated the PV feed forward (PVFF) compensation term is computed as,

$$I_{pvp} = \frac{2P_{pv}}{V_u} \tag{5}$$

A RAD based control algorithm is used to estimate the average power consuming portion of load current. The average power consuming component of loads currents of all three phases are calculated independently. The principle of operation of RAD_a block shown in Fig. 2 is as follows.

The i_{ea} is multiplied with in-phase unit vector (u_{pa}) to get the output P_{1a}. The P_{1a} is summed up by an integrator. The output of this integrator is designated as I_{oa}, which is again multiplied with u_{pa}. The output of the second multiplier is designated as i_{pa} which is fundamental component of load current in phase with u_{pa}. The i_{pa} is then subtracted from actual load current and the error is sent round back to the first multiplier. The loop settles when the average value of I_{oa} becomes constant. The gain of the integrator (μ) governs the dynamic response of the system. The lower the value of μ higher is the steady state accuracy but poorer the dynamic response. In this proposed system μ is selected as 250. The output of RAD is sampled and hold at zero crossings of quadrature unit vector (u_{qa}) to estimate the peak value of active power consuming component of load current. Similarly, the average power consuming component of all phases is estimated using this adaptive algorithm.

A PI controller is used to maintain the dc bus voltage of VSC to reference value decided by MPPT controller. The output of PI controller (I_{dcp}) in steady state condition is designated the loss component of VSC. The PI controller adjusts I_{dcp} continuously in order to maintain the dc link voltage. A sign convention considering the direction of power flow is used to estimate the peak amplitude of average power consuming component of grid current. According to considered directions of grid currents as shown in Fig. 1, the load and loss components are responsible for power expenditure at PCC whereas the PV array injects power into the PCC. The grid currents are considered coming out from grid source hence the power expenditure component is given the positive sign and PV array contribution is given the negative sign. The mathematical estimation for I_{pnf} is as,

$$I_{prf} = I_{pap} + I_{pbp} + I_{pcp} + I_{dcp} - I_{pvp} \tag{6}$$

This I_{prf} is equally divided into all three phases of grid. The equal division causes the feature of grid currents balancing all the times. The reference grid currents are estimated as,

$$i_{gar} = \frac{I_{prf}}{3} u_{pa}, i_{gbr} = \frac{I_{prf}}{3} u_{pb}, i_{gcr} = \frac{I_{prf}}{3} u_{pc} \tag{7}$$

The sensed and reference grid currents are given as the inputs to hysteresis current controller and logic switching pulses are output of the current controller.

IV. RESULTS AND DISCUSSIONS

The proposed single stage grid interfaced SPV system is modeled in MATLAB along with Simulink and Sim Power System toolboxes. A three phase load of 20 kW and SPV array of 25 kW is considered. The simulation performances are shown for SECS operating under nonlinear/linear loads and change in insolation level. The intermediate signals of the control algorithm are also shown for assessment of the proposed control algorithm. The performance under steady state and dynamic condition are shown via simulation studies.

A. Behavior of SECS under Linear Loads

The behavior of SECS operating under linear load condition is shown in Fig. 3 (a). A 3 phase load of 20 kW and 0.8 lag is considered for this steady. Before, time t= 0.4s, one of the load line is opened (phase-a) and the load is unbalanced in nature. However, even under unbalanced load currents the grid currents are balanced which shows the grid current balancing nature of SECS. The phase-a line is connected at time t = 0.4 s, which causes effective increase in load power. The increase in load power decreases the power to be fed into the grid which can be observed in terms of decreased magnitude of grid current. After time t = 0.4 s, the SECS works in order to correct the overall power factor to unity as seen into the PCC terminals. During transients no appreciable effect is observed on dc link voltage (v_{dc}) and power from solar PV-array (P_{pv}).

B. Behavior of SECS under Nonlinear Loads

The behavior of SECS operating under nonlinear load condition is shown in Fig. 3 (b). A 3 phase nonlinear load of 20 kW is considered for this steady. A diode bride rectifier with RL load is considered for emulation of nonlinear load. Before, time t= 0.4s, one of the load line is opened (phase-a) and load is unbalanced nonlinear load. This load can be considered as a single phase diode bridge rectifier connected between two lines of ac supply system. The load current waveforms are square wave in nature which confirms the operation as single phase diode bridge rectifier. However, even under nonlinear unbalanced load currents, the grid currents are balanced and sinusoidal which shows the grid currents balancing and harmonics mitigation nature of SECS. The phase-a line is connected at time t = 0.4 s, which causes effective increase in load power. The increase in load power decreases the power to be fed into the grid which can be observed in terms of decreased magnitude of grid current. After time t = 0.4 s, the SECS works in order to mitigate the harmonics and to make the overall power factor to unity as seen into the PCC terminals. During transients no appreciable effect is observed on dc link voltage (v_{dc}) and power from solar PV-array (P_{pv}).

All salient intermediate signals for RAD based control algorithm under load current dynamics and steady state condition are shown in Fig. 3 (c). The phase-a load line is disconnected at time instant t = 0.31 s whereas the at time t = 0.45 s the line is reconnected. Both the dynamic and steady state responses are found satisfactory. The PV power is kept constant during this whole period hence PVFF term can be considered as constant. The assessment of intermediate signal shows that the RAD control algorithm responds almost instantaneously to the changes in load current and settles within one cycle of fundamental frequency.

C. Behavior of SECS under Change in Solar Insolation

The behavior of SECS for step change in irradiance is shown in Fig. 3 (d). The load on the system is kept constant to demonstrate the effect of insolation change only. The unaltered load currents confirm the constant load condition. The insolation is 800 W/m^2 before time t = 0.4 s. The power from the solar PV array is around 20 kW and load power is also 20 kW hence, approximately zero current is observed on grid side currents. The VSC currents consist of reactive power corresponding load currents and fundamental active power component of currents corresponding to active power from solar PV array. At time t= 0.4 s, the irradiance is changed to 1000 W/m^2. The increase in irradiance causes an increase in power from SPV array. The increased power is now fed into the grid which can be observed from increased magnitude of grid currents.

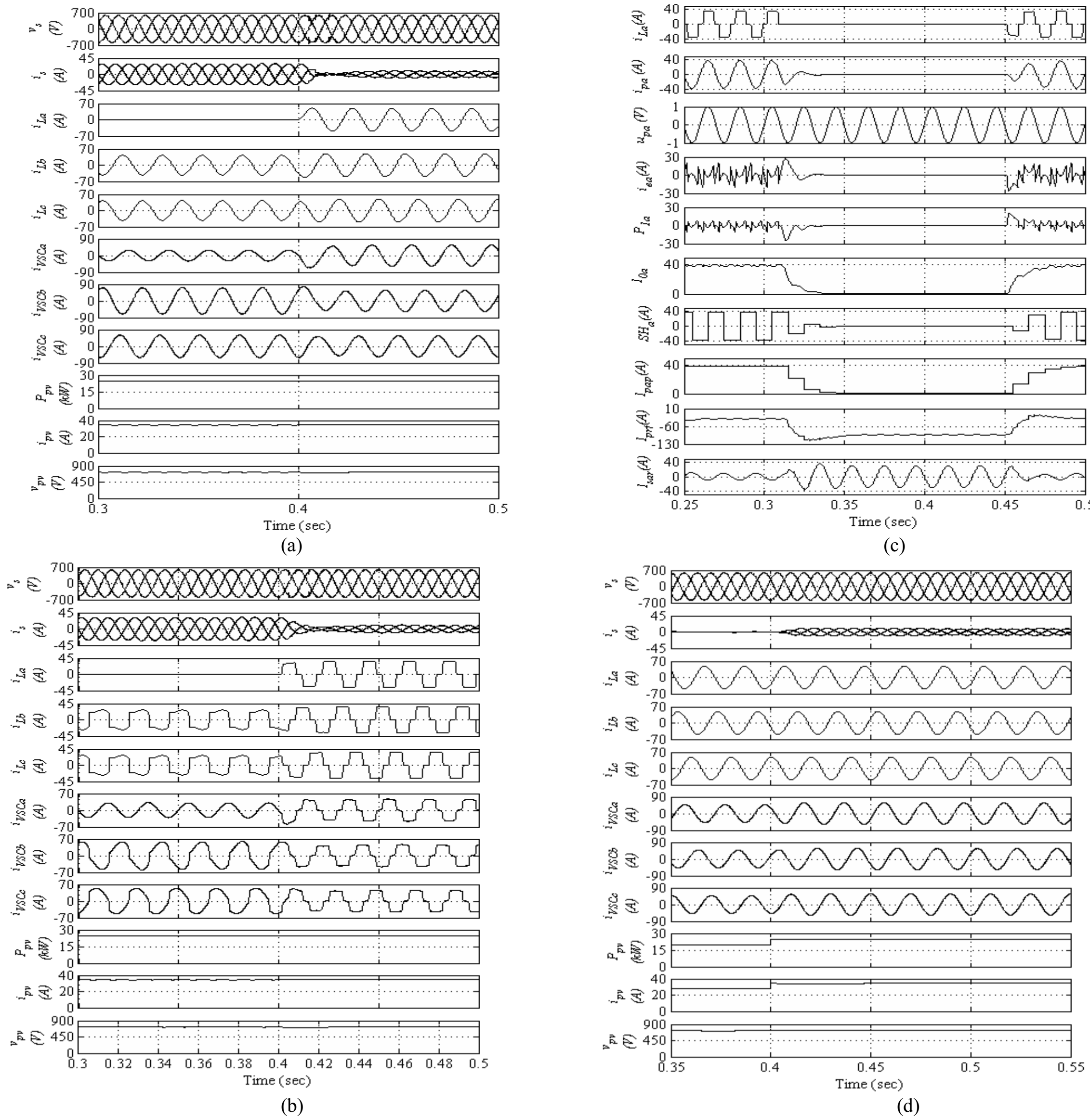

Fig. 3 Performance evaluation of SECS for (a) linear load, (b) nonlinear load, (c) intermediate control signal, (c) sudden change in insolation level

D. Harmonics Analysis

The harmonics analysis of load and grid currents of proposed system is shown in Fig. 4. Fig. 4(a) shows the harmonics spectrum of the nonlinear load current. The THD of the load current is of order of 26 %. Fig. 4 (b) shows the harmonics spectrum of grid current and the THD of grid currents is found of order of 2 % (below 5%) which is well under IEEE-519 standard.

V. CONCLUSION

A single-stage, three-phase, 3-leg VSC based system has been proposed to interface solar PV array with a 3P3W distribution system. A PLL-less control has been proposed for the control of multitasking grid tied VSC. A RAD based control algorithm has been proposed. The adaptive nature provides the benefit of stable and fast convergence. The performance of proposed system has been found satisfactory under dynamics and steady state conditions. The SECS feeds extracted solar energy into the grid along with the harmonics and reactive power required by the local load. Moreover, the SECS also supplies negative sequence current required by the local load in order to maintain balanced grid currents. The THDs of the grid currents are found less than 5% (within IEEE-519 standard) even under nonlinear loads at PCC. These type of distributed generation system helps in reduction of losses in transmission line and distribution transformer. Moreover, the need for separated power quality improvement device is eliminated with minimal increment in power rating.

Hence the proposed solution poses a suitable dynamic control with future ancillary services to be provided by SECS.

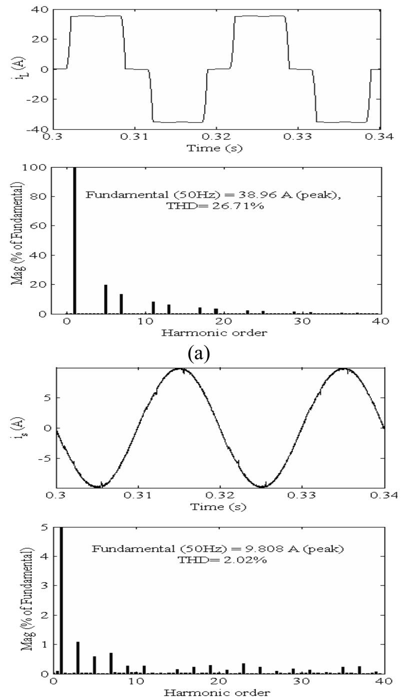

Fig. 4 Harmonics analysis (a) load current, (b) grid current.

APPENDIX

Parameters of the system: three-phase line voltage 415 V, frequency = 50Hz, supply inductance = 2 mH and supply resistance = 0.5 Ω, interfacing inductor = 2 mH, ripple filter R = 5 Ω, C = 5μF, PI controller parameter K_p = 0.3, K_i = 1, PV array open circuit voltage: 840 V, PV array short circuit current: 38 A, PV array peak power: 25 kW. RAD parameter μ = 250.

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