RESEARCH ARTICLE OPEN ACCESS

Performance Analysis of Off-Grid Solar System for Linear and Non-Linear Loading

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ABSTRACT
To obtain usable solar power with Solar Photo Voltaic (SPV), Power Electronic Converters (PEC) are required. PEC converts DC output power from solar into AC. PEC interfacing hinders the operation of utility system. The high frequency switching operation injects the harmonics into the system, hence various Power Quality (PQ) issues are generated. In this paper, performance analysis of off-grid Solar Energy Conversion System with two-level Voltage Source Inverter (VSI) to reduce harmonics is presented. Mathematical modeling of solar PV (SPV) system is described. For satisfactory performance of SECS, Maximum Power Point Tracking (MPPT) algorithm also play very important role. Brief overview of conventional MPPT algorithms is also given. The performance of the system has been analysed for various operating conditions of linear and non-linear load.
Keywords - Maximum Power Point Tracking (MPPT), Power Electronic Converters (PEC), Power Quality (PQ), Solar Photo Voltaic (SPV), Voltage Source Inverter (VSI).

I. INTRODUCTION

Solar power is becoming one of the vast power generation systems all over the world. The sharp drop in prices of solar technologies by about 52% between 2010 and 2015 (in terms of kW) has changed the relative importance of solar energy. Tropical countries, including India, are rich in the solar resource, and can use this in an innovative way to meet energy needs at decentralized locations [1]. The Solar Power Generation System (SPGS) is proving to be a promising future energy technology of RE projects. The SPGS is a technology through which solar energy obtained from sun’s radiation can be converted into useful electricity via various synthesizing stages of conversion. The synthesizing stages comprises of PV cell which is the elementary building block of SECS; PV panel, which is the series/parallel combination of PV module. MPPT which track the maximum output for the given input at any instant and DC/AC conversion controllers. While designing SECS the biggest challenge is to transform the stochastic behavior of PV sources into a system with ease of controllability [2].

Installation of solar PV panels to produce bulk power can be Stand Alone Mode (SAM) or Grid Connected Mode (GCM). The stand-alone (SA) system is installed to meet the local supply demand and to operate as application-oriented utility like pump storage system, street lighting, solar heater etc. SA-SECS is worthy in forming a microgrid which can be operated to meet the power demand of remote area where transmission is either infeasible or uneconomical. In Fig. 2., SECS will operate in SAM. In SAM, SECS comprises of PV-panel, DC-DC converter, DC-AC inverter, Filter, and load bus.. In this paper performance analysis of SA-SECS is presented. The complete simulation model of each component of SECS in off-grid operation is presented and results are obtained for constant and variable irradiance, to check the efficiency of two-level VSI DC-AC converter.

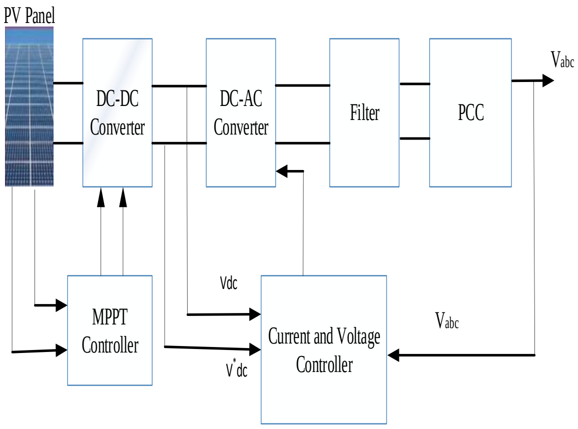


Fig. 1 Generalized block diagram for SECS in stand-alone mode

II. COMPONENTS OF SOLAR POWER GENERATION SYSTEM

2.1 PV-ARRAY

The elementary building block of PVA is PV cell, which is formed with p-n junction having thin wafer of semiconductor material. When light with energy greater than the energy band-gap (E_g) of the semiconductor falls it get absorbed and electron-hole pairs are formed resulting in the generation of DC output across terminals. In this work single diode module of PV cell with Ns series and N_P parallel module is employed as represented in Fig 2.

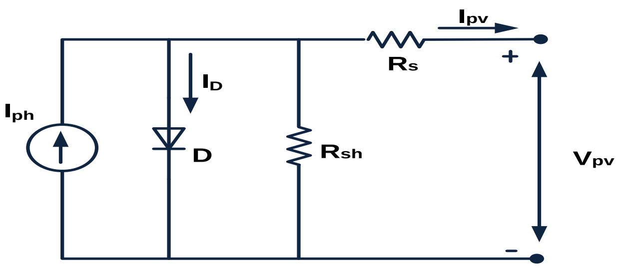


Fig. 2. Simplified equivalent circuit of a PV cell

$$I_{PV} = I_{PH} - I_D \qquad (1)$$

$$I_D = I_S\left[exp\left(\frac{q(V_{PV}+IR_S)}{N_SKAT_O}\right) - 1\right] \qquad (2)$$

$$I_{PV} = I_{PH} - I_S\left[exp\left(\frac{q(V_{PV}+IR_S)}{N_SKAT_O}\right) - 1\right] \qquad (3)$$

For a PV array having N_P parallel module eq. (3) can be modified as;

$$I_{PV} = N_P * I_{PH} - N_P * I_S\left[exp\left(\frac{q(V_{PV}+IR_S)}{N_SKAT_O}\right) - 1\right] \qquad (4)$$

I_{PH} is the photon current
I_D=is the current across diode
I_{ph}= is the solar induced or photon generated current
G_{ref} =is the reference irradiance 1000 W/m^2
G =is the measured irradiance W/m^2
I_s = diode saturation current
V_{PV} =is the output voltage across terminal of solar cell
k = Boltzmann constant
K_i= is the temperature coefficient of Isc
T_O = solar cell operating temperature
q = elementary electron charge
A =diode quality factor (diode emission coefficient).
I_{SC} = is the short circuit current of solar cell

R_S is the series resistance which a solar cell offers to the movement of electrons R_{SH} depicts the losses associated with leakage current through a parallel resistive path within the device. The parameters of the module is given in Table 1.

Table 1. Paramaters for designing SECS system

S No.	Parameter	Variable	Value
1	Maximum PV power (STC)	Pmax	15 KW
2	Maximum voltage at Pmax	Vmp	65 V
3	Maximum current at Pmax	Imp	6 A
4	Open-circuit voltage	Voc	46.22 V
5	Short-circuit current	Isc	9.06 A
6	Series cells	N_S	10
7	Parallel cells	N_P	10
8	Ideality factor of diode	A	1.3
9	Cell short circuit current temperature coefficient of Isc	Ki	0.058 ◦C
10	Reference-temperature	Tref	25 ◦C
11	Irradiance	Gref	1000 at STC

2.2 Maximum Power Point Tracking (MPPT)

As the temperature and radiation vary, the maximum output across the terminal fluctuates and it degrades the efficiency of the PV cell. The maximum power point tracking is a technique which holds the operating terminal voltage value corresponding to the maximum power point [4]. The function of the MPPT is to regulate the solar operating voltage close to the MPP in varying atmospheric state. It has become an essential constituent for evaluating the design performance of PV systems. In literature various MPPT techniques are available to track the maximum operating point of PV voltage and current for given temerature and iraadiance [5]. Some of them are listed below;

- Hill climbing,
- Perturb andobserve(P&O),
- Incremental conductance(Inc. Con.),
- Fractional open circuit voltage(Voc),
- Ripple correlation control(RCC),
- Current sweep,
- Fuzzy logic, Particle Swam Optimization (PSO) and Neural Network (NN) control,
- Constant voltage method and constant current method,

All the above methods have their advantages and limitations. The simple methods like constant voltage method and constant current method are less accurate. P&O method is commonly used method because its implementation circuitry is not complex but it shows good response where environmental conditions changes rapidly. In the proposed work, P&O Method of MPPT is employed to track the maximum power operating point due to its ease to control and good tracking characteristics. The method is basically iterative approach, in which operating point of solar PV oscillates around the maximum power point. The power versus voltage curve of solar PV shows that, change in power with respect to voltage *(dP/dV)* is positive, negative and zero for region before maximum power point, after maximum power point and at maximum power point respectively. This method is applied by perturbing the operating voltage at regular interval and oscillating around the point *dP/dV=0* i.e. MPP.

2.3 DC-DC Boost converter

In MPPT the role of DC-DC converter is to shift the V_i, i.e., input voltage to DC-DC converter corresponding to the V_{MPP}. The methodology found in literature to design DC-DC converters is basically starts with the calculation of duty cycle D, which is allied on the output voltage of the converter [10]. In the proposed DC-DC boost converter is used to regulate the PV output voltage. Boost converter increases the generated voltage as compared to low input voltage. The boost converter topology is shown in Fig. 3. When the switch S_1 is turned on by the pulse of PWM, current flows through the inductor (L) and energy are stored in it. When switch is turned off, energy stored in the inductor in the form of magnetic field provides an induced voltage across the inductor that adds to the input voltage. The input voltage and voltage across the inductor are in series and collectively charge the output capacitor (C_{out}) to a voltage higher than input voltage. The values for D, switching frequency f_s, load current I_o, Ripple current ΔI_0, Inductor L, Capacitor C_{out}, is presented in Table 2. with the design parameter of DC-DC converter. Fig. 4 shows the comparison of input voltage (Ppv) and the DC-DC converter output voltage at the output terminal. The V_i is around 400 V and the V_o is around 600 V.

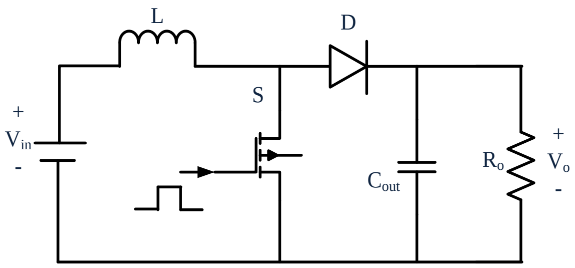


Fig. 3 Circuit diagram of boost converter

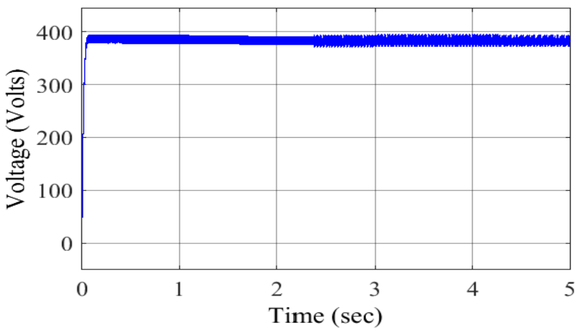
2.4 DC-AC Converter

The PV generates DC power which is converted into AC using DC-AC converter to supply the load or to feed the grid. For DC-AC conversion in SECS, generally conventional voltage source inverter (VSI) is preferred. The structure of a 3-Φ VSI comprises of six switches and a capacitor on DC side [98]. The triggering of the switches in each of the three legs of the VSI is initiated by Pulse Width Modulation (PWM) Scheme [11]. The commonly used PWM techniques are Sinusoidal PWM (SPWM), Space Vector Modulation (SVM), and random PWM. The detailed comparison of all the PWM techniques is presented in [12].

Table 2. Design parameter of DC-DC converter

S No.	**Parameter**	**Expression**	**Value**
1	Duty cycle (D)	$D = 1 - \left(\frac{V_i}{V_o}\right)$	70%
2	Switching frequency	f_s	5 KHz
3	Load current (*Io*)	$\frac{V_o}{R_0} = \frac{V_i}{R_0(1-D)}$	100 A
4	Ripple current	$\Delta I_O = 0.1 \times I_O$	0.04

	(ΔI_0)		
5	Inductor (L)	$L = \dfrac{V_i \times D}{\Delta I_L \times f_s}$	0.99mH
6	Capacitor (C_{out})	$C = \dfrac{D}{R_o \times f_s \times 0.01}$	1000µF



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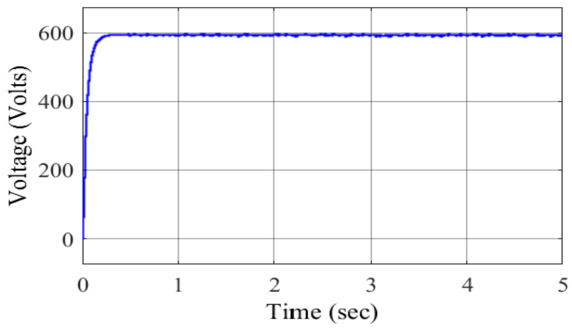

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Fig. 4 Voltage waveforms of DC-DC converter: a) input voltage to the converter, b) output voltage of the converter

In this research work, SPWM technique is used which is a carrier based PWM technique. In SPWM modulating signal is generated by comparing the pulses with the sine wave which helps in reducing distortion factor remarkably. The converter control is designed in Synchronous Reference Frame (SRF) with DC voltage control and AC current/voltage control using PI controller. The Phase Locked Loop (PLL) synchronizes the control by detecting the amplitude and the phase angle vector of the grid voltage/current [13]. The designed inverter control is presented in Fig. 5. The source voltages are taken as reference signal which are the input to the PLL and abc-dq0 transformation. PI controller helps in obtaining error free output by rectifying the feedback error between a desired set-point input and the measured processed value. In case of SAM, a 3-Φ reference signal is considered to design the control.

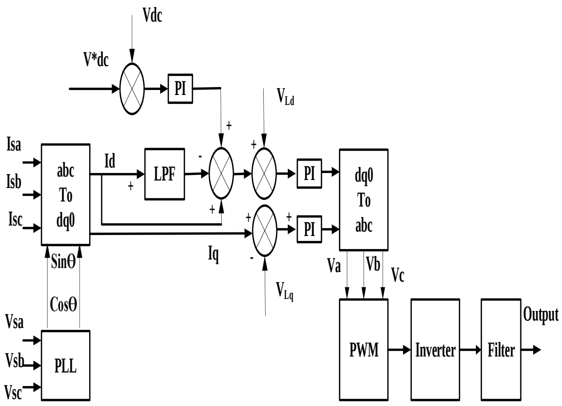


Fig. 5 Inverter control

III. SIMULATION MODEL FOR SPGS IN STAND-ALONE MODE (SAM)

In this research work MATLAB simulation model of 15KW SPGS in SAM is designed as shown in Fig. 6. The DC-output is 600 V as presented in Fig. 7. The parameter of the designed SECS is presented in Table 3. The system has been analysed for both constant irradiance of 1000w/m^{2}and variation from 600 -1000w/m^2 from t = 1.5-3 sec. The output voltage and current for linear load of 10KW is presented in Fig. 8 and Fig. 9 respectively. The power-flow is shown in Fig. 10. The load connected is linear therefore no reactive power is demanded. The system has been designed for 415V RMS for a peak value of 586V. For this system phase voltage will be 338.3 V as shown in Eq. (5).

$$V_{PH} = \frac{V_{L-L}}{\sqrt{3}} = \frac{586}{\sqrt{3}} = 338.2V \qquad (5)$$

Where V_{PH} is peak value of phase voltage and $V_{L-L}$is peak value of line voltage.

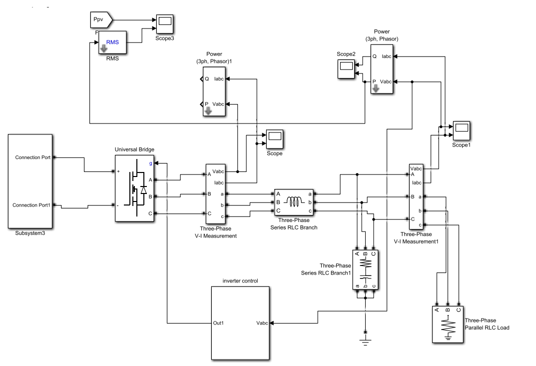


Fig. 6 Simulation model of the proposed Stand-alone solar system

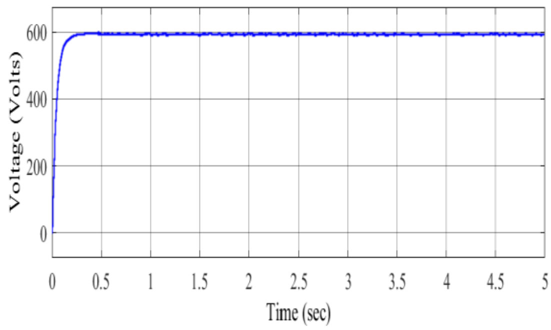


Fig. 7 Output DC voltage of boost converter for constant irradiance

Table 3. Parameters for the designed system

PARAMETER	VALUE
RMS nominal Voltage	415 V
Phase voltage	338.2 V
Peak Voltage	586 V
PV rating	15KW
Filer resistance	0.5Ω
Filter inductance	10mH
Filter conductance	8.7µF
Integral gain	500
Proportional gain	0.04
PWM switching ratio	2000

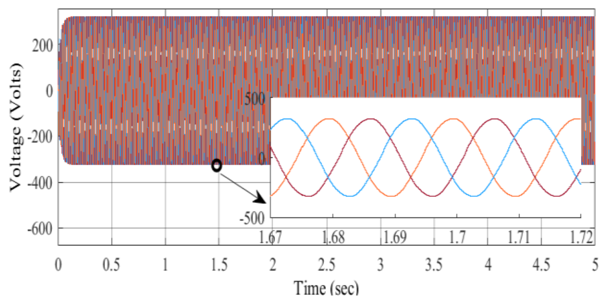


Fig. 8 Output voltage for constant irradiance in SAM

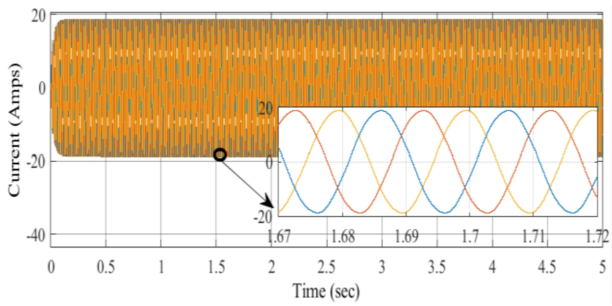


Fig. 9 Output current at load bus for constant irradiance in SAM

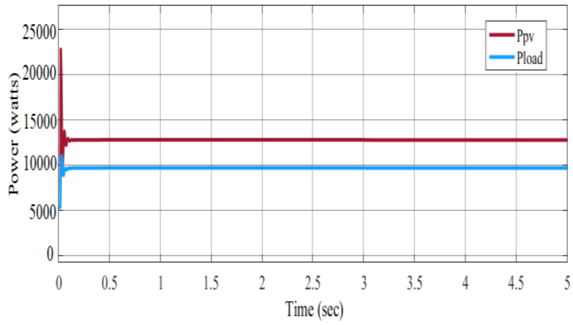


Fig. 10 Power-flow for constant irradiance in SAM

For analyzing system under variable irradiance, the solar irradiance is varied from 600 -1000 w/m2 for time t = 1.5-3 sec. The DC voltage for variable irradiance is shown in Fig. 11. The voltage and current are shown in Fig. 12 and Fig. 13 respectively.

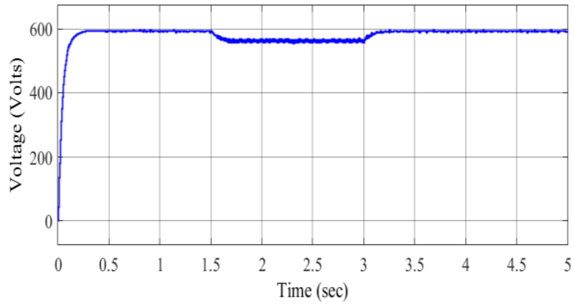


Fig. 11 DC voltage for variable irradiance

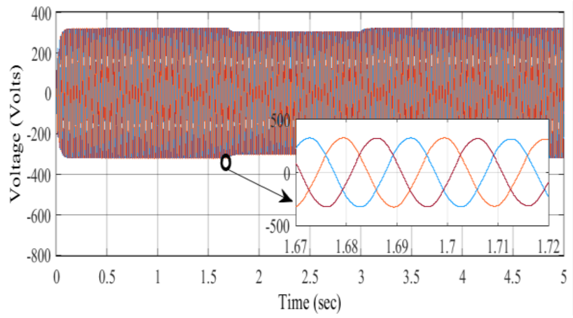


Fig. 12 Load-voltage for variable irradiance in SAM

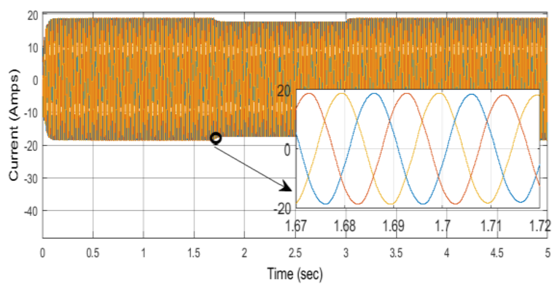


Fig. 13 Load-current for variable irradiance in SAM

From the voltage and current wave-shapes it can be seen that, though variation in irradiance also leads to the variation of voltage and current inverter side but it shows less variation as compared to the variation in irradiance. Irradiance is varied from 1000-600-1000 w/m^2 during t=1.5-3 sec and voltage varies from 335-280-335 V, while current varies from 19-15-19 A.

A three-phase non-linear load having 40 Ω resistance connected across full-bridge rectifier is analysed. Loads with non-linear behavior distorts the system. The grid voltage and current at this condition is shown in Fig. 14. and Fig. 15. respectively. From the waveforms it can be observed that the non-linear distorts the grid voltage and current. The THD of the grid voltage (6.16%) and current (8.5%.) is shown in Fig. 16. The load voltage is also distorted and contains the same harmonics as in grid voltage, while the load current harmonics are very high as shown in Fig. 17. and Fig. 18. respectively.

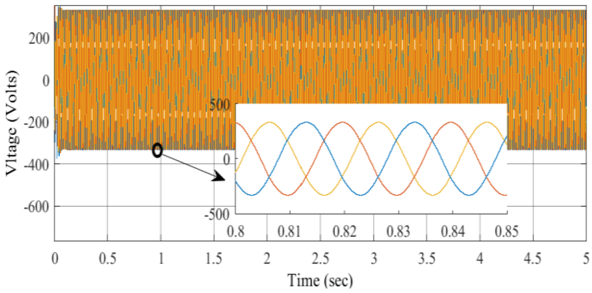


Fig. 14 Grid voltage for non-linear load

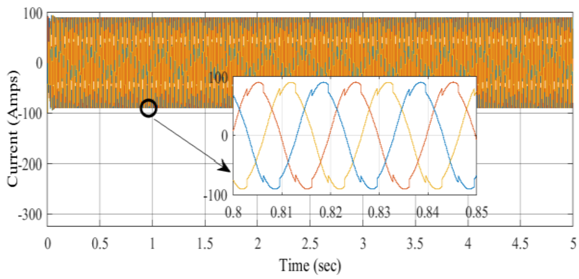
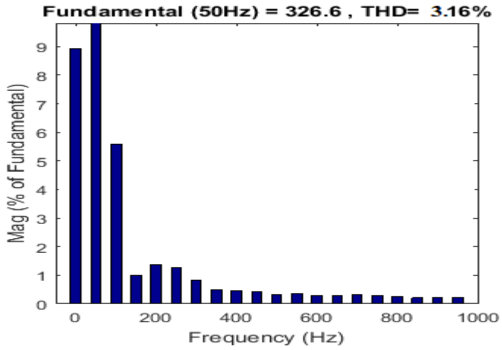
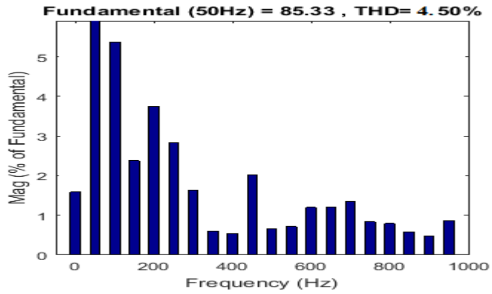


Fig. 15 Grid current for non-linear load



(a) THD of voltages



(b) THD of currents

Fig. 16 THD of PCC voltage and current with non-linear load

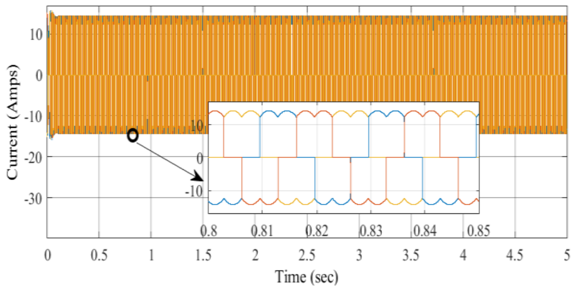
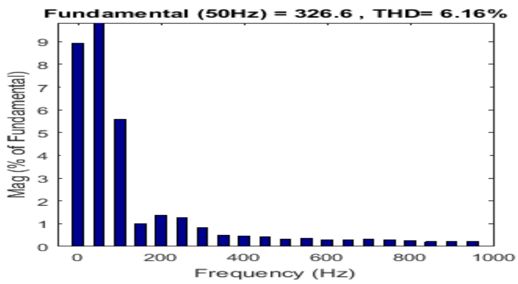
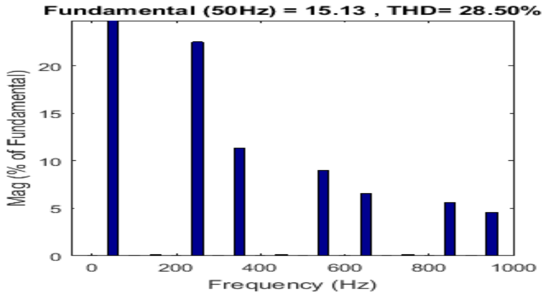


Fig. 17 Load current wave-shape for non-linear load



(a) THD of voltages



(b) THD of currents

Fig. 18 THD of load voltage and current with non-linear load

IV. CONCLUSION

The SPGS is formed using PV-array whose DC output has been regulated using boost converter. The DC-AC converter converts the DC generated output of SECS into AC. The DC-AC converter is designed using two-level VSI whose control is designed using PQ-theory in SRF and PLL. The stand-alone operation of SECS is analysed for application-oriented electrification. The designed SPGS is analysed for reducing THD in PCC voltage and current since PEC injects harmonics and high harmonics content in voltage and current waveform may hinder the operation of sensitive load connected. SA-SECS is also analysed for operating conditions like non-linear loading. It can be seen that the high THD adversely effects the performance of SECS leading to the generation of various PQ issues. The mitigation of these issues in SECS using proper controller for VSI is been presented in this paper.

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