Simulink Modeling and Analysis of Grid connected PV System

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Abstract: **Due to lack of abundant availability of conventional energy sources, energy demand across the world met by renewable energy and is harnessed from natural resources such as sunlight, wind, rain, tides and geothermal heat which can be replenished. This paper gives the simulink modeling and analysis of grid connected Photo Voltaic (PV) system. Incremental conductance Maximum Power Point Tracking (MPPT) technique used to track maximum power from PV and is connected to boost converter to boost the voltage to maintain the voltage from PV. A two level inverter is used for DC to AC conversion with Pulse-Width Modulation (PWM) control. To synchronize the grid to solar PV at certain phase angle and frequency, Phase-Lock-Loop (PLL) technique used. Control circuit is designed to supply the power according to the load variations.**

Index Terms: **MPPT, Boost Converter, Two level Inverter, PWM, PLL.**

I. Introduction

The increasing energy demand and the less availability of conventional resources to meet the energy demand made a big focus on renewable energy sources .Renewable energy has a greater importance in the world because of the clean and environmentally safe energy, .besides classification of renewable energy based on the source of generation of solar Photo voltaic energy has become more popular as it is noise free and almost maintenance free. By arranging Solar cells in series -parallel fashion a PV module is designed which further connect series –parallel to form a solar . The maximum power can be extracted from PV panels which depends on temperature, irradiance and also on the non linear characteristics of the PV cell.

To obtain maximum power from the PV which is essential due to non linear characteristics of PV array Maximum power point Techniques (MPPT) are used. The different types of MPPT techniques are listed below [3].

1. Incremental Conductance MPPT
2. Perturb and Observe
3. Fractional open circuit voltage
4. Fractional short circuit current

In this paper incremental conductance technique is used to track maximum power for the Duty Cycle adjustment in modeling the system. A two stage conversion strategy is used to feed the supply to grid. First stage of conversion uses boost converter to boost the input DC voltage level. In Second stage two-level inverter is used to convert DC to 3-phase AC supply by pulse width modulation (PWM) control. For synchronization of the system to the grid PLL(phase lock loop) technique is used [6].

II. Solar Cell Modelling

A. PV CELL

A solar module is formed by connecting solar cells in series and parallel for required voltage and current. The equivalent circuit of solar cell has one current source where diode is connected parallel to it.

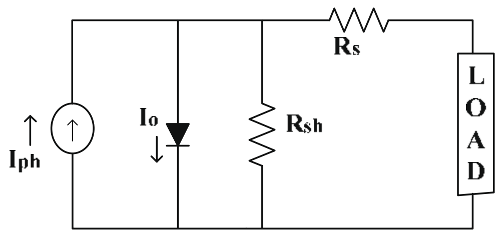

Figure. 1. Single diode solar circuit

The characteristic equation for a photovoltaic cell is given by

$$I_{ph} = [I_{scr} + \{k_i * (T_{ak} - T_{rk})\}] * \frac{s}{1000} \quad (1)$$

$$I_d = I_{rr} * \left(\frac{T_{ak}}{T_{rk}}\right)^3 * \exp\left[\frac{qe_g}{kA}\left(\frac{1}{T_{rk}} - \frac{1}{T_{ak}}\right)\right] \quad (2)$$

$$I_{rr} = I_{scr} / \exp\left(\frac{V_{oc}q}{kN_s AT_{rk}}\right) - 1$$

$$I_{pv} = N_p I_{ph} - N_p I_d \left[\exp\left\{\frac{q \times (V_{pv} + I_{pv}R_s)}{N_S AKT}\right\} - 1\right]$$

(3) & (4)

T : Temperature of the cell;
k : Boltzmann's constant, 1.38 * 10^{-19} J/K;
q : Electron charge, 1.6*10^{-23} C;
K_i : Short circuit current
I & V : output current and voltage;
I_{os} : Reverse saturation current;
I_d : Solar irradiation in W/m^2;
I_{scr} : Short circuit current;
E_{go} : Band gap;
A : Ideality factor;
T_r : Reference temperature;
I_{or} : Saturation current at Tr;
R_{sh} : Shunt resistance;
R_s : Series resistance

The characteristic equation of a solar cell is dependent on the number of cells in parallel and number of cells in series.

B. MPPT

In incremental conductance method the terminal voltage is controlled according to the maximum voltage which depends on the incremental conductance of the PV .For the change in output conductance if dI/dV is negative then the voltage is decreased and if dI/dV is positive then voltage is increased to track the maximum power at every instant..

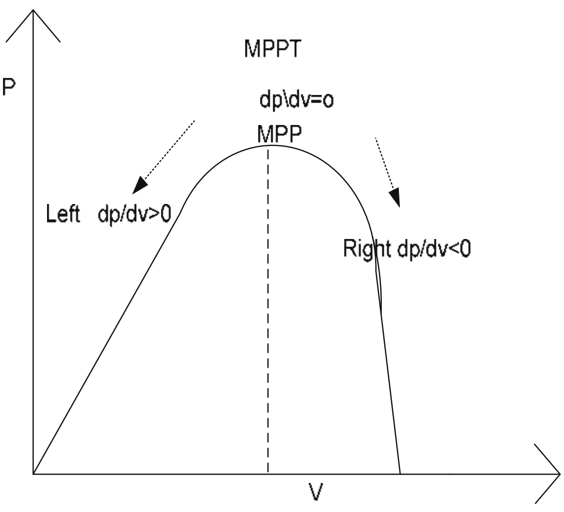

Figure.2. PV characteristics of a solar cell

Power=Voltage*current
By differentiating power with respect to voltage;
$dP/dV=(V*I)/dV$
$dP/dV = I + V*(dI/dV)$
For maximum power point is reached the slope $dP/dV=0$. Thus the condition would be;
$dP/dV=0$
$I + V*(dI/dV)=0$
$dI/dV= -I/V$

C. Boost Converter

Boost converter gives the output voltage greater than input voltage. PV cell DC voltage is necessary to step up for maintaining required rms AC Voltage using Boost Converter [8]. The Boost Converter consists of Voltage Source, Inductor, Switch (IGBT), Diode, Capacitor, Load. It involves two modes of operation [09].

Mode1: Switch is ON state, current flows through Inductor (L), Switch.
Mode2: Switch is OFF state, current flows through Inductor, Diode, Capacitor, Load.
The general circuit diagram of Boost Converter shown in Figure.3.

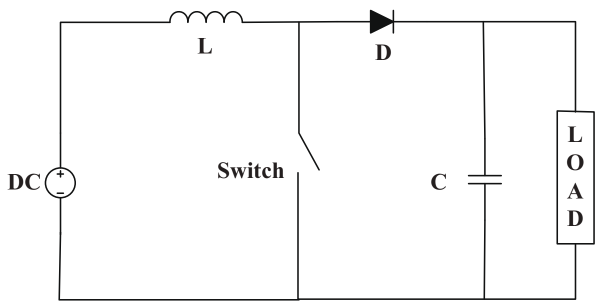

Figure.3. Boost Converter

The output of Boost Converter voltage is

$$V_o = \frac{V_s}{1-Z} \quad (4)$$

Where,
V_o = Output voltage
V_s = Input voltage
Z = Duty cycle ratio

Duty cycle is extracted from MPPT and given to switch (IGBT) through PWM generator.

D. Inverter

A DC to AC conversion with desired output voltage for any frequency. The inverters can be broadly divided into

- **Voltage source inverter**
- **Current source inverter**

A two level Voltage Source Inverter (VSI) is fed with DC voltage which converts fixed DC voltage to 3-Phase AC voltage. Mostly these inverters are employed in machines and converter control. The VSI consists of three legs with two IGBT switches on each leg, DC Source and Load. General diagram of VSI is shown in Figure.4.

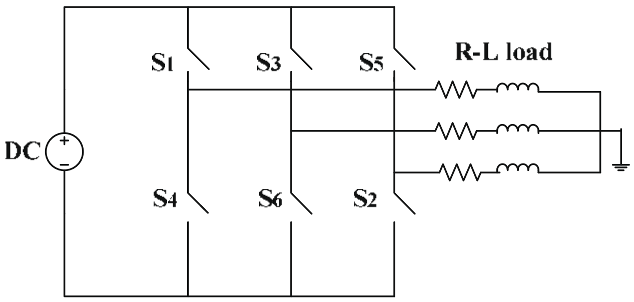

Figure .5. Three phase Voltage source inverter

Various controlling techniques are implemented out of which two most popular techniques are [10]

A. Pulse Width Modulation (PWM)
B. Space Vector PWM (SVPWM)

Switching purpose pulses of IGBT are driven by Pulse Width Modulation (PWM) Technique. In PWM triangular carrier Wave is compared with Sinusoidal reference wave of desired frequency. According to the condition ($f_r > f_c$) which provides switching instant pulses to IGBT. VSI is equipped with DC link of Capacitance bank which is used for grid synchronization purpose.

III. Grid Connected System

A. Phase Lock Loop

Phase locked loop is used to obtain the rotational frequency, direct and quadrature voltages. To interface the voltage source inverter with the grid phase angle information is necessary In PLL, Three-phase AC voltage (V_a, V_b, V_c) are transformed to two -phase stationary frame(V_α, V_β) using equation (1) and again two-phase voltage are transformed to rotating frame of d, q axis (V_{dr}, V_{qr})using equation (2). To transform from rotating frame to synchronous frame PI Controller and Integrator are used to estimate angular frequency and phase angle [6].

. In PLL, Three-phase AC voltage (V_a, V_b, V_c) are transformed to 2-phase stationary frame (V_α, V_β) using Equation (1) and again two-phase voltage are transformed

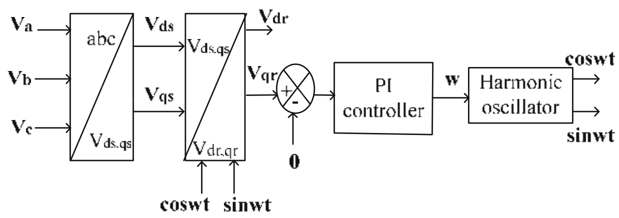

Figure 6.Phase Lock Loop

to rotating frame of d, q axis (V_{dr}, V_{qr}) using equation (6). To transform from rotating frame to synchronous frame, PI Controller and Integrator are used to estimate angular frequency and phase angle [8].

$$\begin{pmatrix} V_\alpha \\ V_\beta \\ V_o \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} V_{dr} \\ V_{qr} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} V_\alpha \\ V_\beta \\ V_o \end{pmatrix} \quad (6)$$

If the estimated frequency (w^*) equals to actual frequency (w) at the estimated phase angle (θ^*) which is integral of (w^*), then rotating frame voltages (V_{dr}, V_{qr}) appear as DC Value [12]. These estimated values are feed backed as cos (wt), Sin (wt) to determine rotating frame voltages and PLL gets locked at ($\theta^* = \theta$).

B. Control

The PV real power output is given by

$P_s = 3/2\ V_\alpha\ I_d$ (7)

Where I_d proportional to real power
The reactive power is given by

$Q_s = -3/2\ V_\alpha\ I_q$ (8)

Where I_q controls Q_s

The above equations give the dependence of P_s and Q_s on I_d and I_q. The paper presents current-control scheme for controlling the voltage. So that I_d and I_q track their respective I_{dref} and I_{qref} . When I_{dref} and I_{qref} are limited then it is also used to protect the voltage source control against overload and faults. The current-control scheme is designed using the equations shown below.

$$L\frac{di_d}{dt} = L\omega i_q - Ri_d + m_d\frac{v_{dc}}{2} - v_{sd}$$

$$L\frac{di_q}{dt} = -L\omega i_d - Ri_q + m_q\frac{v_{dc}}{2} - v_{sq}. \qquad (9\ \&\ 10)$$

From the equations the state variables are I_d and I_q ; the control inputs are e_d and e_q and V_α, V_β, ω,and V_{dc} are the disturbances. Due to the presence of the factor Lω, dynamics of id and iq are coupled and are nonlinear. To decouple and linearize the dynamics, m_d and m_q are determined based on the control laws:[10]

$$m_d = \frac{2}{v_{dc}}\left(u_d - L\omega i_q + v_{sd}\right)$$

$$m_q = \frac{2}{v_{dc}}\left(u_q + L\omega i_d + v_{sq}\right) \qquad (11\ \&\ 12)$$

$$L\frac{di_d}{dt} = -Ri_d + u_d$$

$$L\frac{di_q}{dt} = -Ri_q + u_q. \qquad (13\ \&\ 14)$$

Equations 7 & 8 shows the dependency of u_d and u_q, respectively. Figure.7. shows the block diagram of the dq-frame current-control scheme. Similarly, u_q is the output of another compensator, kq(s), that processes $e_q = i_{qref} - i_q$. It should be noted that, to produce m_d and m_q, the signals $2/v_{dc}$, ωi_d and ωi_q are employed as feed-forward terms to decouple the dynamics of i_d and i_q from that of v_{dc}.

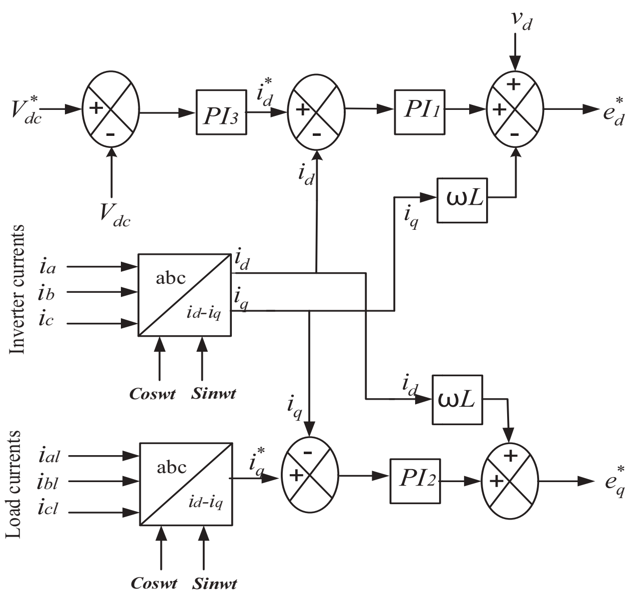

Figure.7.controlcircuit of inverter

The Pulse width modulation signals are obtained by the transformation of m_d and m_q into m_a, m_b and m_c, based on:

$$\begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} = \begin{bmatrix} \cos(\rho) & -\sin(\rho) \\ \cos(\rho - \frac{2\pi}{3}) & -\sin(\rho - \frac{2\pi}{3}) \\ \cos(\rho - \frac{4\pi}{3}) & -\sin(\rho - \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} m_d \\ m_q \end{bmatrix} \qquad (15)$$

m_a, m_b, and m_c are compared with a triangular PWM carrier signal, and the switching pulses are generated from the VSC valves. Since the d- and q-axis control plants are identical, the compensators kd(s) and kq(s) can be picked to be identical. Let the compensator be of a PI type as:

$$k_d(s) = k_q(s) = \frac{k_p s + k_i}{s} \qquad (16)$$

Where the values are

$$k_p = \frac{L}{\tau_i}$$

$$k_i = \frac{R}{\tau_i} \qquad (17\ \&\ 18)$$

the closed-loop transfer-functions of the d- and q- axis current controllers assume the first-order form. where τ_i is the time-constant, usually selected in the range of 0.5 to 5 ms, depending on the desired speed of response. [7]

$$\frac{I_d}{I_{dref}} = \frac{I_q}{I_{qref}} = G_i(s) = \frac{1}{\tau_i s + 1} \qquad (19)$$

IV. Simulation Results

In standalone system from the data values provided simulation study is done where the power from the solar is extracted and supplied to the 3 phase balanced load. Here the output voltage of the array is the input to the boost converter of (120v) is converted to 600v following the equation as calculated. The output voltage of boost appears to be dc as shown in Figure.9.

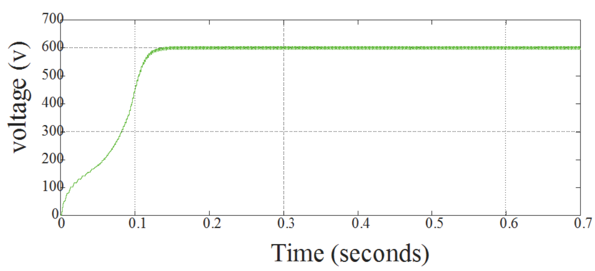

Figure 8. Boost converter voltage(Vdc)

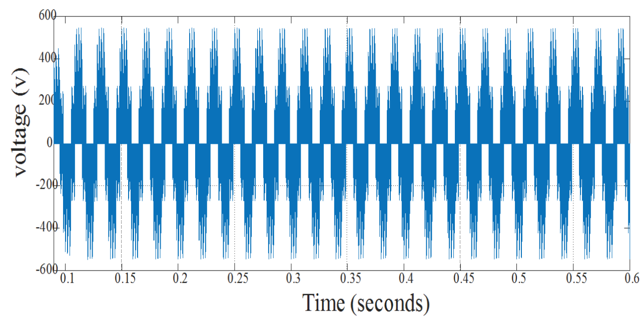

Figure.9. Inverter phase voltage V_a

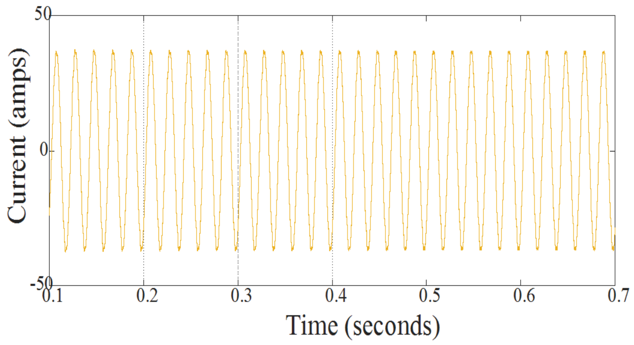

Figure.10. Inverter line current (I_a)

TABLE.I
PHASE LOCK LOOP PARAMETERS

Parameters	values
Source phase –phase voltage	440 v
Source frequency	50 hz
Load p-p voltage	1000v
Load frequency	50
Active power	$10e^3$
Reactive power	100
PI controller	P=5,I=10

A. Control

The PLL is used for the measurements of the frequency and phase-angle. It can estimate the real and reactive power flow to the load. PLL is a central component in a control structure. From the input signal phase values are detected for the source values as shown in Figure.11 where the phase values of inputs appears to be dc voltage of V_{dr}=340 v and V_{qr} = 0. The error signal in phase is passed through the loop filter which helps in determining the angular frequency (w) at the estimated value of (314) rad/sec as shown in fig 1.5 and phase angle is determined as unit vectors by the harmonic oscillator as shown in fig 1.6

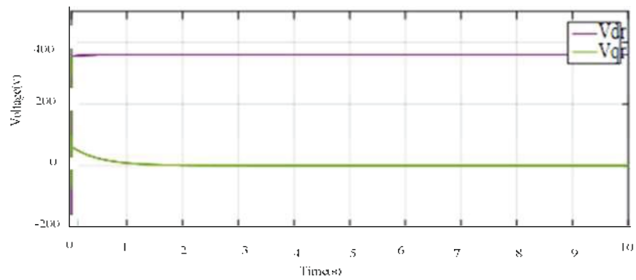

Figure.11. V_{dr},V_{qr} voltages

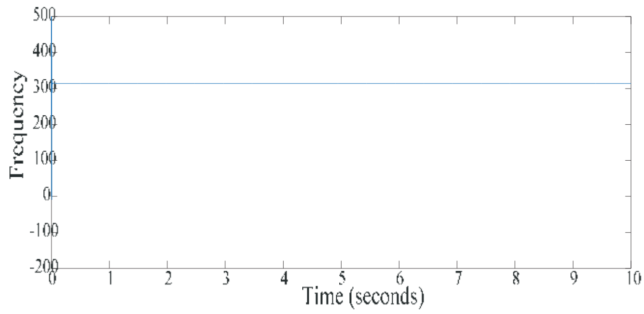

Figure.12. Angular frequency (w)

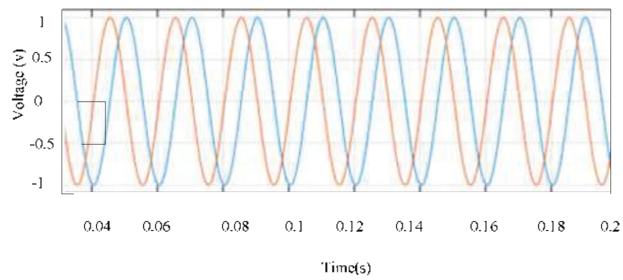

Figure.13. unit vectors

TABLE.II
GRID CONNECTED PV SYSTEM SIMULATION DATA

Parameters	Values
Grid voltage	400 v
Grid frequency	50hz
Load	R=4.6 Ω, L=0.0146H
Inverter capacitor	$60e^{-6}$
Pll PI control	P = 50, I= 100
Control PI	P = 0.1, I= 0.2
Filter	$5e^{-3}$

In this system solar system is interfaced to grid and load so that pv system supplies active power to the load where as the source supplies reactive power to load. such that I_{dinv} tracks the I_{dre}f as shown in Figure.14.

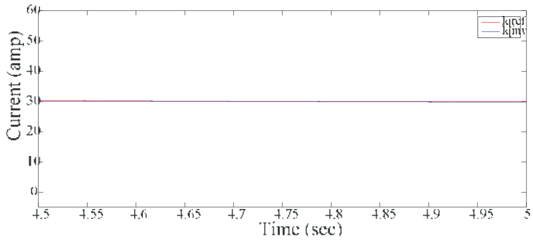

Figure .14. Idref and Idinv currents

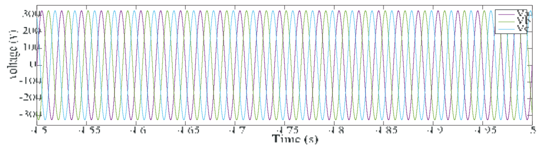
Figure 15. Grid voltage

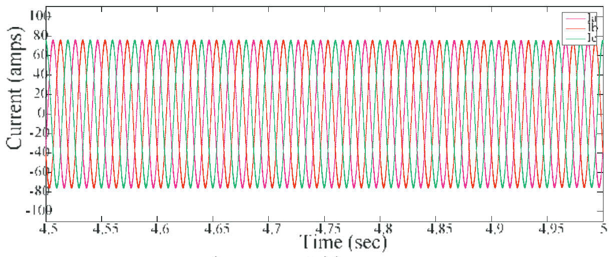

Figure 16. Grid current

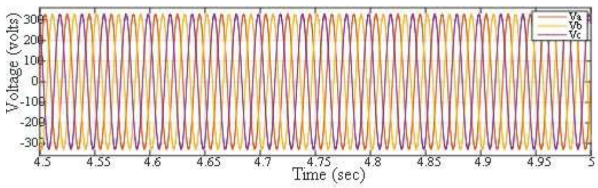

Figure 17. Inverter voltage

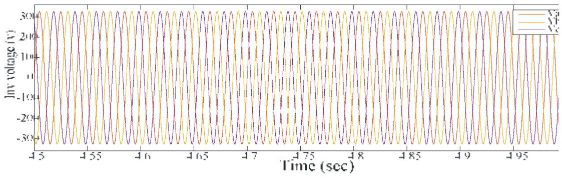

Figure 18. Inverter currents

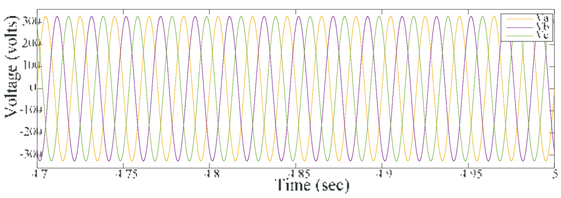

Figure 19. load voltage

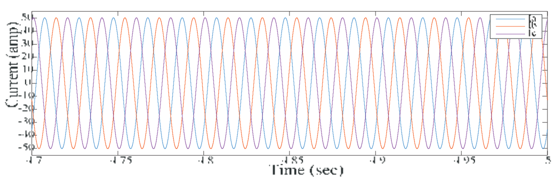

Figure 20. Load current

V. CONCLUSIONS

The grid connected PV system suffers form ground leakage currents by which distortion factor will increase during the operation which can be reduced by using transformer less inverters in the circuit.

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