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Solar System Integration to Distribution Grid using Simplified Control Strategy

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Abstract: This paper presents solar system integration to single phase distribution grid using a simple control strategy. Solar system is a renowned source of energy these days due to non-availability of fossil fuels and their high cost. The output from the solar system is low voltage output and needs to be boosted so as to meet the load voltage. A boost converter which can boost the voltage from solar system is employed in this paper. Boost converter is controlled in closed loop operational mode sensing the output of boost converter and accordingly producing gate pulse. For integration of solar system to distribution grid, DC output from solar system is converted to AC employing an inverter. Inverter is controlled using a simple hysteresis controller. MATLAB/SIMULINK models were developed and results were obtained and shown for open loop boost converter, fixed reference and variable reference conditions of operation. Close loop operation tives the output irrespective of the input, and so boost converter in close-loop operation delivers fixed output irrespective of the input conditions in PV.

Keywords: Solar system, inverter, integration, distribution system, boost.

1. INTRODUCTION

Fossil fuels like coal and natural gas can produce electrical energy in bulk but they pollute the environment by emitting carbon flue gases. Availability of fossil fuels is also a concern for the next generations. Renewable energy sources are viable option to generate electricity with very low running cost [1-3]. Renewable sources are freely available from the environment and extracting energy from renewable sources is important [4-6]. With the advancements of technology, European countries are employing more of renewable energy sources and evolving as a new capable source. Solar cells, fuel cells, wind energy systems are some of the examples of renewable energy sources out of which solar systems are widely used for electrical power generation. Photo voltaic (PV) cells are generally made of semiconductor layers on flat panel constituting a PN layer [3].

The output of PV system is of low voltage and needs to be stepped-up to a voltage level required at connecting end [7-10]. A boost converter is employed in this paper to boost up the output of PV cell. Boost converter is a power electronic converter consisting of a switch controlled by gate pulses. By controlling the duty cycle of boost converter, required voltage level is obtained at the output of boost converter. The output from PV cell or fuel cell is a DC type of output. To integrate the power generated from the PV system to grid, DC is to be converted to AC type of power. For conversion of DC to AC, a voltage source converter can be employed which is simple in operation.

A simple PV cell equivalent circuit was shown in Figure 1 which contains a current source with an anti-parallel diode, a series resistance and a parallel resistor. As said, PV cells are made up of silicon layers forming a PN junction. The band gap reduces between the semiconducting layers due to the absorption of photos from sunlight. As the gap still reduces, the electrons get more excited and cross the barrier giving current flow. This current flow due to movement of electrons is denoted with a current source. The PN layer is denoted with its equivalent diode and internal drop of diode is given with parallel resistor and internal

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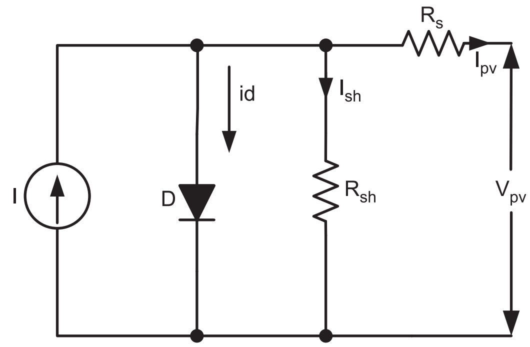

Figure 1: Equivalent circuit of PV Cell

resistance of circuit is denoted by series resistor. Current from the PV cell is denoted by I_{pv} and voltage output of PV cell is denoted by V_{pv}. The single exponential equation is showed in below which models a PV cell is extracted from the physics of the PN junction and is

$$I = I_L - I_{SC}\left(\exp^{\frac{V + R_s I}{v_L}} - 1\right) - \frac{(V + R_S I)}{R_{sh}} \tag{1}$$

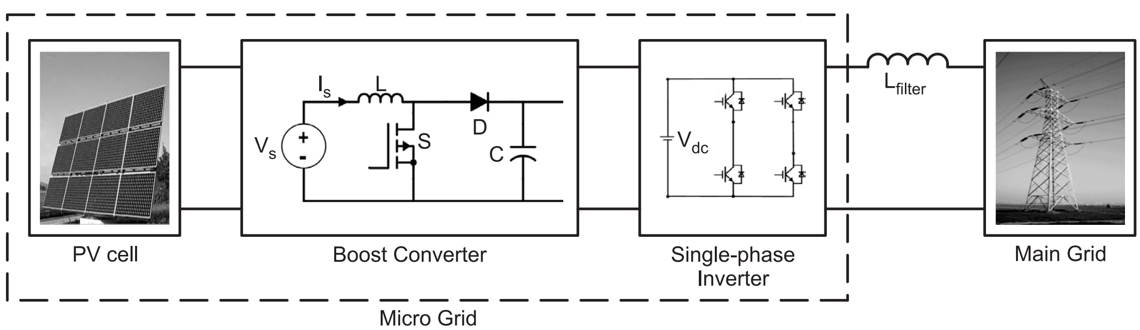

Figure 2: Solar system integration to distribution grid

Solar system integration to distribution grid model was shown in Figure 2. A PV cell producing low voltage output by absorbing photons from sunlight is fed to boost converter. Boost converter increases the output of PV system to required level of voltage. DC output is fed to inverter to convert DC to AC type of supply required to integrate produced power from PV cell to distribution grid. Close loop operation tives the output irrespective of the input, and so boost converter in close-loop operation delivers fixed output irrespective of the input conditions in PV.

2. DESIGN OF BOOST CONVERTER

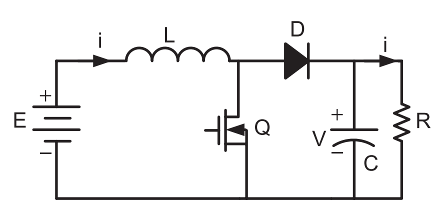

Figure 3: Boost converter

In Boost converter we have two modes of operation that explained with two conditions is when switch is in ON condition and switch is in OFF condition. The modes of operation of this converter are describes as follows. To simplify the calculation, it is assumed that the inductance value of inductor are L_1, where $L_1 = L$, and the duty cycle denoted as D.

Mode I: During the On-state, the switch S is closed as in Figure 4(a), which makes the input voltage (V_i) appear across the inductor, which causes a change in current (I_L) flowing through the inductor during a time period (t) by the formula:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L} \tag{2}$$

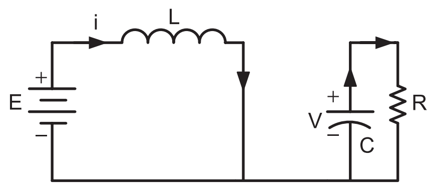

Figure 4: (a) Boost converter when Switch Q is ON

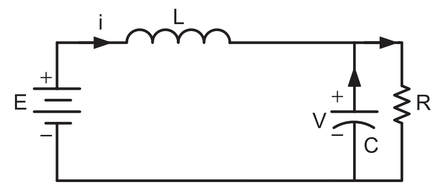

Figure 4: (b) Boost converter when Switch Q is OFF

Mode II: During the Off-state, the switch S is open as in Figure 4(b), so the inductor current flows through the load. If we consider zero voltage-drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$V_i - V_0 = L\frac{dI_L}{dt} \tag{3}$$

Mode 1: T_1 is ON

Assume

$$\Delta I = I_2 - I_1$$

$$V_{in} = L_1 \frac{\Delta I}{t_1}$$

$$t_1 = \frac{L \times \Delta I}{V_{in}} \tag{4}$$

Mode 2: During T_1 off

For inductor L_1

$$V_{in} - V_0 = -L_1 \frac{dI}{dt}$$

$$t_2 = \frac{\Delta I L_1}{V_0 - V_{in}} \tag{5}$$

Substitute t_1=DTs and t_2=(1-D)T_s

$$\Delta I = \frac{V_{in} \times t_1}{L}$$

$$\Delta I = \frac{V_0 - V_{in} \times t_2}{L}$$

$$\frac{V_{in} \times DT_s}{L} = \frac{(V_0 - V_{in})}{L}(1 - D)T_s$$

$$\frac{V_0}{V_{in}} = \frac{1}{1 - D} \tag{6}$$

Total time period

$$T = t_1 + t_2 = \frac{\Delta IL}{V_{in}} + \frac{\Delta IL}{V_0 - V_{in}}$$

$$T = \frac{\Delta ILV_0}{V_{in}(V_0 - V_{in})} \quad (7)$$

Peak to peak ripple current

$$T = \frac{1}{f}$$

$$\Delta I = \frac{V_{in}(V_0 - V_{in})}{f LV_0} \quad (8)$$

$$\Delta I = \frac{V_{in}D}{f L} \quad (9)$$

For output capacitor

$$\Delta V_c = V_c - V_c(t = 0) = \frac{1}{c}\int_0^{t_1} I_c \, dt = \frac{It_1}{c}$$

Substitute

$$t_1 = \frac{(V_0 - V_{in})}{V_0 \times f}$$

$$\Delta V_c = \frac{I_0 K}{fc} \quad (10)$$

In condition for CCM operation, take worst case ripple $\Delta I = 2I_L$

$$\Delta I = \frac{V_s K}{f L} = 2I_L = 2I_0 = 2 \times \frac{V_0}{R} = \frac{2 \times V_{in}}{(1 - K)R} \quad (11)$$

Take worst case ripple for capacitor

$$\Delta V_c = 2V_0$$

$$2V_0 = \frac{I_0 K}{fc} = 2I_0 R$$

Specifications

$$P = 20 \text{ KW};\ V_0 = 300 \text{ V};\ I_0 = \frac{P}{V_0} = \frac{20 \times 10^3}{300} = 66.66 \text{ A}$$

$$F = 20 \text{ KHz};\ R = 4.5\Omega$$

$$\frac{V_0}{V_{in}} = \frac{1}{1 - D} = \frac{300}{100} = \frac{3}{1}$$

$$1 - D = \frac{1}{3}$$

$$D = 1 - \frac{1}{3} = \frac{2}{3}$$

In order to operate in CCM Mode we are choosing

Ripple current is

$$\Delta I = 5\% \text{ of input current}$$

$$\Delta I = \frac{5}{100} \times 200$$

$$\Delta I = 10A$$

Ripple Voltage is

$$\Delta V_c = 5\% \text{ of output voltage}$$

$$\Delta V_c = \frac{5}{100} \times 300$$

$$\Delta V_c = 15 \text{ V}$$

We know

$$\Delta I = \frac{V_{ink}}{f \times L}$$

$$L = \frac{V_{in} \times D}{f \times \Delta I}$$

$$L = \frac{100 \times 2}{3 \times 20 \times 10^3 \times 10}$$

$$= 0.33 \text{ mH}$$

Let

$$I_0 = I_c = \frac{V_0}{R} = \frac{C d \Delta V_c}{dt}$$

$$C = \frac{V_0 \times D}{R \times \Delta V_c \times f} = \frac{300 \times 2}{3 \times 4.5 \times 20 \times 10^3 \times 15}$$

$$= 148 \ \mu\text{F}$$

3. CLOSED-LOOP CONTROL OF BOOST CONVERTER

Boost converter consists of a DC source connected to inductor, switch, diode and a capacitor. Boost converter is operated in two modes when switch Q is ON and OFF. When Q is ON, inductor gets charged while the supply current passes through DC link capacitor and load. When Q is OFF, inductor starts discharging the stored energy while the supply also tends to be active hence voltage across capacitor becomes more than the supply voltage. ON and OFF times of switch Q decides the output voltage. To get precise output at the output of boost converter closed-loop operation is employed. Closed loop control of boost converter is shown in Figure 5.

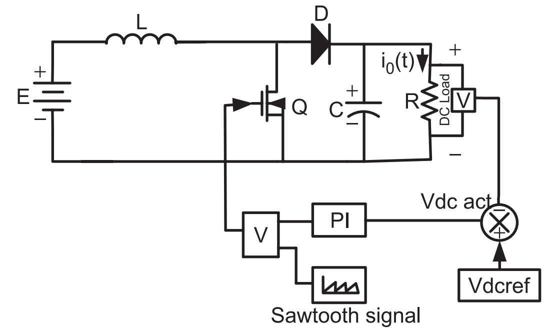

Figure 5: Closed loop Boost converter

Output of boost converter is sensed and is compared to actual reference DC voltage. The error generated is fed to PI controller. Output signal from PI controller is compared to saw-tooth reference and thus producing duty cycle and operated switch Q in boost converter. With this a stable DC output can be obtained from closed-loop boost control.

4. SIMPLE CONTROL STRATEGY FOR INVERTER

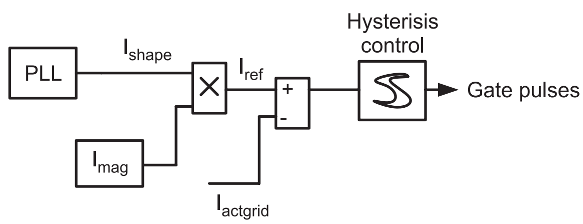

Figure 6: Simple control technique for controlling inverter

Control strategy used to control the switches in inverter was shown in Figure 6. The grid voltage is fed to phase locked loop (PLL) and information regarding current shape was obtained. The obtained current shape is mux with the current magnitude to obtain reference current signal. The obtained current reference is compared to actual grid current and error signal is sent to hysteresis current control (HCC) to produce gate pulses to inverter switches. Complete structure of solar system integration to distribution grid with control strategy was shown in Figure 7.

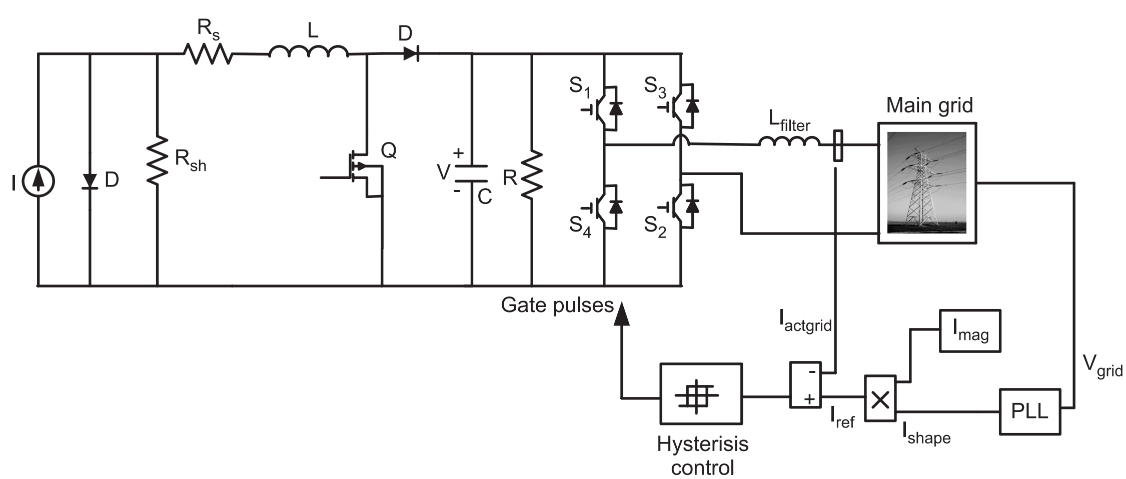

Figure 7: Solar system integration to grid with control technique

5. RESULTS AND ANALYSIS

Table 1
Simulation Model Parameters

Input voltage	*100 V*
Inductors	0.33 mH
Capacitor	148 μF
Resistance	4.5 Ω
Power	20 kW
Switching frequency	20 kHz
Grid voltage	420 V

Case 1: Open-loop Boost converter

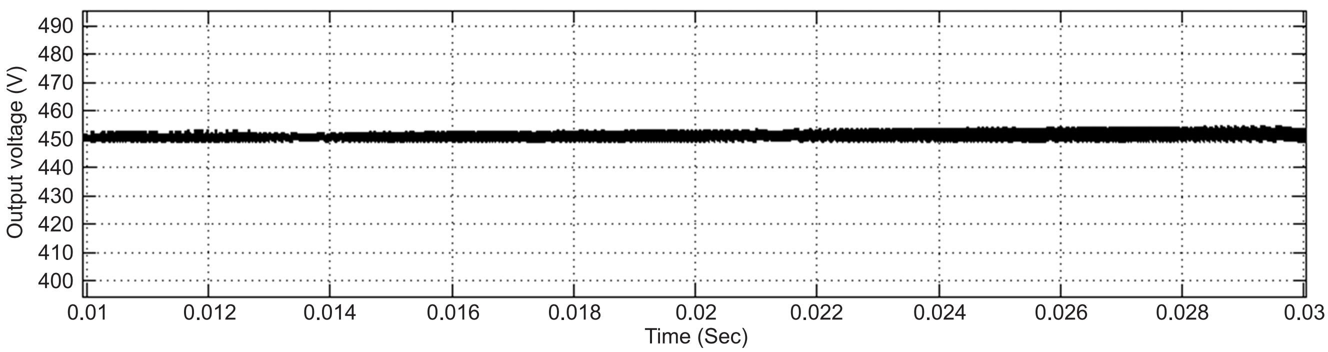

Figure 8: Wave form for Output voltage of Boost converter under open loop

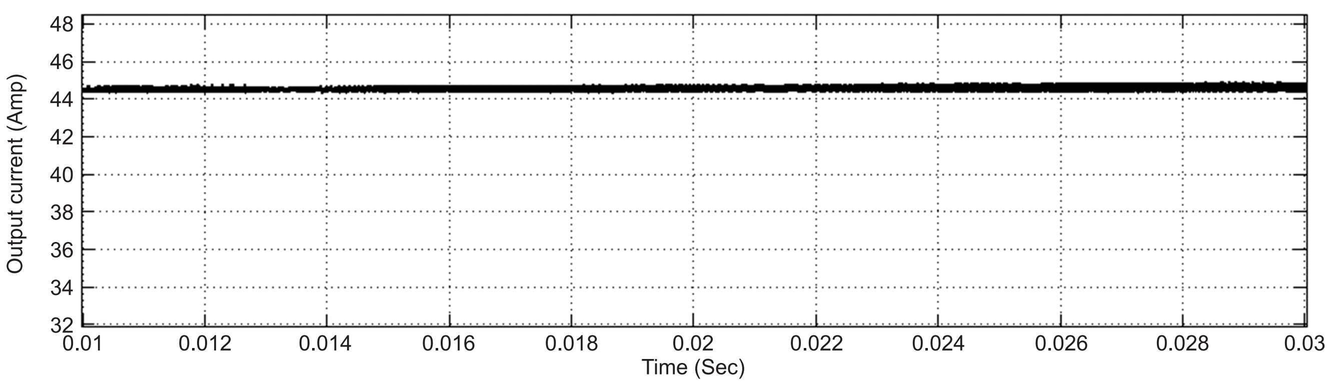

Figure 9: Waveform for Output Current of Boost converter under open loop

Figure 8 shows the output voltage of boost converter and Figure 9 shows the output current of boost converter in open loop mode of operation. Boost converter gives output voltage of 440 V and maintained constant, but consists of voltage ripples which need to be filtered further. Output current of boost converter is 44 A and also contains current ripples as the boost converter is operated under open loop control. Both output waveforms of current and voltage are maintained constant at their respective values. Boost converter output when delivered at constant values requires less sized filters at the output.

Ripples in output voltage of boost converter are shown in Figure 10 and the ripples in inductor current of boost converter are shown in Figure 11. Since boost converter is in open loop mode of control, presence of ripples is observed from the output waveforms of boost converter. The output ripple in voltage and current might affect the performance of the output load to which it was connected. Ripples need to be reduced to give better output and feed load effectively.

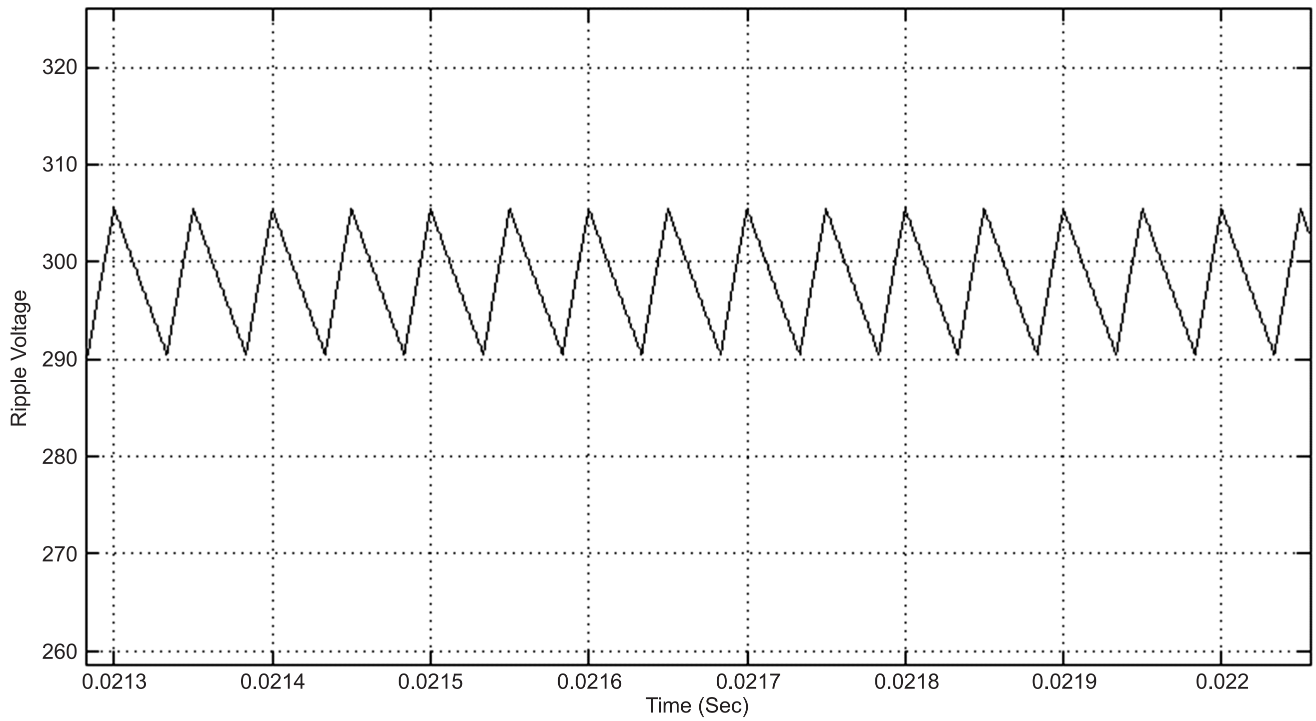

Figure 10: Waveform for Output Ripple voltage

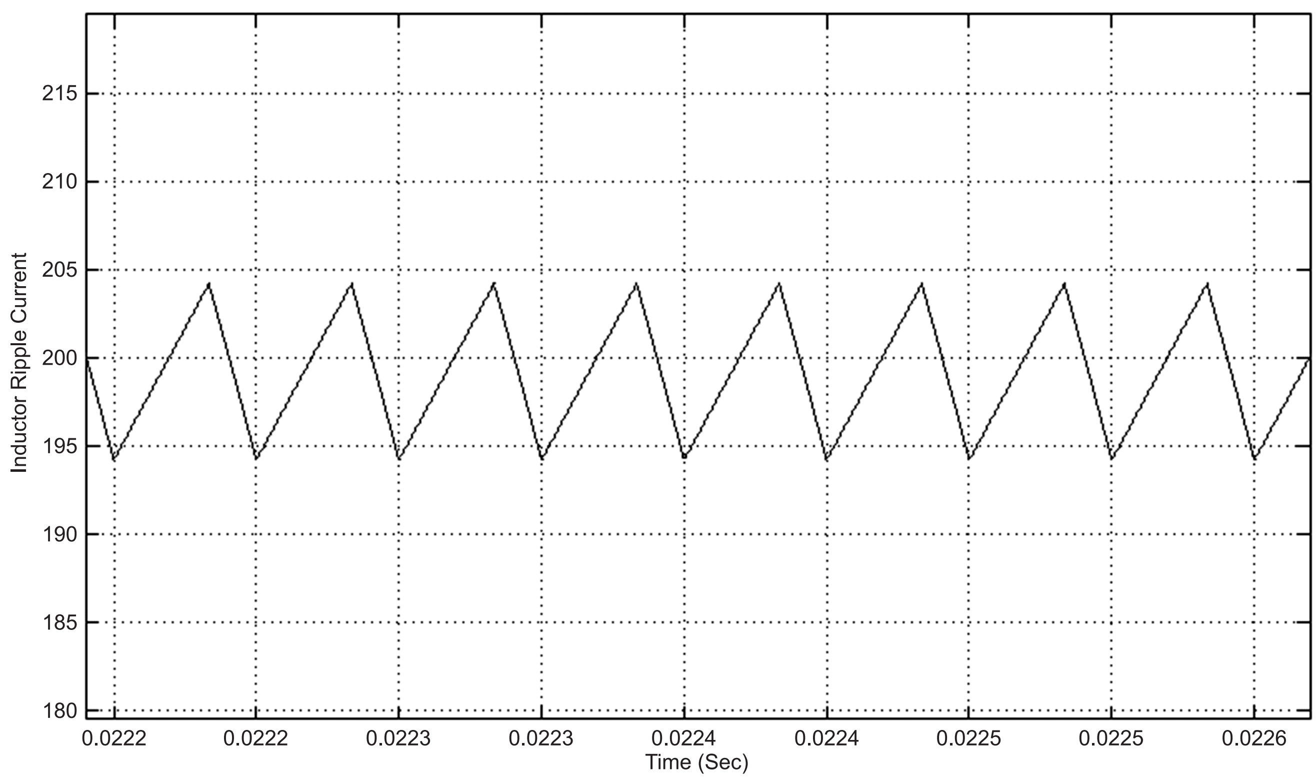

Figure 11: Wave form for Inductor ripple Current

Case 2: Closed-loop Boost converter with fixed current reference

Figure 12 shows the output voltage waveform of boost converter when operated in closed loop mode of operation. Output voltage of boost converter is maintained constant at 440 V. No ripples are observed in output waveform as boost converter is operated in closed loop mode.

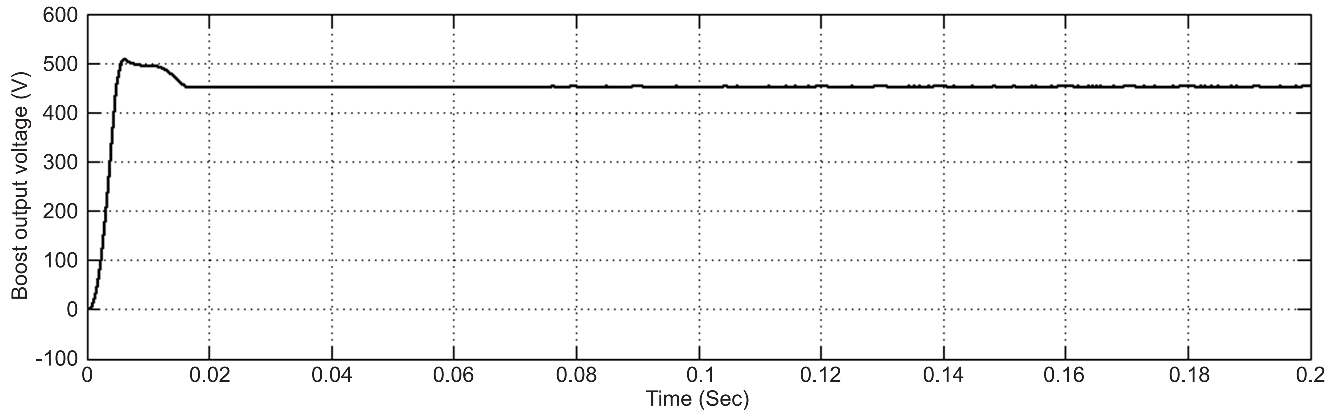

Figure 12: Waveform for Output voltage of boost converter in closed loop

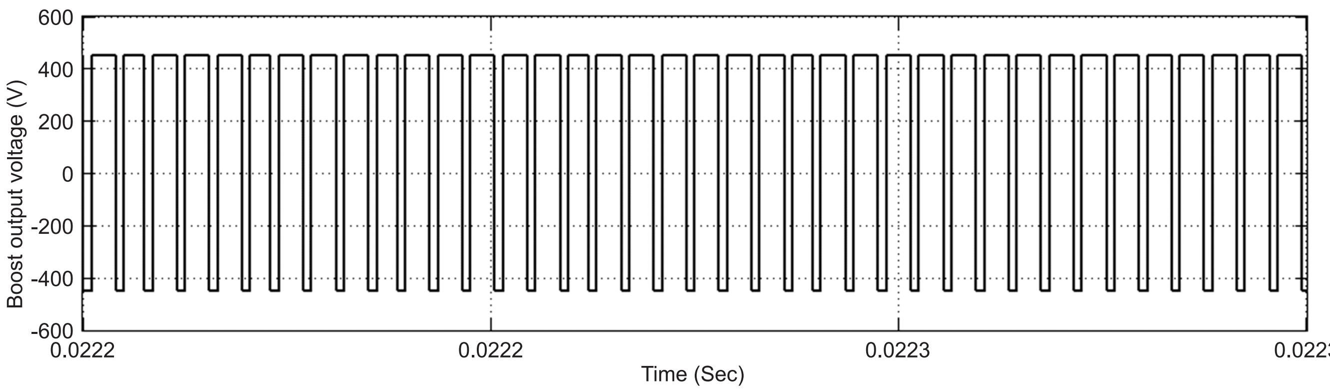

Figure 13: Waveform for Output voltage of inverter before filter

Figure 13 shows the inverter output waveform before filter. The output from the boost converter is inverted to AC type of voltage and is observed in output waveform. As the inverter is of basic two-level inverter, output contains only two levels of positive and negative 440 V.

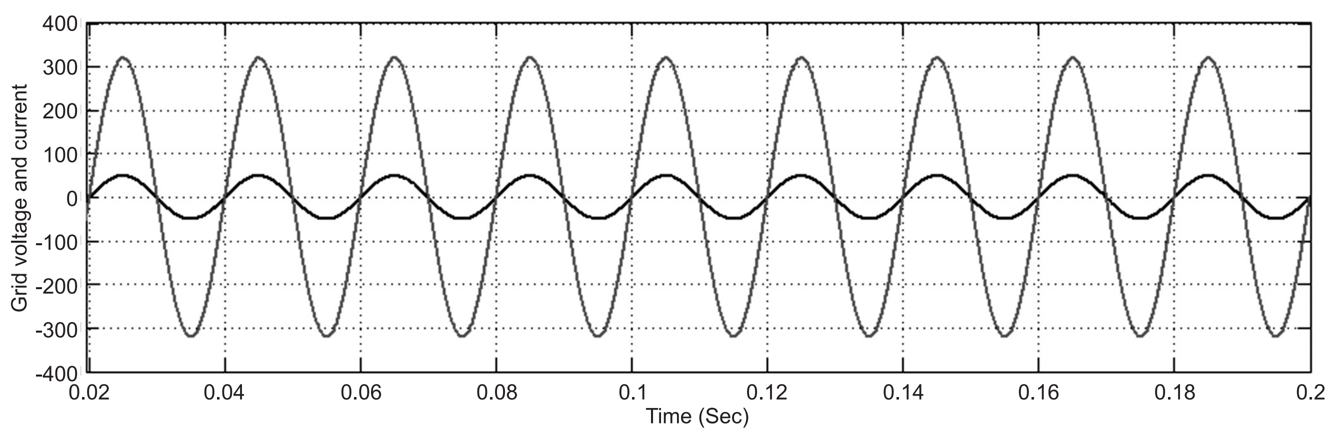

Figure 14: Power factor angle between voltage and current in grid

The power factor angle between grid current and voltage is illustrated in Figure 14 where no phase difference is observed which means power factor is maintained nearer to unity.

THD in grid current with 0.56% with total harmonic distortion in current was shown in Figure 15. Total harmonic distortion was very low and maintained within acceptable limit of 5%.

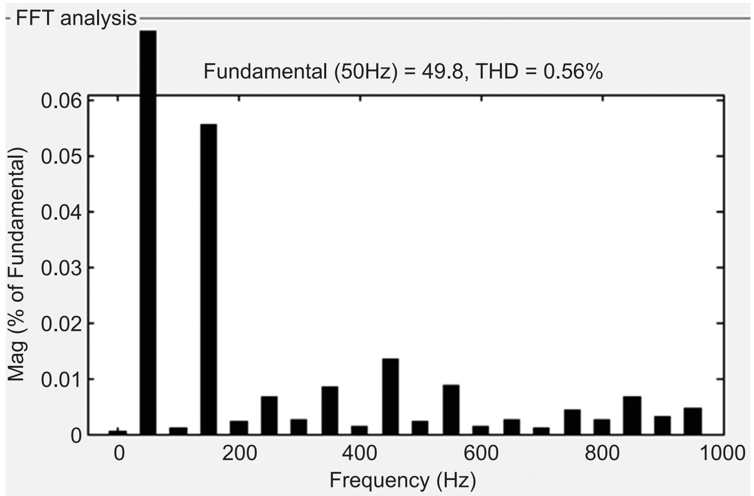

Figure 15: THD in grid current

Case 3: Closed-loop Boost converter with variable current reference

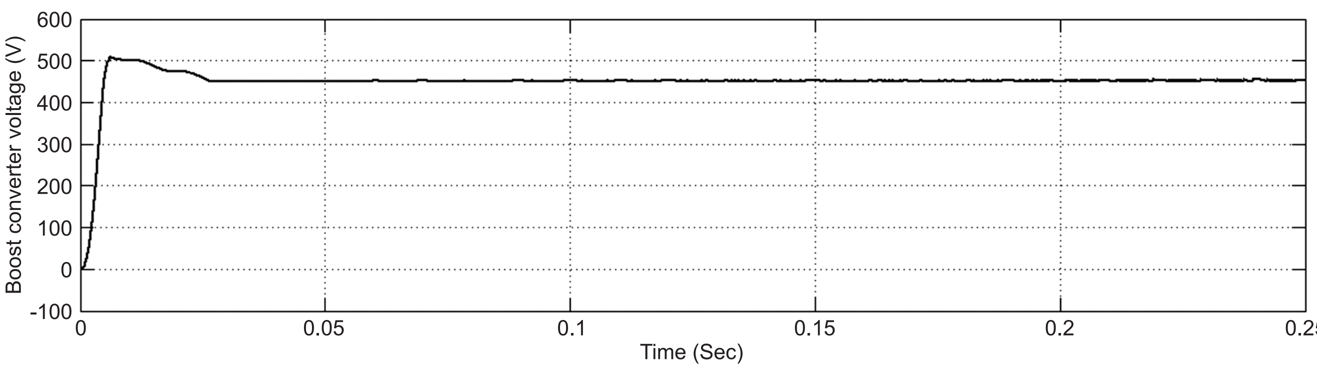

Figure 16: Output of boost converter with closed loop and variable current reference

Figure 16 shows the output voltage waveform of boost converter when operated in closed loop mode of operation and variable current reference value. Output voltage of boost converter is maintained constant at 440 V. No ripples are observed in output waveform as boost converter is operated in closed loop mode. Even though variable current reference is subjected, output is maintained constant and not varied. Close loop operation tives the output irrespective of the input, and so boost converter in close-loop operation delivers fixed output irrespective of the input conditions in PV.

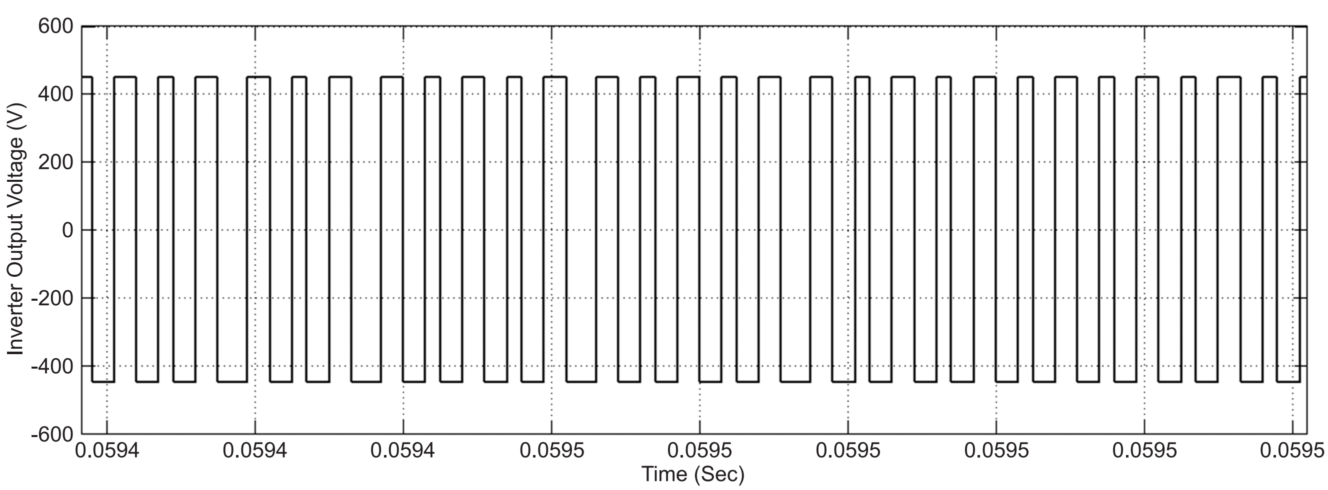

Figure 17: Output of inverter before filter

Figure 17 shows the inverter output waveform before filter. The output from the boost converter is inverted to AC type of voltage and is observed in output waveform. As the inverter is of basic two-level inverter, output contains only two levels of positive and negative 440 V.

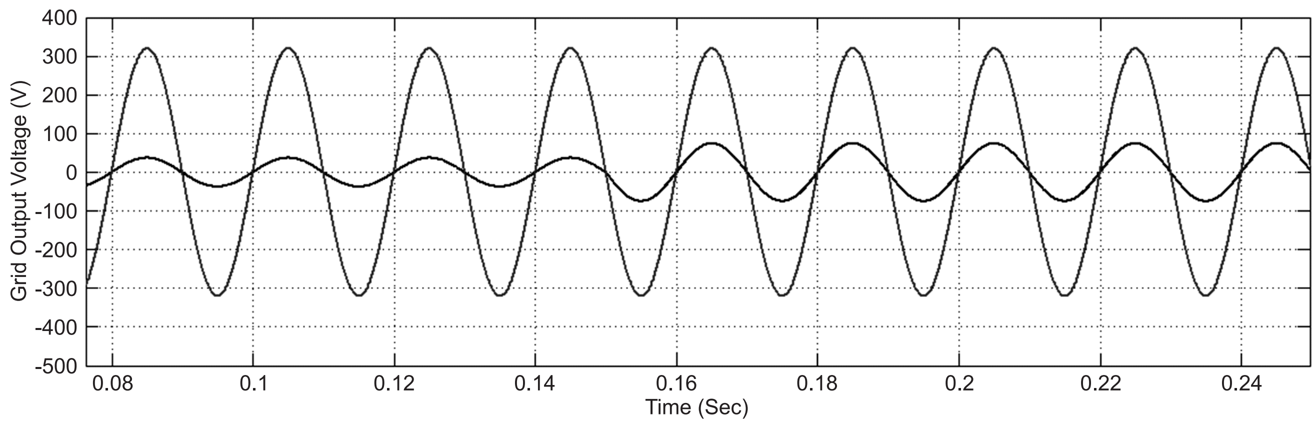

Figure 18: Power factor angle between grid voltage and current

The power factor angle between grid current and voltage is illustrated in Figure 14 where no phase difference is observed which means power factor is maintained nearer to unity.

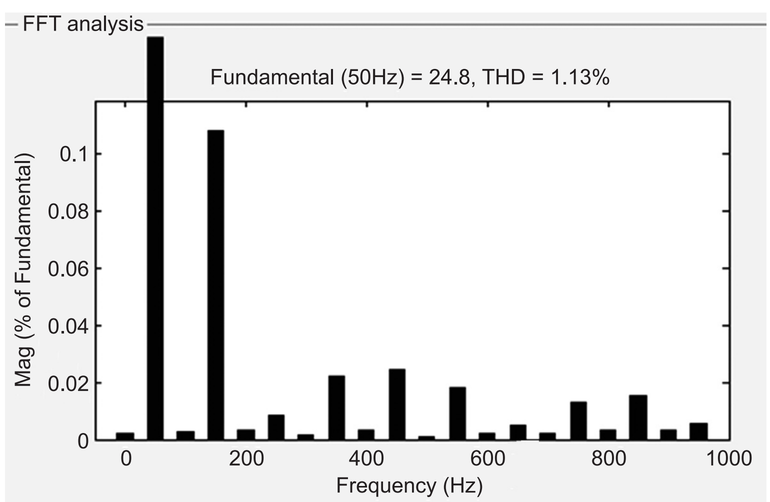

Figure 19: THD in grid current

THD in grid current with 1.13% with total harmonic distortion in current was shown in Figure 19. Total harmonic distortion was very low and maintained within acceptable limit of 5%.

6. CONCLUSION

This paper illustrates solar system integration to distribution grid. The system consists of solar system to produce electrical energy, boost converter to increase the level of voltage from solar system to required level of voltage to grid and an inverter to invert DC power produced from solar system to AC for integration to grid. Boost converter is operated in closed-loop mode of operation and the closed loop mode of boost operation was explained. Inverter is controlled with simple control strategy and was explained. Solar system integration to distribution grid was illustrated in detail with simple control technique. The complete system was modeled for fixed current reference and for variable current reference signal and the results were obtained using MATLAB/SIMULINK software. Total harmonic distortion was well maintained within nominal value of 5% and was shown for both the cases. Output of boost converter and output of inverter were also shown. Close loop operation tives the output irrespective of the input, and so boost converter in close-loop operation delivers fixed output irrespective of the input conditions in PV.

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