DESIGN & SIMULATION OF A SEPIC CONVERTER FOR HOME SOLAR PV SYSTEMS

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Abstract*— This paper presents a designing and simulation of Single-Ended Primary Inductance Converter (SEPIC), which is proposed to be used in the domestic solar photo voltaic (PV) systems. The basic domestic solar power system consists of an arrangement of several components including, PV arrays, a DC/DC converter as well as an inverter. To obtain a ripple free stable voltage from PV arrays, a highly efficient DC/DC converter is required. SEPIC converters make it possible to convert a DC voltage to either a lower or higher voltage efficiently and it is also useful for maximum power tracking purposes. In this study, we describe step by step process of designing and simulation of a SEPIC DC/DC converter which can be used in solar PV systems in typical homes. The proposed SEPIC converter's output is set at 325V DC since, the household utility voltage is around 230V-250V AC. Whereas, the converter's input voltage can be varied up to 180V DC. A proportional, integral and derivative controller (PID) is also employed to the converter to obtain a constant output voltage, under variable input voltage conditions. The system is designed using MATLAB/Simulink software. Its high efficiency (91%), low ripple factor (1.32%) and the usefulness are proved through simulation results. The efficiency of the proposed converter is determined for the range of applicable input, and its performances are discussed at the end of this paper.

Keywords—SEPIC; Home solar PV; DC/DC converter

I. INTRODUCTION

Among several renewable energy sources, solar photovoltaic technology has become the most favorite type of electricity generation. As a cleaner and safer investment for families and businesses, it can help everyone reducing their electricity bills, enjoying energy independence and help to reduce global emission levels.

Solar panels made up of PV cells which capture sunlight particles or photons. Using a semiconductor material like silicon, the PV cells convert this captured energy into DC electricity. A DC/DC converter is then used to step-up this DC voltage to a required level and then turns this DC electricity into usable AC using an inverter. There are five basic processes of harnessing solar energy for day to day use. Those are,

- Solar Panel
- Combiner
- DC/DC Converter
- DC/AC Inverter
- Utility Switch

A series of PV cells form a PV module and a combination of PV modules form a PV array to generate required power to specified loads. In general, solar PV modules are connected in series to increase the PV output voltage since available PV modules can generate a low DC output voltage in the range of 12V to 75V. Therefore, an appropriate power electronic DC/DC converter is compulsory to convert this low DC output to the required utilization voltage level. Apart from that, the low DC output voltage generated by the PV panel is varying widely with the solar irradiation, the shadowing effects, ambient temperature, tidiness of the PV module surface, etc. Moreover, selection of suitable DC-DC converter topology is more important to harness solar energy from solar PV arrays efficiently.[6]

Therefore, there is a crucial need of designing highly efficient DC-DC converter to regulate the low and varying DC output voltage obtained from the PV arrays. The available converters in the market are expensive but their efficiency is low. So, to cater the above needs, this paper presents a designing and simulation of a Single-Ended Primary Inductance Converter (SEPIC) in the MATLAB/Simulink software environment. The SEPIC converter is designed with a PID controller to ensure constant regulated voltage output from solar PV array under variable irradiance levels. Besides, an inverter is also designed and connected after SEPIC converter to convert DC power into AC power which feeds AC voltage to home electrical appliances. Moreover, performance of the converter is analyzed and further improvements to the design are also discussed.

II. RELATED WORKS

Designing of a DC/DC converter for solar PV applications is not intact. Many researchers have already proposed and implemented different types of power electronic converters for this purpose. Few of recent works are mentioned below.

Maglin, J., Ramesh R. and Vaigundamoorthi M. [1] proposed a SEPIC converter for solar PV systems in which MPPT algorithm has been used to track the maximum power point from solar array. The nominal duty cycle of the main switch of DC-DC SEPIC converter is adjusted, so that the solar panel output impedance is equal to the input resistance of the DC/DC converter which results better spectral performance in the tracked voltages when compared to conventional PWM control

Bruno G. De Assis and Eduardo P.C Braga [2] have designed and analyzed the performance of SEPIC converter for renewable energy applications. A voltage multiplier has been employed at the output of the SEPIC, which was connected in series with the output to achieve high step-up ratio operation with limited duty cycle values. The primary objective of the study was to design an improved converter which is more robust and can maintain constant output.

III. ANALYSIS OF SEPIC CONVERTER

A. Operational Principle

SEPIC stands for The Single-Ended Primary Inductance Converter**.** It has certain advantages over the normal buck boost converter. Like the buck boost converter, it can step up or step down the output voltage. The ability to have an output voltage greater or less than the input with no polarity reversal makes this converter suitable for many applications. Here, capacitor is the main energy storage element. It helps to ensure continuous current flow, and the inductor which is placed at the load side also reduces ripples of the output current.[3]

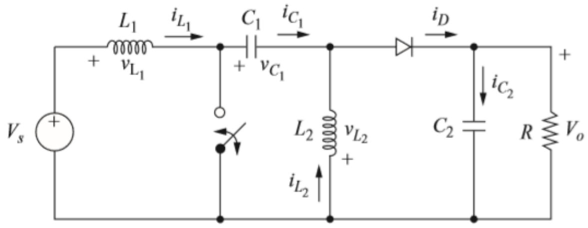

Fig.1. Schematic of conventional SEPIC converter

The inductor currents are assumed to be continuous in this analysis (continuous current mode-CCM). Other observations are that, the average inductor voltages are zero and that the average capacitor currents are zero for steady-state operation. The circuit has two states of operations; switch closed and switch open. Analysis is done using these two states of operation as illustrated below.

1) State1 Circuit- (Switch closed)

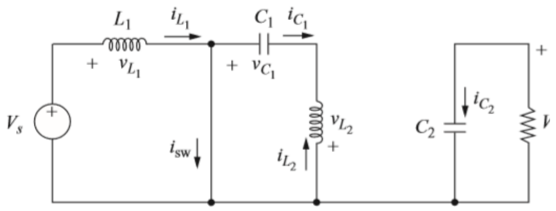

Fig.1. State1 Circuit operation (Switch closed)

2) State2 Circuit- (Switch open)

State2 begins when the transistor is switched OFF, the energy stored in inductor 2 is released through the diode to the load. When the switch is open, the diode is ON, and the circuit is as shown in Fig. 3.

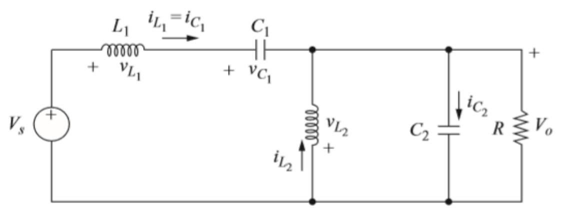

Fig.2. State2 Circuit operation (switch open)

IV. DESIGNING THE SEPIC CONVERTER

A. Design Specifications

Domestic utility voltage level is considered as 230V AC (rms) thus, its peak voltage is 325V (= $\sqrt{2}$x 230). Therefore, output voltage of the SEPIC converter is set at 325V DC.

Below is the design specification of the SEPIC converter, which is based on the daily electrical power demand of a typical house calculated in Table 3.

Table I
Daily power demand of a typical house

Electrical Device	Power
Lighting	50W
Television	50W
Rice Cooker	500W
Computer	50W
Refrigerator	350W
Water Pump	500W
Total Demand	**1500 W**

- Input voltage: <180 V
- Output voltage: 325 V
- Output power: 1.5kW
- Output current: 5A
- Switch. Freq.: 25kHz
- Voltage ripple 2%
- Current ripple 3%

To achieve enhanced operation of the converter, accurate determination of circuit element is essential. Component parameters are calculated assuming CCM operation using the following formulas, where D is the duty cycle,ΔIL is the ripple current, Fs is the switching frequency and ΔV is the ripple voltage.

$$D = \frac{V_{out}}{V_{in} + V_{out}} \tag{01}$$

$$L_1 = \frac{V_{in} x\ D}{\Delta IL_1 x F_S} \tag{02}$$

$$L_2 = \frac{V_{in} x\ D}{\Delta IL_2 x F_S} \tag{03}$$

$$C_1 > \frac{D x I_{out}}{\Delta V_{C1} x F_S} \tag{04}$$

$$C_2 > \frac{D x I_{out}}{\Delta V_{C2} x F_S} \tag{05}$$

Duty cycle calculation,

$$D_{max} = \frac{V_{out}+V_D}{V_{in}+V_{out}+V_D} = \frac{325+0.5}{180+325+0.5} = 0.64$$

Table 2 gives the theoretically calculated parametrs and the available standard components parameters.

B. Calculated Component values

Table II 2
Selected Components for SEPIC converter

Component	Calculated Values	Standard Values
L_1 - Inductor	1.28 mH, 10 A	1.676 mH, 9 A
L_2 - Inductor	1.28 mH, 5 A	1.676 mH, 9 A
C_1- Capacitor	18.28 μF, 180V	22 μF, 240V
C_2 -Capacitor	32.77 μF, 325V	33 μF, 240V
R - Resistor	65 ohms	68 ohms
D_1 - Diode	325V, 5A	600V, 5 A

V. MODELLING & SIMULATION

A. SEPIC Converter Simulink Model

The SEPIC converter is modelled using MATLAB/ Simulink software. Initially the converter is considered as fixed input voltage and it is adapted to a variable source input voltage (solar PV array block) later. Therefore, 180V DC voltage source is used as the input source voltage, because the maximum output voltage of the PV array is considered as 180V. Frequency (F) of the pulse generator is set at 25kHz and the duty ratio D = 0.64 (64%). Fig. 5 shows the simulation model of the fixed input SEPIC converter.

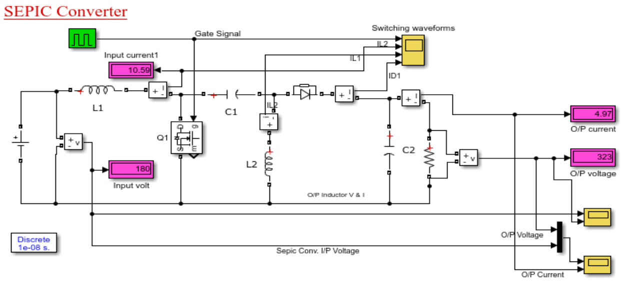

Fig.5. SEPIC converter Simulink model (Fixed Input)

The input voltage, V_I is 180 V and the obtained output voltage, Vo is 323.5V. The experiments are made with a resistive load of 65 Ω. Therefore, the load current, I_L is almost 5A.

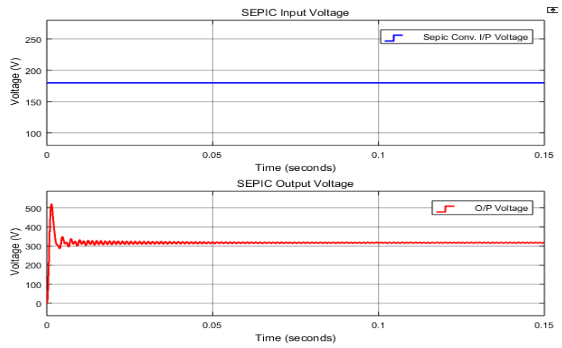

Fig.6. SEPIC converter input & output waveforms

The graph shown in Fig. 6 depicts that, the desired output voltage of 325V for a constant input voltage (180V) is properly achieved by the converter. The converter's simulation output waveforms are shown in Fig.7.

When the switch is closed, the diode is reverse biased. Since the rate of change of inductor current is a constant, the current increases linearly. When the switch is opened, the inductor current cannot change instantaneously, so the diode becomes forward biased providing a path for inductor current. Since the rate of change of inductor current is a constant, the current decreases linearly. Therefore, the inductor current depicts a sawtooth like waveform.

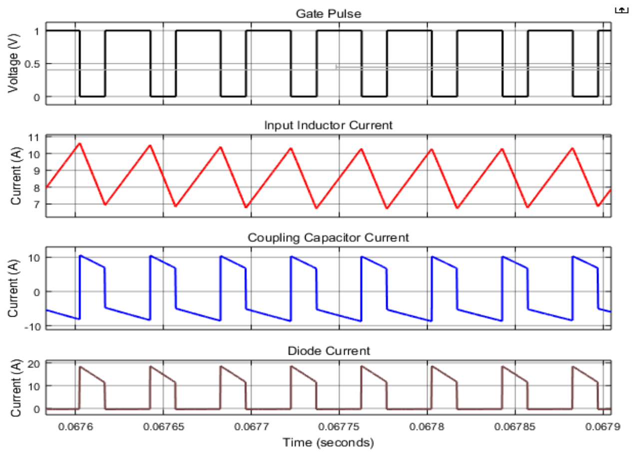

Fig.7. SEPIC Converter switching wave forms

Even though the required output voltage is achieved, an undesirable transient overshoot is also observed in the output waveform as shown in fig.6.

Apart from that, PV arrays do not produce constant voltage, but the converter must be able to supply regulated voltage output. Therefore, a suitable digital controller must be employed with the converter to reduce undesirable transients and to obtain constant voltage output. Controller designing is discussed in the next section.

B. Controller Design

A simple PID (Proportional, Integral and Derivative) controller has been employed to the SEPIC converter to achieve improved voltage regulation (constant voltage output). The proposed closed loop controller maintains constant output voltage despite changes in input voltage and significantly reduces overshoots thereby improving the efficiency of the converter.

The closed loop control circuit compares feedback voltage continuously with a set reference voltage and a desired control signal is produced and improved with the help of PID Controller operation. Controller corrects the error between measured value and the set point value that can adjust the whole process thus dynamic response can be improved and the steady-state error in the system is reduced.

To find the gain values K_P, K_D and K_I, of the PID controller, trial and error method is used and following gain values are obtained for the optimum performance. (K_P=0.008, K_D = 0.0001, K_I= 120).

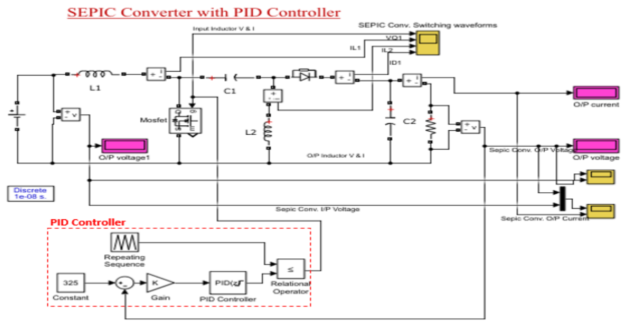

Fig.8. SEPIC converter with PID controller

The graph shown in Fig.10 evident that the undesirable transient behavior has been eliminated by the PID controller. So, the DC/DC converter can provide well-regulated output voltage for varying input voltage with the help of the PID controller.

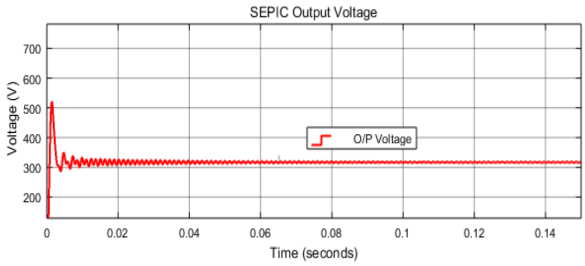

Fig. 9. Output voltage without controller

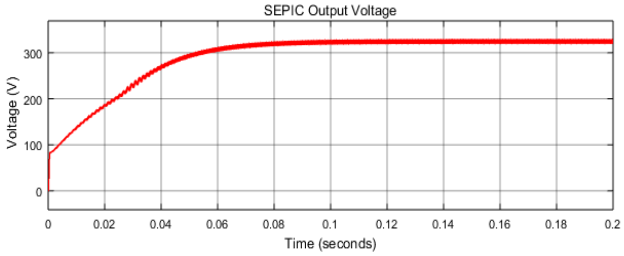

Fig. 10. Output voltage with PID controller

C. Connecting Solar PV Array with Converter

The Simulink PV Array block formed by an array of photovoltaic (PV) modules. The array is built of strings of modules connected in parallel, each string consisting of modules connected in series.

Fig.11 below illustrates how PV array block is connected to the source side of the SEPIC converter.

Fig. 12 clearly shows that, even though the input voltage has changed with the solar irradiance, the SEPIC converter output voltage is kept unchanged because of the PID controller.

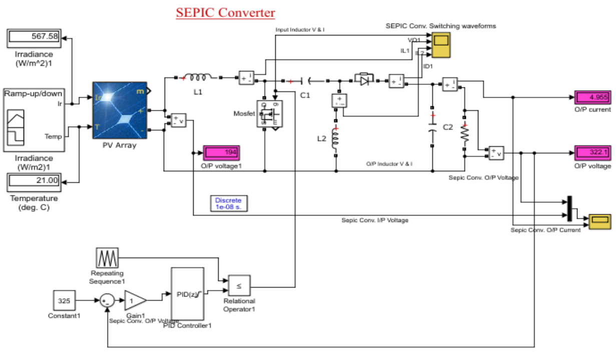

Fig. 11. Solar PV array connected to SEPIC converter

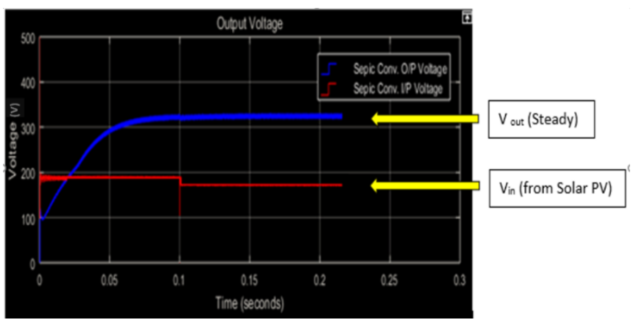

Fig. 12. Stable output voltage for different input voltages

D. DC/AC Inverter Design

Single phase full bridge DC/AC inverter is used to convert DC output voltage into AC utility voltage. In this inverter, four MOSFETs are used as switches. In full bridge inverter, peak voltage is same as the DC supply voltage. The circuit diagram of full bridge inverter is as shown in Fig.13.

The gate pulse for MOSFET 1 and 2 are same. Both switches are operating at same time. Similarly, MOSFET 3 and 4 has same gate pulses and operating at same time.

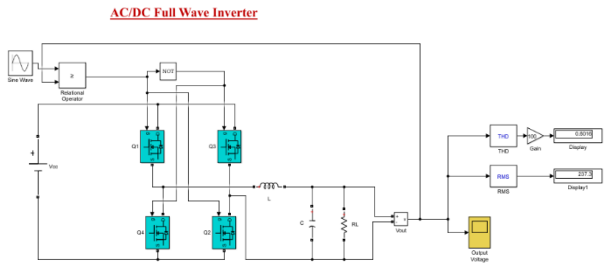

Fig. 13. Schematic block diagram of full bridge Inverter

The above inverter model is simulated with 325V DC input voltage. Fig. 14. below shows the sinusoidal output waveform.

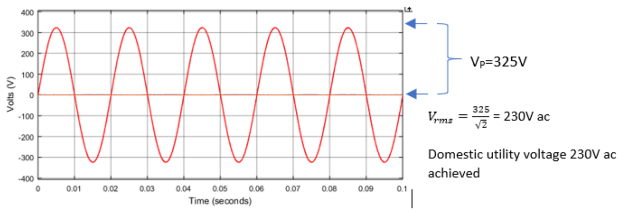

Fig. 14. Sinusoidal output waveform of the Inverter

The rms value of the inverter output is 230V which is the domestic utility voltage level.

E. Overall Home Solar PV System Simulation

Fig.15 illustrates the overall home solar PV system. It consists of solar PV Array, SEPIC Converter, PID Controller and DC to AC full wave inverter.

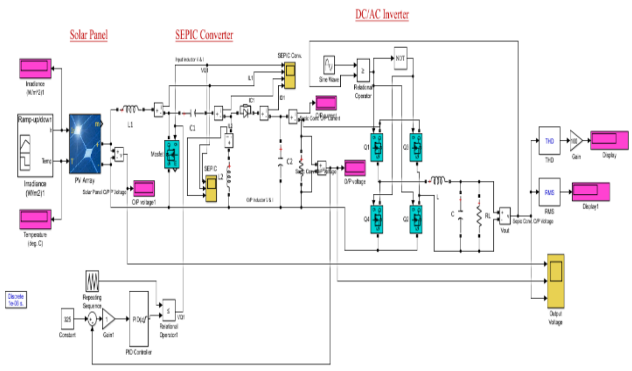

Fig. 15. Overall home solar PV system

Below figure shows the simulation results of the overall home solar PV system.

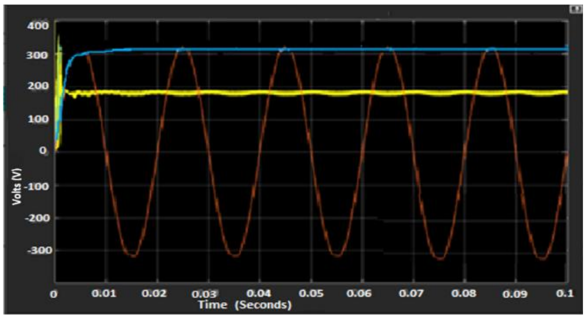

Fig. 16. Overall solar PV system simulation waveforms

The yellow curve represents the PV array output voltage ~180V DC which is varying time to time. The blue curve represents the SEPIC converter output 325V DC which is regulated and steady. The red curve is the sinusoidal A/C output. Its peak voltage is 325V thus the rms value is 230V A/C household utility level.

VI. ANALYSIS OF RESULTS

A. Efficiency Calculation

Output voltage is measured for the range of input values to the converter and its efficiency is calculated as shown in Table 3.

$$(\eta) = \frac{Output\ Power}{Input\ Power}\ x\ 100\% = \frac{V_O\, I_O}{V_I\, I_{L1}}\ x\ 100\%$$

Throughout the entire input voltage range(10-180V) the efficiency is maintained at a satisfactorily level (84.87% - 91.71%).

Table III
Converter efficiency for different Input values

Input		Output		Efficiency (η) %
Vin (V)	I in (A)	Vout (V)	I out (A)	
10	0.56	17.8	0.26	84.87
20	1.16	34.54	0.57	85.01
30	1.66	52.87	0.81	86.16
40	2.17	69.36	1.08	86.54
50	2.66	89.91	1.28	86.30
60	3.62	108.60	1.72	86.25
70	3.98	123.81	1.94	86.21
80	4.13	132.62	2.17	86.96
90	4.30	147.80	2.28	87.13
100	4.40	161.41	2.41	88.33
110	4.76	178.33	2.61	88.58
120	5.07	192.51	2.78	88.09
130	7.67	232.80	3.78	88.37
140	8.10	249.34	4.11	90.39
150	8.56	271.61	4.30	90.90
160	8.98	290.52	4.52	91.02
170	9.30	305.11	4.72	91.11
180	9.90	323.80	5.05	91.71

B. Voltage Ripple Calculation

Voltage ripple factor is another important parameter which defines the performance of a converter. It is calculated using the steady state output voltage waveform as shown below.

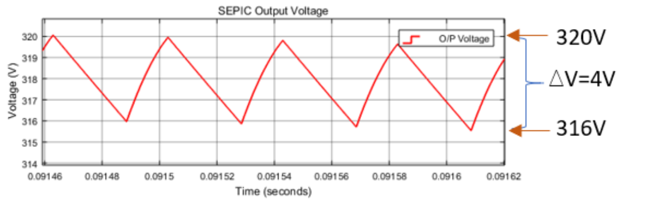

Fig. 17. Output voltage ripples

$$\text{Ripple factor} = \frac{\Delta V}{V_O} x100 = \frac{320-316}{325} x100 = 1.23\%$$

C. Discussion of Results

A SEPIC converter is designed and simulated using MATLAB/ Simulink environment. The designed converter can step up voltage from 180 V to 325 V. Output power up to 1500W is tested with an efficiency of 91 %. Efficiency is the prime factor of evaluating the performance of power converter. It is proved by the simulation that, efficiency of the designed converter is maintained between 84% to 91.71% when the input voltage is varying from 10V to 180V and the load current is 5A. Apart from that the voltage ripple factor is calculated as 1.32% which is another important parameter which defines the performance of a converter.

Moreover, the converter's transient behavior is analyzed. PID controller made the converter very convenient to obtain more stable regulated output voltage with quick rise and settling time, less overshoot and steady state error.

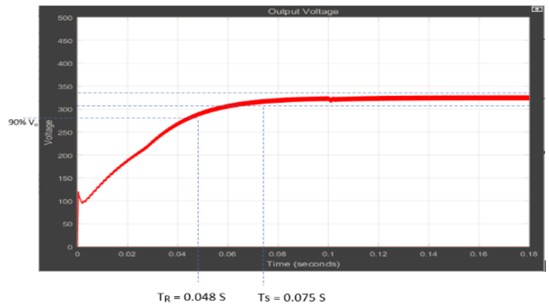

Fig. 18. Transient behavior of output voltage

Here, rise time **TR** refers to the time required for the waveform to go from 0.1 of the final value to 0.9 of the final

value. In this case, the rise time is 0.048s. Whereas, peak time, **TP** is the time required to reach the maximum peak. Here, it is 0.05s. The percentage overshoot, %OS is the amount that the waveform overshoots the steady state, and it was eliminated. The settling time, **TS** is the time required for the transient's damped oscillations to reach and stay within ±2% of the steady-state value and here it is 0.075s.

Total harmonic distortion (THD) of the output current is defined as the ratio of the rms values of the harmonics over the rms value of the fundamental component. Here, THD for inverter output is shown as 2.798% in the Simulink display.

VII. CONCLUSION

A SEPIC converter for home solar PV applications is designed, simulated and analyzed for 1.5kW home electrical appliances and the following conclusions are drawn from the simulation work. Major focus of the investigation is on efficiency, low output voltage ripple and stability required for applications in residential solar PV system. Experimental results showing that the designed SEPIC converter when used with proposed PID controller provides better output voltage regulation and overshoot reduction higher efficiency thereby, improving the overall performance of the system. More stable output voltage can be maintained throughout the wide input range. Moreover, as the key features of the designed converter, regulated output voltage and current, simple procedure and improved efficiency up to 91% can be emphasized. Therefore, the proposed SEPIC converter design is highly recommended for small family home solar PV applications.

VIII. FUTURE WORKS

This study precisely discussed designing of DC-DC converter which can be used with solar PV sources with associated control scheme. However, it is realized that the converter efficiency is slightly reducing at lower input voltage. Therefore, future studies can investigate a possible configuration to further increase its efficiency at lower input voltages too. A modified SEPIC converter with magnetic coupling could be a good approach towards that. Other control mechanisms such as MPPT are also possible with this converter.

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