Robust and highly efficient wide-input range power converter for space application

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Robust and Highly Efficient Wide-Input Range Power Converter for Space Application

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Abstract— This paper presents the output voltage regulation stability of the output voltage in a Single Ended Primary Inductor Converter (SEPIC) operating in the continuous conduction mode using a voltage control feedback system. The performance of the developed controller is validated at different working conditions using PSIM simulation software. The results show that the designed controller produced a good output voltage regulation under different operation condition such as varying the input voltage in a wide input range. The efficiency of the designed SEPIC converter is greatly improved and robust to the wide input range typically encountered in space application employing solar energy as the primary source of energy.

Keywords—Voltage regulation, Solar energy, SEPIC, Dc-Dc converter, Feedback controller, PSIM.

1 INTRODUCTION

Extreme weather variations in space environment result into wide variation of the output voltage of solar cells deployed for harnessing the solar energy. As part of the Nanosatellite programme at the FSATIE unit in the Department of Electrical Electronic and Computer Engineering (DEECE) of the Cape Peninsula University of Technology (CPUT) it is required that a new Dc-Dc power converter system with better solar cells utilization and higher efficiency without compromising better system performance and robustness. Designing such a robust and highly efficient Dc-Dc converter is nontrivial and requires iterative design cycles which may lead lengthy developmental time and increased cost.

A DC to DC converter is a platform where a DC input voltage is converted from one level to another level DC output voltage. Among the DC to DC converters, a SEPIC converter is capable of operating in either step- up or step-down mode of operation depending on the duty cycle [1]. Many power electronics converter circuits such as buck, boost and buck-boost are used to step-up or down voltages depending on the application requirements. However, pulsating input and output current, reverse polarity output voltage are limited for these topologies. In the case of the step-down topology floating switch make it unreliable for some application [2]. Designing a power converter that maintains high efficiency is not easy especially when it comes to step up or down the voltage. All these characteristics are obtained in SEPIC DC to DC power converter system.

The SEPIC converter has unique features over other converter topologies, such as the non-inverting output voltage, low equivalent series resistance (ESR) of coupling capacitor to minimize the ripple which makes it reliable for wide range of operation. In many studies, attempts have been made to implement various control techniques such as PI, PID, etc for enhance the performance characteristics of static power converter system.

For a SEPIC converter a PI controller is capable of providing good static and dynamic responses. If a PID controller is used for SEPIC converter, it will display unacceptable static and dynamic responses. [3].

The next section of the paper provides an overview of SEPIC converter providing the main functionalities it performs and the space mathematical representation of the converter model. Section three details how PI controller is designed for the studied SEPIC converter. Simulation results and discussion is made in section four of the paper.

2 SEPIC CONVERTER OVERVIEW

The single ended primary inductor (SEPIC) is a DC-DC converter topology which provides a positive output voltage regulated from the wide range of input voltage that varies from above to below the nominal output voltage [4]. The switch of the SEPIC is controlled by changing the duty cycle; the uses of a series capacitor couple the energy from input stage to the output stage. The SEPIC converter response rapidly to a short circuit state condition and when the switch is turned off its act in a true shutdown mode; its output drops to 0V by following a hefty transient dump of charge [5].

The SEPIC is used in applications where the input voltage could be lower or higher of the regulated intended output voltage. Its transfer energy between the capacitors and inductors during the switching operation, this process is done in order to convert a voltage from one to another. The quantity of energy is controlled by the switch, which employ transistor such as an IGBT, MOSFET. MOSFET offer wide range of advantage such as high input impedance which makes it to require simple drive circuit, low voltage stress, as well as do not required any biasing resistors. In addition, MOSFET switching can be controlled in voltage mode rather than a current mode [2].

There are many methods available for modeling power electronics power processors such as the state space average, signal flow graph, average circuit model and the small signal model. The state space averaging method is adopted in this paper. This method allows an elegant mathematical expression that can easily be manipulated and used for controller design in most of the available simulation software platforms. The converter is analyzed for a continuous conduction mode of operation.

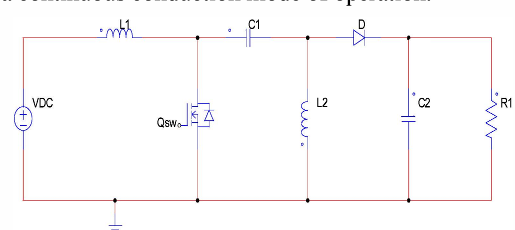

Figure .1. SEPIC converter topology.

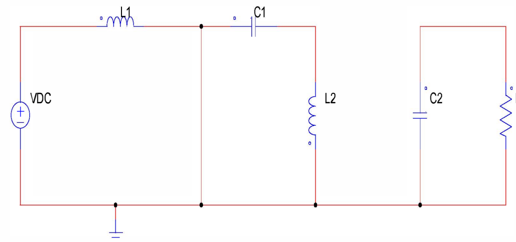

Figure.2. SEPIC converter state, during on-time of the MOSFET.

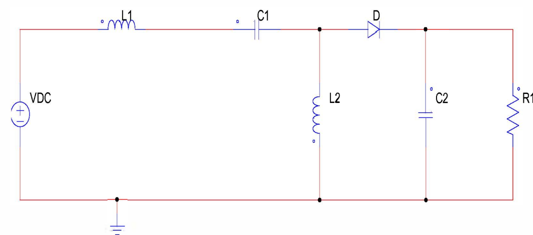

Figure.3. SEPIC converter during Off-state of the MOSFET.

2.1 SEPIC converter mathematical modeling

Figure 1 shown above a SEPIC power converter circuit. It includes a DC input voltage V_{DC}, inductors L1 and L2, C1 and C2, a switch implemented with MOSFET, a diode D and the load resistance R. It is assumed that the converter operates in and all the components are ideal.

Figure 2 and figure 3 illustrate the operation mode of the SEPIC converter. Figure 2 shows the converter state when the switch is on (closed), the diode is reverse biased, the inductor L1 is charging from the input voltage, while C1 is charged by L2. The inductor current in figure 3 varies at the rate of:

$$\frac{di_{L1}}{dt} = \frac{VDC}{L1}, 0 \leq t \leq dT \tag{1}$$

$$VDC = VC1 \tag{2}$$

Where VC1 is the voltage across capacitor C1, when the switch is off (open), the diode D is forward biased, L1 inductor charge capacitor C1, L2 discharge and charge C2. At this off state, the equation can be written as follow:

$$IDC_{in} = IL1 \tag{3}$$

$$I_{out} = I_D \tag{4}$$

Where I_D is the average diode current, Iout is the output current. When the SEPIC is on a conduction continuous mode [6], [7], the conversion ratio voltage of the SEPIC could be obtained from the volt second balance of the inductor L1 in one switching period as expressed by:

$$\frac{V_{out}}{VDC} = \frac{D}{1-D} \tag{5}$$

Where D is the duty cycle and Vout is the output voltage of the SEPIC.

In this paper the state space representation is developed for the SEPIC converter because it has several advantages when compared to other methods. The state space has the ability to handle the system easily with multiple inputs or outputs. The state variables of the SEPIC are considered as currents (I_{L1}, I_{L2}) and voltage (V_{C1}, V_{C2}). When the switch is closed; the state space equation can be obtained as:

$$\begin{pmatrix} I_{L1} = -\dfrac{V_{DC}}{L_1} \\ I_{L2} = \dfrac{V_{C1}}{L_2} \\ V_{C1} = -\dfrac{I_{L2}}{C_1} \\ V_{C2} = -\dfrac{V_{C2}}{RC_2} \end{pmatrix} \tag{6}$$

$$\frac{d}{dt}\begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \dfrac{1}{L1} & 0 \\ 0 & \dfrac{-1}{C1} & 0 & 0 \\ 0 & 0 & 0 & \dfrac{-1}{RC2} \end{bmatrix} \begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} + \begin{bmatrix} \dfrac{-1}{L1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{DC} \tag{7}$$

During a turned off state as shown in Fig 3.

$$\frac{d}{dt}\begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dfrac{-1}{L1} & \dfrac{-1}{L1} \\ 0 & 0 & 0 & \dfrac{-1}{L2} \\ \dfrac{1}{C1} & 0 & 0 & 0 \\ \dfrac{1}{C2} & \dfrac{1}{C2} & 0 & \dfrac{-1}{RC2} \end{bmatrix} \begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{DC} \tag{8}$$

$$\frac{d}{dt}\begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{L1} & \frac{-1}{L1} \\ 0 & 0 & 0 & \frac{-1}{L2} \\ \frac{1}{C1} & 0 & 0 & 0 \\ \frac{1}{C2} & \frac{1}{C2} & 0 & \frac{-1}{RC2} \end{bmatrix} \begin{bmatrix} IL1 \\ IL2 \\ VC1 \\ VC2 \end{bmatrix} + \begin{bmatrix} \frac{VC1 + VC - 2VDC}{L1} \\ \frac{VC1 + VC2}{L2} \\ \frac{-IL1 - IL2}{C1} \\ \frac{-IL1 - IL2}{C2} \end{bmatrix} Y + \begin{bmatrix} \frac{1}{L1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{DC} \quad (9)$$

$$\dot{X} = AX + BY + C \quad (10a)$$

Where Y is the status of the switches, and $X, \dot{X}$ is the state variables of the current IL1 and IL2, and the voltage VC1 and VC2 their derivatives, respectively.

$$y = \begin{pmatrix} 1 \rightarrow S \rightarrow ON \\ 0 \rightarrow S \rightarrow OFF \end{pmatrix} \quad (11)$$

3 PI CONTROLLER AND DESIGN CONSIDERATIONS.

The Table 1 is a parameter data of SEPIC converter.

Table 1:

Parameter	Symbol	Value
Input voltage	Vin	3V - 20V
Power of the converter	P	8 W
Switching frequency	Fsw	250 kHz
Output voltage	Vout	10V
Inductors	L1,L2	8.7uH
Capacitors	C1,C2	10uF,27uF
Load resistance	Rload	12Ω
Range of duty ratio	D	0.334 to 077

The PI control is the most common linear method control application used in industry. Linear PI controllers are design for DC-DC converters topology; whereby using the frequency response techniques and converter standard of small signal model [8]. The PI control technique offer many advantage over the PID control technique such as robustness, good dynamic response, reduces steady state error, load variation and simple implementation [9].

Optimizing the stability of the SEPIC converter, by ensuring the correct operation and working condition at any stage; the PI control is a more feasible approach presenting to a better alternative of the control to a switching power converter. The principal advantage of the PI control schemes is the insusceptibility to the system (plant) parameter variations which leads to invariant dynamics and static response of the ideal case [2].

Fig.4 shows the block diagram of the PI controller design. The large dc gain is achieved to improve the steady state error when the P controller is used. Combining P and I will eliminate forced oscillations and steady state error. The integral term has a negative effect on response speed and the overall stability of the system.

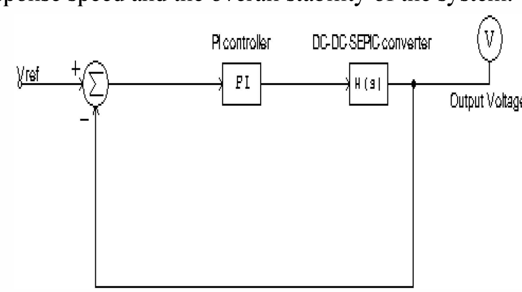

Figure.4. Design of PI controller.

PSIM with its add-on package-smart control software is used to approach the solution of PI controller. The main goal is to choose the nominal input voltage value and tune a controller by adjusting the loop transfer function to the ideal gain vs. frequency response desired.

The bandwidth (crossover frequency) could be chosen between 10-20% of the switching frequency of the SEPIC converter and the phase margin between 45^0 to 60^0 to obtain satisfactory overshoot and stability margin; by running the AC-sweep analysis of the SEPIC converter on PSIM software (Fig.5), the loop gain and the phase of the converter as illustrated in the Figure 5 is obtained and the loop transfer function file is then exported to smart control platform. Once a transfer function file has been exported, the implementation of the voltage mode control design can easily be performed. The procedure involves choosing single loop sensor type, which in our case is a voltages divider and the regulator type is a PI controller. Figure 6 shows a single loop voltage controlled with a PI controller.

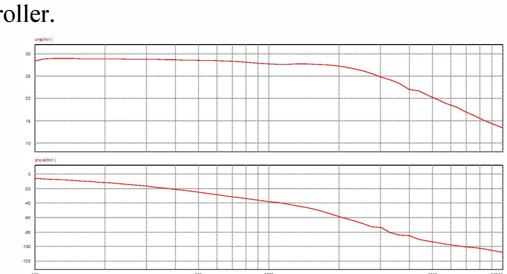

Figure.5. Bode plot, gain and phase graph vs. frequency.

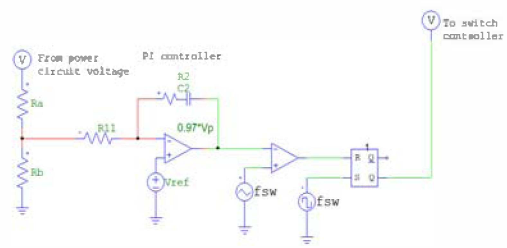

Figure.6.Voltage controlled; PI controller schematic diagram.

4 SIMULATION RESULTS

This section analyses the simulation results of the SEPIC converter with two different control methods. The simulations are performed on the SEPIC converter circuit with the parameters listed in Table 1, the use of PSIM software under the following conditions:

- Open loop controller (without a feedback).
- Closed loop controller (with a feedback).

4.1 SEPIC converter open loop model simulations

The proposed topology of the SEPIC converter has been verified by analysing the simulation results using the open-loop and closed loop model. For the closed loop model, the PI controller parameters have been calculated using PSIM-smart control Bode-plot technique explained in section 3.

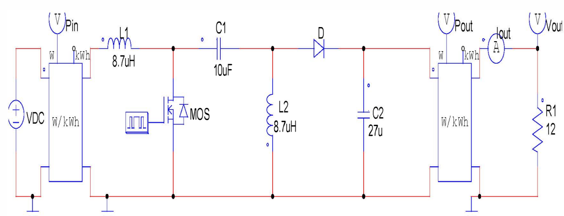

Figure.7. Psim model for the open loop SEPIC converter circuit.

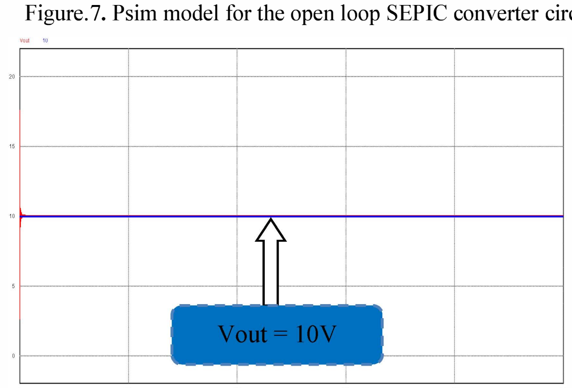

Figure.8.Open loop output voltage graph at 3V input, maximum duty cycle (D_{max}).

Fig.8 depicts the open loop output voltage when a 3 V is applied to the input. It can be seen that the output voltage value was achieved at the maximum duty cycle with a high efficiency as depicted in Figure 9. While applying the maximum input voltage, the output voltage becomes unstable (Figure 10) and the efficiency decrease by 6% less as illustrate in Figure 11.

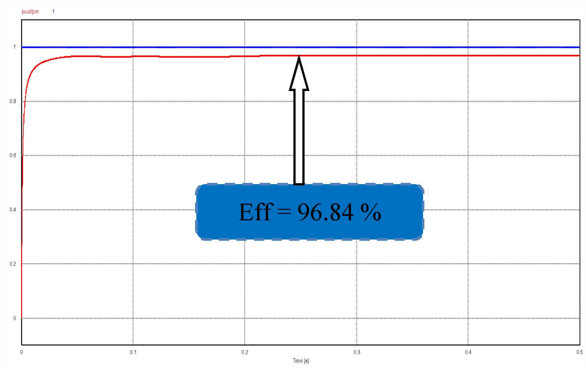

Figure.9.Open loop efficiency graph at 3V input, maximum duty cycle (D_{max}).

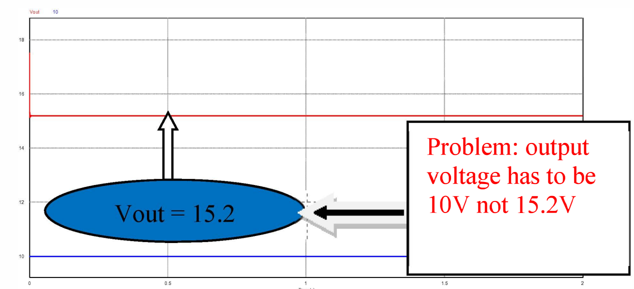

Figure.10.Open loop output voltage graph at 20V input, maximum duty cycle (D_{min}).

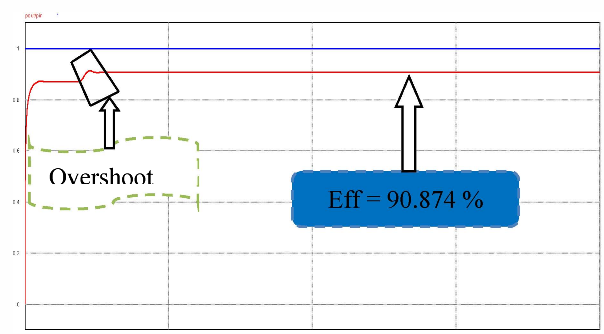

Figure.11.Open loop efficiency graph at 20V input, minimum duty cycle (D_{min}).

There is also a negligible overshoot that lasts for a very short of period of time. To overcome the problems of increased output voltage and decreased efficiency, the PI controller has been design in a voltage control mode in such a way to keep the output voltage stable at 10V maximum.

4.2 SEPIC converter closed loop model simulations

The closed loop model is implemented for better transient and steady state response of the system. The PI controller is connected to the power circuit to form the complete closed loop system as illustrated in Figure 12 using the voltage control model.

It can be see when using the closed loop, the output voltage become stable to 10V (Fig.13) and high efficiency is achieved as illustrate in Fig.14.

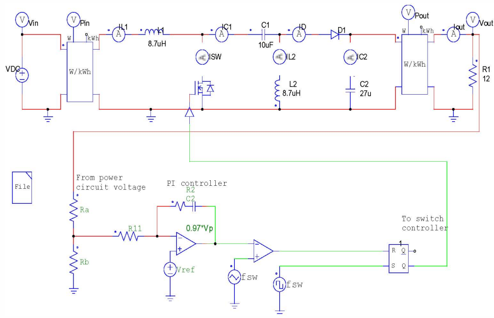

Figure.12. Psim model for the closed loop SEPIC converter circuit.

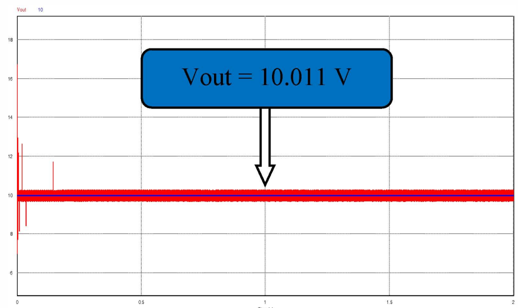

Figure.13. Closed loop output voltage graph at 20V input with minimum duty cycle (D_{nom}).

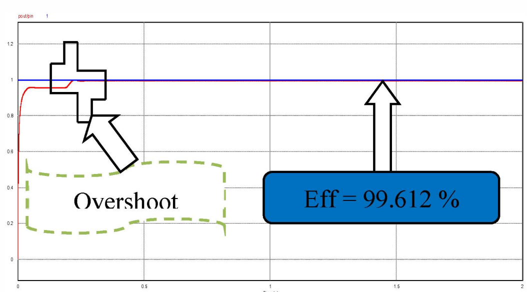

Figure.14.Closed loop efficiency graph at 20V input, minimum duty cycle (D_{nom}).

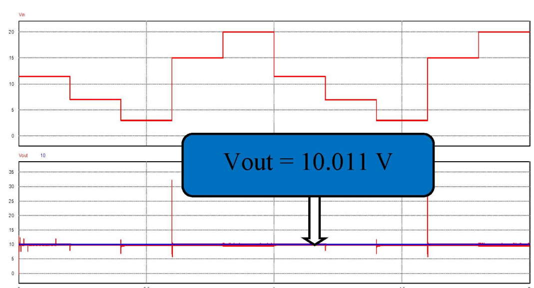

Figure.15. Closed loop output voltage response of SEPIC for input voltage controlled, piecewise linear source.

Further simulations has been done; applying a voltage controlled to the input of the SEPIC converter which controlled a piecewise linear source. It can be seen that the output voltage has the maximum value of 10V, however there is a negleted overshoot and and the transient effect between 0.4s to 06s as illustrated in Fig.15. The same test has been done by using a input voltage as atriangle wave and the 10V output voltage was obtained.

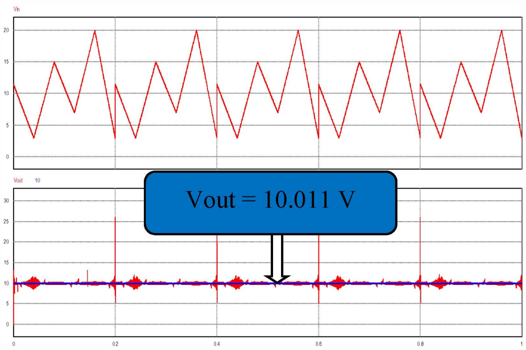

Figure.16.Closed loop output voltage response of SEPIC for input voltage controlled, piecewise triangle linear source.

5 CONCLUSION

All the specification of a SEPIC converter was determined. PSIM-software simulation was performed in the open loop and closed loop, the corresponding waveforms were obtained. It can be seen from the simulation that the closed loop system is more accurate than the open loop system.

A number of simulations are carried out in order to demonstrate the performance of PI voltage controlled. Possibility of implementing a single current controlled or double loop in the future work and the propose system is suitable for space application, such as Nanosatellite, for real world commercial applications, like power supplies for medical equipment, computer power supplies, uninterrupted power supplies.

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This paper is presented by K.D. Mananga Bayimissa

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