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Implementation Of Sepic Dc-Dc Voltage Converter Using Voltage Mode And Proportional Integral Controllers.

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ABSTRACT:*Achieving a regulated DC output from a fluctuating DC source that is efficient and ripple free posed a challenge in power electronic applications. This paper presents a Single-ended Primary Inductor (SEPIC) DC-DC voltage converter which has the advantage of mitigating these challenges by supplying a regulated DC output voltage to a variable-load from a fluctuating DC input voltage with high efficiency.Voltage Mode and Proportional Integral Controllers were applied to the power circuit and the results were compared. The voltage level at the output of the converter is controlled by the duty cycle of the controller using pulse width modulation (PWM). Due to the cyclic switching nature of the Pulse Width Modulation of a SEPIC converter, the converter circuit was modelled using State Space Average (SSA) technique. SEPIC converter is a fourth order system, Pade approximation technique was used to reduce the fourth order model to a linearsecond order model.The linearized model of the SEPIC voltage converter was simulated using MATLAB/SIMULINK. The best tuned values using trial and error method of the rise time, settling time, overshoot, peak value, gain margin and phase margin were achieved at 3.78e-12 secs, 2.86e-11 secs, 20.4%, 1.2, -280dB at 2.92e+04 rad/s and 63.4 degrees at 3.86e+11 rad/s respectively. The output voltage under load condition gives 11.98 V and it is almost ripple free. It shows an estimated percentage error range from 0.17 % to 1.41 %, which is within the design limits.In comparison, the PI controller gives a more efficient output voltage with less ripples and settles faster compared to the VMC.*

Keywords:*DC-DC converter, Proportional-Integral (PI) controller, Voltage Mode Control (VMC), Single Ended Primary Inductor Converter (SEPIC), Continues Conduction Mode (CCM, Pulse Width Modulated (PWM), State Space Average (SSA), Pade approximation technique,trial and error method.*

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I. INTRODUCTION

The ever increasing reliance on electronic devices that utilize DC power supply with stable output voltage cannot be overemphasized. Voltage regulators have been used to provide such reference voltages but they are not efficient in terms of power lost. Batteries have been used as an option but they lose their energy content rapidly, have limited life cycle and depth of discharge (Venkatanarayanan and Nanthini, 2014). Single-ended primary inductor (SEPIC) DC-DC voltage converter stems these challenges by supplying a regulated DC output voltage to a variable-load resistance from a fluctuating DC input voltage with high efficiency(Kanaanet al., 2009). The essential characteristic of this converter is that the switch is operated only in one of two states;either fully on or fully off (Continuous Conduction Mode (CCM), or Discontinuous Conduction Mode (DCM) unlike other types of electrical circuits where the control elements are operated in a linear active region (Vorperian, 1990, Venkatanarayanan and Saravanan2014).

SEPIC exchanges energy between the capacitors and inductors in order to convert from one voltage level to another and is controlled by the duty cycle of the controller using pulse width modulation (PWM)(Rashid, 2004). Ideally, when a switch is on, it has zero voltage drops and will carry any current imposed on it, but when a switch is off, it blocks the flow of current regardless of the voltage across it (Vadivooet al., 2014 and Paranthagan et al 2015). For this application a switching frequency of 100 KHz is selected as a good compromise between the size of inductors and efficiency.Furthermore, by keeping the signal digital most noise effects are minimized which is a prime benefit of choosing pulse width modulation (PWM) to control the switch(Holmes et al, 2003).Due to the SEPIC converter cyclic switching nature of the PWM, the

converter is modelled using State Space Average (SSA) technique that linearized the non-linear system to a linear system for analysis(Ramasamy and Thangavel, 2012). Pade Approximation method was used to reduce system from fourth order to a linear second order system.

SEPIC converter comes with the advantage of a regulated output that can easily extended to multiple outputs, smaller output voltage ripple, good steady-state performances, excellent transient performance and the same output polarity with input.SEPIC DC-DC converters are commonly used in applications requiring regulated DC power, such as computers, medical instrumentation, communication devices, television receivers, switch mode power supply, solar systems, inverters and battery chargers (Comines and Munro, 2002).

II. SEPIC DC-DC VOLTAGE CONVERTER

Single-ended Primary Inductance Converter (SEPIC) is a DC-DC voltage converter that will boost, buck or allow the electrical potential (voltage) at its output to be at the desired level with the same polarity as that of the input Figure 1. The term "single ended" means that only one switch (MOSFET) in the converter controls energy exchange between capacitors and inductors. SEPIC DC-DC voltage converter consist of two inductors ($L_1$and L_2), two capacitors (C_1, and C_2), a diode(D_1) and switch (Q_1). The inductors and capacitors have equivalent series resistances r_1, r_2, r_3, r_4, respectively. When the pulse is high, the switch is on, inductor L_1 is charged by the input voltage and inductor L_2 is charged by capacitor C_1. The diode is off and the output is maintained by capacitor C_2. When the pulse is low, the Switch is off, the inductors output through the diode to the load and the capacitors are charged. During a SEPIC's steady-state operation, the average voltage across capacitor C_1 (V_{C1}) is equal to the input voltage (V_{in}). Capacitor C_1 blocks direct current (DC), the average current across C_1 (I_{C1}) is zero, making inductor L_2 the only source of load current.

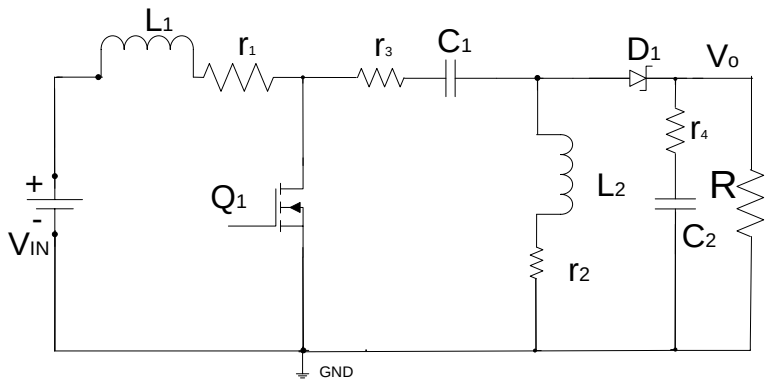

Figure 1:SEPIC DC-DC voltage converter schematic circuit diagram.

When $Q_1$is turned on, the energy stored in L_2 is transferred to C_2 through D_1 and supplying the energy to Load. Therefore the current across the inductor L_1 and L_2, are

$$I_{L1} = \frac{V_{in}}{L_1} t_{on}, \quad (1)$$

$$I_{L2} = \frac{V_{C1}}{L_2} t_{on} \quad (2)$$

And the currents across $I_{L1}$and $I_{L2}$when the switch is off are

$$I_{L1} = \frac{V_{in} - V_{c1} - V_o}{L_1} t_{off} \quad (3)$$

$$I_{L2} = \frac{-V_o}{L_2} t_{off} \quad (4)$$

From equations 1 to 4, the average output voltage is

$$V_o = \frac{D}{1-D} V_{in} \quad (5)$$

V_o/V_{in} is the transfer function of the SEPIC converter in continuous conduction mode as:

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \quad (6)$$

Similarly for the lossless circuit, the current relationship will be:

$$I_o = \frac{1-D}{D} I_{in} \quad (7)$$

$$D = \frac{t_{on}}{t_{on} + t_{off}} \quad (8)$$

$$D_{(max)} = \frac{V_o + V_{D1}}{V_{in(min)} + V_o + V_{D_1}} \text{ and } D_{(min)} = \frac{V_o + V_{D1}}{V_{in(max)} + V_o + V_{D_1}}$$

Where T = Switching Period, f_{SW} = Switching Frequency, t_{on} = Switch on time, t_{off} = Switch off time and D = Duty cycle.

The change in current is estimated at 25% of the input current, therefore the inductor ripple current is

$$\Delta I_L = I_{in} \times 25\% = \frac{I_o \times V_o \times 25\%}{V_{in\,(min)}} \quad (9)$$

With two separate inductors, the inductance is given by:

$$L_1 = L_2 = \frac{V_{in\,(min)} \times D_{max}}{\Delta I_L \times f_{sw}} \quad (10)$$

If the ripple voltage estimated at 5%, then the capacitor C_1 will be

$$C_1 = \frac{I_o \times D_{max}}{\Delta V_{C1} \times f_{sw}} \quad (11)$$

The output Capacitor (C_2):

$$C_2 \geq \frac{I_o \times D_{max}}{\Delta V_{ripple} \times f_{sw}} \quad (12)$$

C_1 = 450 µF, C_2 = 220µF, $L_1 = L_2$ = 8.16 µH and $P_o = 120$ W

2.1 Modelling Of The Sepic Converter

The state space equations of the circuit in each of the circuit configurations can be written, when Q_1 = 1, DT ≤ t ≤ T

$$\dot{x} = A_1 x + B_1 V_{in}$$

$$y = A_1 x + B_1 V_{in} \quad (13)$$

D(t) = 0 and when Q_1= 0

$$\dot{x} = A_2 x + B_2 V_{in}$$

$$y = A_2 x + B_2 \quad (14)$$

Where;

ẋ- Represent electric charge

A - Represent system matrix of the uncontrolled converter (SEPIC)

B - Represent input matrix of the converter

C - Represent output matrix of the converter

D - Represents the direct transmission matrix of the converter

V_{in} - Represent control input (U)

y - Represent output voltage (V_o)

Given the two binary values of the switching function D(t) 1 and 2 can be combined to obtain the non-linear and time variant state space model of the converter.To produce an average description of the circuit over a switching period using equations 13 and 14, the equations are time weighted and average resulting in equations 14 and 15 over one cycle.

$$\dot{x} = (A_1 D + A_2(1 - D))x + (B_1 D + B_2(1 - D))V_{in} \quad (15)$$

$$V_o = (C_1 D + C_2(1 - D))x + (E_1 D + E_2(1 - D))V_{in} \quad (16)$$

Where $A_1$and $B_1$for switch on, A_2 and $B_2$for switch off, D and (1 - D) represent t_{on} and t_{off} respectively.

$$\dot{x} = \begin{matrix} \frac{dI_1}{dt} \\ \frac{dI_2}{dt} \\ \frac{dV_1}{dt} \\ \frac{dV_2}{dt} \end{matrix}, x = \begin{matrix} I_1 \\ I_2 \\ V_1, \\ V_2 \end{matrix} \quad (17)$$

Thus, the transfer functions of the output voltage over duty cycle from equations 1 to 4 will be:

$$\frac{V_o(s)}{\dot{d}(s)} = \frac{A_1 S^4 + A_2 S^3 - A_3 S^2 - A_4 S + A_5}{S^4 + A_6 S^3 - A_7 S^2 - A_8 S - A_9} V_{in} \quad (18)$$

The above equation is the small signal averaged state space model of the transfer function of output to variation in duty cycle control.Applying Padé approximation on the 4th order equation 18 will yield

$$\frac{V_o(s)}{\grave{d}(s)} = \frac{B_1S+B_2}{B_3S^2+B_4S+B_5}V_{in} \quad (19)$$

The plant (SEPIC) DC-DC converter transfer function from equation (18) in terms of VMC: $\frac{V_o(s)}{V_{in}(s)} = \frac{A_1S^4+A_2S^3-A_3S^2-A_4S+A_5}{S^4+A_6S^3-A_7S^2-A_8S-A_9}\grave{d}(s) = G_s$ (20)

And

The characteristic equationequated to zero from equation 20 above:

$1 + G_cG_s = 0$ (21)

Substituting,

$$1 + \frac{A_1S^4 + A_2S^3 - A_3S^2 - A_4S + A_5}{S^4 + A_6S^3 - A_7S^2 - A_8S - A_9}\grave{d}(s) \quad G_c = 0$$

$G_c \geq -\frac{S^4+A_6S^3-A_7S^2-A_8S-A_9}{(A_1S^4+A_2S^3-A_3S^2-A_4S+A_5\ )\grave{d}(s)}$ (22)

G_c, is the tuning parameters for the trial and error method

2.2.1 Control Methods

If G_s is the Plant (SEPIC) transfer function and G_c PI controller in negative feedback mode to the SEPIC (feed forward) system, then

$$Kp + \frac{K_i}{s} = G_c \quad (23)$$

Where Kpis the Proportional term and $\frac{K_i}{s}$ is the Integral term

The values of the PI controller parameters (Kp and Ki) are selected by using the trial and error method.The PI controller ensures the movement of the process towards the set point and eliminates the residual steady state error.A properly designed PI controller makes the system insensitive to disturbance and change of parameters.

III. RESULTS AND DISCUSSION

The system was simulated using MATLAB/SIMULINK for easy analysis and the feedback tuned using trial and error method. The trial and error tuning approach of PI controller is based on estimation of the input voltage, the nonlinear disturbances due to changes in circuit parameters, input source and load. This implies that the tuning is repeated a number of times to obtain the best power quality values for the voltage converter. Figure 4 and Table 1 are the results of the trial and error tuning of the rise time, settling time, overshoot, peak value, gain and phase margin of the tuning of the steady state parameters of the PI controller. The best values of the trial and error tuning were achieved rise time of 3.78e-12 secs, settling time 2.86e-11 secs and overshoot of 20.4% and peak value of 1.2, gain margin of -280dB at 2.92e+04 rad/s and phase margin of 63.4 degrees at 3.86e+11 rad/s

Table 1: Corresponding parameters values from PI controller tuning snap shot

Controller Parameters

	Tuned
Kp	0.0016003
Ki	2380153478.1603
Kd	0
Tf	n/a

Performance and Robustness

	Tuned
Rise time	3.78e-12 seconds
Settling time	2.86e-11 seconds
Overshoot	20.4 %
Peak	1.2
Gain margin	-280 dB @ 2.92e+04 rad/s
Phase margin	63.4 deg @ 3.86e+11 rad/s
Closed-loop stability	Stable

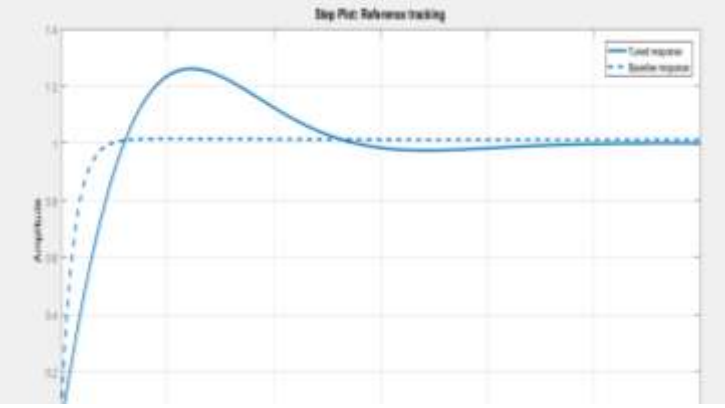

Figure 4: SEPIC DC-DC voltage converter with variable input/load response curve with PI controller trial and error tuning.

The output of the SEPIC converterusing VMC has a lot of ripples as shown on the graph of the output voltage in Figures 5, 6 and 7. The output voltage was between 7.80 to 11.80 V at minimum input voltage of 6 V and between 11.80 to 16.80 V at maximum input voltage.

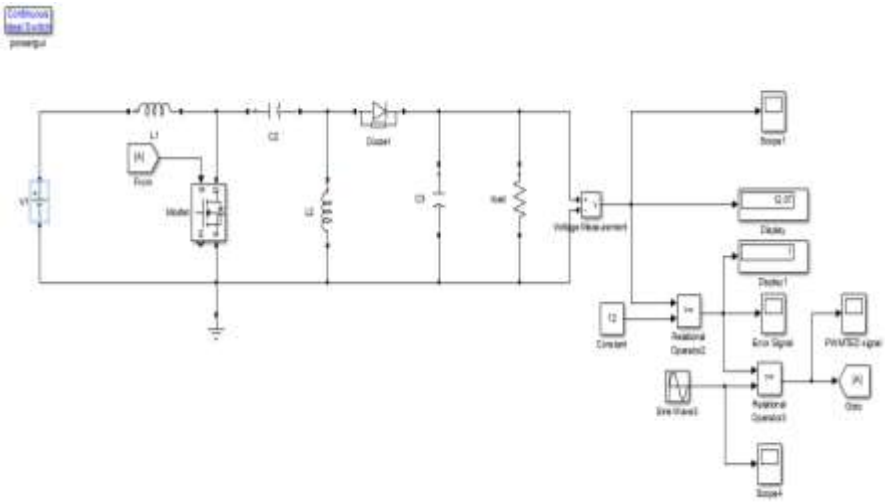

Figure 5: SEPIC VMC simulation diagram under load condition.

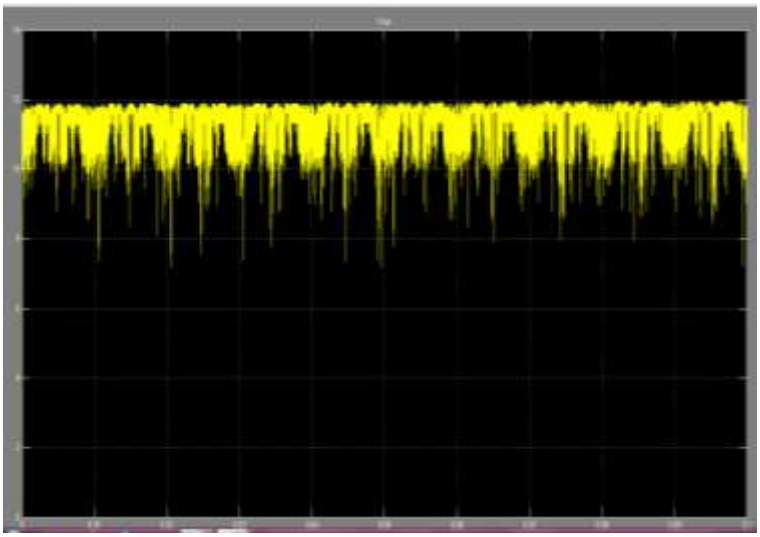

Figure 6: SEPIC VMC output voltage graph under load condition at maximum input voltage

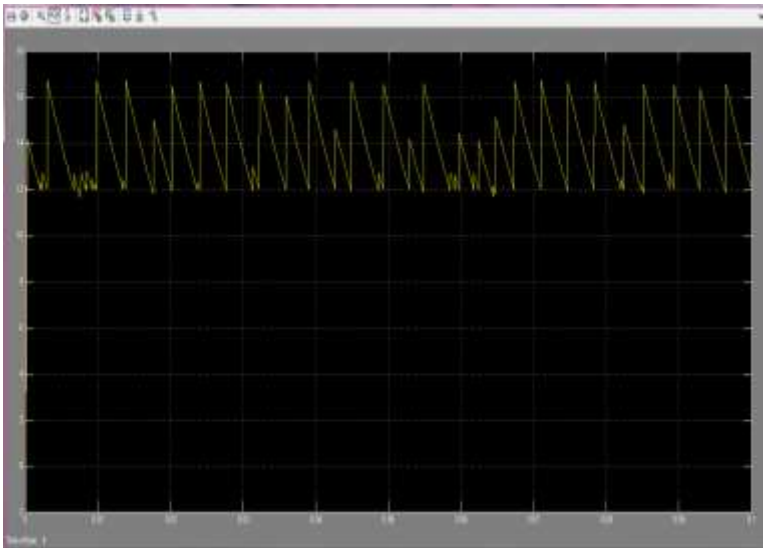

Figure 7: SEPIC VMC output voltage graph under varying input/load condition.

The output voltage SEPIC DC-DC voltage converter using PI controller at minimum and maximum input voltage under no load are as shown on Figures8 and 9. The output voltage under load condition gives 11.98 V and it is almost ripple free. It shows an estimated percentage error range from 0.17 % to 1.41 %, which is within the design limits. In comparison, SEPIC DC-DC voltage converter with PI controller has proven to be more efficient, it has less ripples and settles faster compared to the VMC.

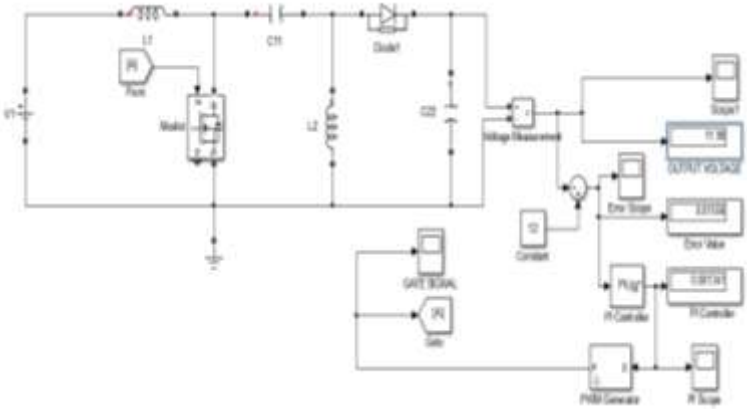

Figure 8: SEPIC converter simulation diagram under no load condition with PI controller

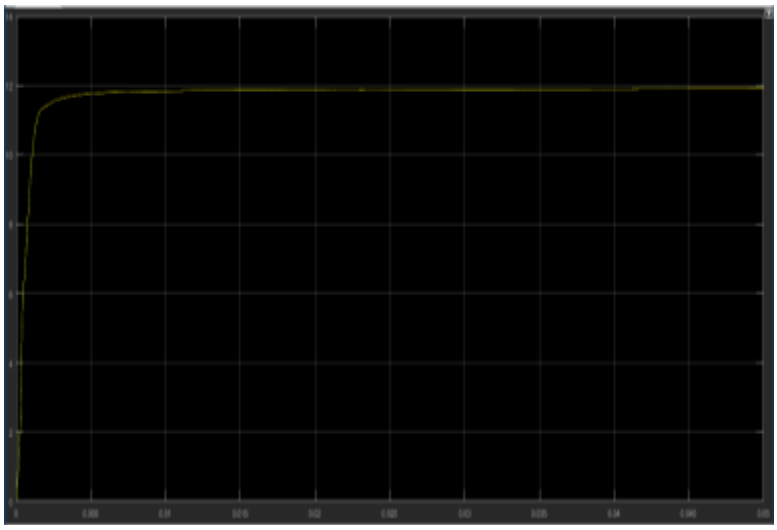

Figure 9: The Graph of the SEPIC on load using PI controller under variable input.

IV. CONCLUSION

This paper has established that SEPIC DC-DC voltage converter with PI controller has proven to be more efficient, it has less ripples and settles faster compared to the VMC.The results from SEPIC output have confirmed the assertion on its excellent filtering properties when reasonable amount of gain is used, hence its preference as converter of choice for DC-DC conversion.The response time and smooth filtering properties of the SEPIC converter equally agree with publications of Zhao and Kaminski, 2009. Furthermore, if the SEPIC DC-DC voltage converter using VMC is use to power any electronic device, the ripples on the power supply will result in overheating.

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