Design of ZVS Resonant SEPIC Converter for High Frequency Applications

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Abstract—This paper presents a resonant SEPIC (Single-Ended Primary Inductor Converter) Converter and Control method suitable for Very High Frequency dc-de Power Conversion. SEPIC is chosen since it has positive voltage gain and higher characteristics than any other converter. The proposed design provides high efficiency over a wide range of input and output voltage ranges, up & down voltage conversion, small size and excellent transient performance. The Converter regulates the output using an ON-OFF control scheme modulating at a fixed frequency and duty ratio operation. This control method enables a fast transient response and efficient light-load operation while providing controlled spectral characteristics of input and Output waveforms. The resonant inductors and capacitors are fine tuned to achieve Zero Voltage Switching (ZVS) condition and thus the converter achieves higher than 80% efficiency across entire input voltage range at nominal output voltage and maintains good efficiency across the whole operating range.

Keywords—SEPIC Converter, ON-OFF control strategy, PID Controller, Zero Voltage Switching.

I. INTRODUCTION

Probably most of the electronic applications could benefit from a Power Converter and it is capable to achieve high efficiency across wide input and voltage ranges at a small size. Although it is difficult for many conventional power converter design to provide wide operation range while maintaining high efficiency, especially if both up & down voltage conversion is to be achieved[2]-[4]. Furthermore, High energy storage required at contemporary switching frequencies of a few megahertz and below, limits the degree of Contraction that can be achieved and obstructs fast transient response. Therefore, design methods that reduce energy storage requirements and expand efficient operation range are desirable. In this paper, we exploit the use of resonant switching along with fixed frequency control techniques to achieve these goals.

DC – DC converters are used in power supply circuits for stabilizing the voltage to any desired value. [1] SEPIC (Single Ended Primary Inductor Converter) converter is a fourth-order nonlinear system and it is extensively used in step-down or step-up dc-de switching circuits and PFC (Power Factor Correction) circuits because it has several characteristics: 1) The same polarity between input and output voltage; 2) Small input ripple current; 3) Step-down and Step-up operation; 4) Easily extended to multiple-output.

Power electronic circuits are rich in nonlinear dynamics. Their operation is characterized by cyclic switching of circuit topologies, which gives rise to a variety of nonlinear behaviour.

This paper introduces a quasi-resonant single-ended primary inductor converter (SEPIC) converter [1], [7] resonant switching and associated control method suitable for converter design at frequencies above 2MHz. Unlike many resonant converter designs the proposed approach provides high efficiency over very wide input and output voltage ranges and power levels. It also provides up-and-down conversion, and requires little energy storage which allows for tremendous transient response. Unlike conventional quasi-resonant and multiresonant converters no bulk inductor which reduces the Electro Magnetic Interference and the converter operates at fixed frequency and duty ratio. These aspects reduce passive component size & progress response speed. A new fixed-frequency ON/OFF control is introduced which provides good control over input and output frequency content. Section II presents the Design of SEPIC Converter and discusses its mode. Modeling of Converter and tuning of the controller are explained in detail in Section III, followed by the discussion of Soft Switching in Section IV. Section V presents the design and experiment result and Conclusion is presented in Section VI.

II. DESIGN OF SEPIC CONVERTER

A Single Ended Primary Inductor Converter (SEPIC) is a dc – dc converter, whose output voltage can be controlled by the duty cycle of the switching device. The circuit diagram of the SEPIC converter is shown in Figure 1. The SEPIC converter consists of a switch (S) with duty cycle D, a diode (D), two inductors (L1 and L2), two capacitors (C1 and C2) and a resistor load (R). For simplicity, R load is used here. As per the application required load can be varied and the response can be obtained. All the elements are assumed to be ideal and assuming the Conduction to be continuous. The equivalent circuits during switch ON and OFF states are...
shown in Figures 2(a) and 2(b) also the design of SEPIC is done.

![Circuit diagram of SEPIC Converter](image)

**Fig.1 Circuit diagram of SEPIC Converter**

When Q turns ON, the energy is stored in the inductor L1. At this time the inductor voltage equals to input voltage, and the energy stored in capacitor C1 will be transferred to inductor L2. The load is supplied by capacitor C2 as shown in Fig. 2(a).

![Equivalent circuit of the SEPIC converter when the switch is ON](image)

**Fig.2 (a) Equivalent circuit of the SEPIC converter when the switch is ON.**

Now, Applying KVL,

Considering L1,

\[
\frac{di_{L1}}{dt} = \frac{V_{in} - V_{C1} - V_o}{L_1}
\]

(5)

We know that, \( V_o = V_{C2} \)

\[
i_{L1} = \frac{V_{in} - V_{C1} - V_o}{L_1} T_{off}
\]

(6)

Considering L2,

\[
\frac{di_{L2}}{dt} = \frac{V_{C1}}{L_2}
\]

(7)

\[
i_{L2} = \frac{V_{C1}}{L_2} T_{off}
\]

(8)

Average Voltage across L1 & L2 is Zero. So,

\[
V_{in} - V_{C1} - V_{L1} - V_{L2} = 0.
\]

(9)

\[
V_{in} = V_{C1}
\]

(10)

Equation (6) becomes,

\[
i_{L1} = \frac{-V_o}{L_1} T_{off}
\]

(11)

Averaging the equations (9) & (2) to zero,

\[
\frac{V_{in} T_{on}}{L_1} - \frac{V_o T_{off}}{L_1} = 0
\]

(12)

We Know that,

\[
T_{on} = DT \text{ & } T_{off} = (1 - D)T
\]

By simplifying the above expression we get,

The average output Voltage is

\[
V_0 = \frac{d}{1-D} V_{in}
\]

(13)

For the lossless Circuit,

\[
I_{out} = \frac{1-D}{D} I_{in}
\]

(14)

The peak-to-peak ripple current in the inductor L1,

\[
\Delta I_1 = \frac{V_{in}}{f_s L_1}
\]

(15)

The peak-to-peak ripple current in the inductor L2,

\[
\Delta I_2 = \frac{V_{in}}{f_s L_2}
\]

(16)

As shown in Fig. 2 (b) When Q turns OFF, the energy stored in Inductor L1 is transferred to C1. The energy stored in L2 is transferred to C2 through D1 and supplying the energy to Load.

![Equivalent circuit of the SEPIC converter when the switch is OFF](image)

**Fig.2 (b) Equivalent circuit of the SEPIC converter when the switch is OFF**
According to the variation in duty cycle $D$, this SEPIC converter acts as either buck or boost converter.

III. MODELLING OF SEPIC CONVERTER

Modeling of a particular converter is done by either Circuit Averaging Method or State Space Averaging method. Here State Space Averaging method is used for modeling of SEPIC converter. It is an approximation technique that approximates the switching converter as a continuous linear system. State Space Averaging requires that the effective filter corner frequency $f_c$ smaller than the switching frequency $f_s$. The power stage of closed loop system is a non-linear system. The non-linear systems are usually difficult to model and are also difficult to predict the behaviour of the non-linear system. So, it is better to approximate the non-linear system to a linear system. For the linearized power stage of dc-dc converter Bode plot can be used to determine suitable compensation in feedback loop for desired steady state and transient response. For this the State Space Averaging technique is used.

In dc-dc converter operating in CCM has two circuit states: one when the switch is turned on and other when the switch is turned off.

During switch on: $(0 < t < DT)$

$$\dot{X} = A_1X + B_1V_{in}$$  \hspace{1cm} (17)

During switch off: $(0 < t < (1-D)T)$

$$\dot{X} = A_2X + B_2V_{in}$$  \hspace{1cm} (18)

and the output voltage is

$$V_o = CX + EV_{in}$$  \hspace{1cm} (19)

To produce an average description of the circuit over a switching period, the equations corresponding to the two foregoing states are time weighted and averaged, resulting in the following equations:

$$\dot{X} = [A_1D + A_2(1-D)]X + [B_1D + B_2(1-D)]V_{in}$$  \hspace{1cm} (20)

$$V_o = [C_1D + C_2(1-D)]X + [E_1D + E_2(1-D)]V_{in}$$  \hspace{1cm} (21)

Where $D$ is the duty cycle of the switch. This equation shows that by controlling the duty cycle of the switch the output voltage $V_o$ can be controlled and output voltage can be higher or lower than or equal to the input voltage $V_{in}$. The duty cycle of the SEPIC converter can be varied during operation by using a controller and the circuit can also be made to reject disturbances.

A. State Space Averaging

The state space equations for SEPIC converter during switch on and off are

During switch ON:

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}$$  \hspace{1cm} (22)

$$\frac{dv_{C1}}{dt} = -\frac{i_{L1}}{C_1}$$  \hspace{1cm} (23)

$$\frac{di_{L2}}{dt} = \frac{v_{C1}}{L_2}$$  \hspace{1cm} (24)

$$\frac{dv_{C2}}{dt} = \frac{V_{in}}{L_1}$$  \hspace{1cm} (25)

During Switch OFF:

$$\frac{di_{L1}}{dt} = \frac{v_{C1}}{L_1} - \frac{v_{C2}}{L_2}$$  \hspace{1cm} (26)

$$\frac{dv_{C1}}{dt} = \frac{i_{L1}}{C_1}$$  \hspace{1cm} (27)

$$\frac{di_{L2}}{dt} = -\frac{v_{C2}}{L_2}$$  \hspace{1cm} (28)

$$\frac{dv_{C2}}{dt} = \frac{i_{L2}}{C_2} + \frac{i_{L2}}{C_2} - \frac{v_{C2}}{RC_2}$$  \hspace{1cm} (29)

And states of the SEPIC converter are $i_{L1}, i_{L2}, V_{C1}, V_{C2}$.

The averaged matrices for the steady-state and linear small-signal state-space equations can be written according to above equations.
With the state space matrices defined above, the output to input transfer function is given by,

\[ G_{yy} = C(\tau I - A)^{-1}B \]  

(33)

\[ X = A^{-1}B \ V_{in} \]  

(34)

Where,

\[ A = [A_1D + A_2(1 - D)] \]  

(35)

\[ B = [B_1D + B_2(1 - D)] \]  

(36)

\[ C = [0 \ 0 \ 0 \ 1] \]  

(37)

\[ E = [0] \]  

(38)

After discovering the values of A, B, C & E evaluate them in MATLAB command window to get the transfer function. Compute \( K_p \), \( K_i \) & \( K_d \) parameters to tune the controller.

### C. Controller Tuning

PID controllers use a 3 basic behaviour types or modes: P - Proportional, I - Integrative and D - Derivative. While proportional and integrative modes are also used as single control modes, a derivative mode is rarely used on its own in control systems. Combinations such as PI and PD control are very often in practical systems.

- When P controller is used, large gain is needed to improve steady state error.
- D mode is used when prediction of the error can improve control or to stabilize the system. Sudden change in error signal will cause sudden change in control output.
- PI controller will eliminate forced oscillations and steady state error and introducing integral mode has a negative effect on speed of the response and overall stability of the system.
- PID controller has all the necessary dynamics: fast reaction on change of the controller input (D mode), increase in control signal to lead error towards zero (I mode) and suitable action inside control error area to eliminate oscillations (P mode).
- Derivative mode improves stability of the system and enables increase in gain K and decrease in integral time constant Ti, which increases speed of the controller response. PID controller is often used in industry, but also in the control of mobile objects.

So, in this paper closed loop analysis of SEPIC Converter is done by PID controller since it can be used in dealing with higher order capacitive processes. Fig. 4 shows the plant model of the controller which uses PID for execution and also better response will be produced since its higher order controller. For PID tuning various methods have been used, here in this paper Cohen-Coon tuning method is used which is duly used for stiff system.

### D. Cohen-Coon Tuning Method

This technique was proposed by G.H. Cohen and G.A. Coon in 1953. The process output is affected not only by the dynamics of the main process but also by the dynamics of the measuring sensor and final control element. They observed that the response of most processing unit to an input change had a sigmoidal shape and it is shown in Fig. 5.
From the obtained steady state response we have to compute the parameters $K_p$, $K_i$ & $K_d$ using these expressions given below.

\[
G_{fpw} = \frac{PV_m}{CO} = \frac{K e^{-T_d}}{\tau s + 1},
\]

where
\[
K = \frac{B}{A}
\]

\[
\tau = \frac{B}{S}, \quad S \text{ is the slope of the sigmoidal response at the point of inflection}
\]

\[
T_d = \text{time elapsed until the system responded}
\]

The Transfer function of PID controller is given by:

\[
G(s) = K_p \left( 1 + \frac{T_d s}{\tau} + \frac{1}{T_i s} \right)
\]

Where,
- $K_p$ = Proportional gain.
- $T_i$ = Derivative time constant.
- $T_d$ = Integral time constant.
- $K = \text{the output steady state divided by the input step change,}$
- $\tau = \text{the effective time constant of the first order response,}$
- $T_d = \text{the dead time (time elapsed until the system responded).}$

By this method initial tuning is done and to get a well-tuned controller output fine tuning must be done manually.

IV. SOFT SWITCHING OF CONVERTER

Conventional PWM power converters were operated in a switched mode operation. There are two types of switching namely,

a. Hard Switching
b. Soft Switching

Hard switching refers to stressful switching behaviour of the power electronic devices. During the turn-on and turn-off processes, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stress. Capacitive snubbers are used to limit the stress.

However; the switching loss is proportional to the switching frequency, thus limiting the maximum switching frequency of the power converters.

In order to reduce the switching loss soft-switching techniques are used (i.e.) Resonant converter is incorporated. Two techniques namely ZVS (Zero Voltage Switching) and ZCS (Zero Current Switching) are used for Turn-on and Turn-off transition of the switch. Tank circuits (L&C) are tuned to obtain these switching which results in increase in switching frequency of the converter, continuous improvement of the switch and reduction in switching loss gradually increase the efficiency of the converter.

A. Proposed Soft Switching Technique

In this paper (Zero Voltage switching) ZVS condition is obtained (i.e.) during Turn-on Transition of the switch. This proposed resonant SEPIC converter is the combination of both quasi resonant SEPIC and Multiresonant SEPIC converter. Multi resonant uses bulk inductors, introduces capacitance in parallel with switch and diode, quasi resonant uses choke inductor $L_f$ along with coupling capacitor $C_s$ to achieve ZVS condition. Combination as Quasiresonant and multi resonant technique ensures fixed frequency and duty ratio operation eliminates the bulk magnetic component and enables ZVS which increases the efficiency of the converter. The proposed Resonant SEPIC converter is shown in Fig.6. In this new resonant SEPIC converter no bulk inductor is used, two resonant inductors and capacitors used namely,

\[
L_{r1} \text{ and } C_{r1}
\]

\[
L_{r2} \text{ and } C_{r2}
\]

\[
L_{r1} = \frac{1}{16\pi^2 f_{SW} C_{r1}}
\]

Fig.6 Proposed Resonant SEPIC converter

Resonant inductor $L_r$ and Capacitance $C_f$ and $C_{EX2}$ are tuned approximately to deliver the output. First design the open loop SEPIC converter and find the parameters after that for achieving resonant condition introduce capacitance in parallel with diode and switch.

V. EXPERIMENTAL RESULTS

In order to verify the proposed topology of the resonating switching of the SEPIC converter the experimental results have been analyzed by open loop and closed loop model of SEPIC converter and by the comparative analysis of Conventional and proposed SEPIC. For Closed loop model
PID controller parameters have been calculated using Cohen-Coon Technique explained in (Section III.D). The experimental simulation have been done by MATLAB software and been verified with the results. The parameters are taken as $V_{in}$ or $V_{dc}=3.6V$; $L_1=L_2=64.89\mu H$, $C_1=10\mu F$; $C_2=39.144nF$; $D_{max}=0.56$.

For resonant SEPIC inductors the parameters $L_{r1}=L_{r2}=64.89\mu H$ and resonant Capacitors $C_{r1}=3.8pF$; $C_{r2}=20nF$; $C_S=10\mu F$ and it is well tuned for better response.

A. Open Loop Model for SEPIC Converter

B. Closed Loop Model for SEPIC Converter
C. Proposed Resonant SEPIC Converter Model

11. Simulink model for proposed resonant SEPIC converter model

D. Comparative Efficiency Analysis of SEPIC Converter

Fig. 13 Comparative Efficiency analysis of SEPIC Converter

From the above experimental results we examine the response of SEPIC converter for Open loop analysis in Fig.8, Closed loop analysis in Fig.10 and the proposed resonant SEPIC analysis in Fig.12. Also the comparative efficiency analysis had been done and verified through the graph shown in Fig.13. The graph implies that resonant SEPIC have higher efficiency compared to conventional SEPIC due to Zero Voltage Switching condition achieved in it. It is obtained by tuning the resonant circuit includes inductors (L_{r1} & L_{r2}) and Capacitors (C_{r1} & C_{r2}) as shown in Fig.6.

VI. CONCLUSION

This work presents a resonant SEPIC converter suitable for extremely high-frequency operation and for operating across a wide input and output voltage range. Here we experimentally set up a SEPIC converter with switching frequency 5MHz. Its input voltage ranges from 3.6V to 7.2 V and its output voltage ranges from 3V to 9V. Its rated power is 3W. This work uses an ON-OFF control with fixed frequency. It is possible for resonant SEPIC converters to achieve a wide operating range, a small size, and excellent transient response while maintaining good efficiency. It provides fast transient response and good control over wide input and output ranges. In this we can eliminate the bulk magnetic components and facilitates high efficient resonant Gating. Soft switching can be achieved for a wide input and output voltage ranges.

Unlike conventional quasi- resonant and multi resonant converters no bulk inductor is used and the converter operates at fixed frequency and duty ratio. These attributes reduce passive component size, improve response speed, and enable the use of low-loss sinusoidal resonant gating. It is hoped that these techniques will contribute to future development of low-power converters operating over wide ranges and extreme high frequencies to meet the increasing demands of modern portable electronics.
REFERENCES


