ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

IJIRSET

International Journal of Innovative Research in Science, Engineering and Technology

Volume 3, Special Issue 3, March 2014

2014 International Conference on Innovations in Engineering and Technology (ICIET'14)
On 21st & 22nd March Organized by

K.L.N. College of Engineering, Madurai, Tamil Nadu, India

Design and Modeling 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 forVery High Frequency dc-dc 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 output 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 fewmegahertz 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 switchingalong with fixed frequency control techniques to achieve these goals.

DC-DC converters are used in power supply circuits forstabilizing 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-dc 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 converterand discusses its mode. Modelingof converterand 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 simulation 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 Fig. 1. The SEPIC converter consists of a switch (S) with duty cycle d, a diode (D1), two inductors (L_1 and L_2), two capacitors (C_1 and C_2) 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

Fig. 2(a) and Fig. 2(b) also the design of SEPIC is done.

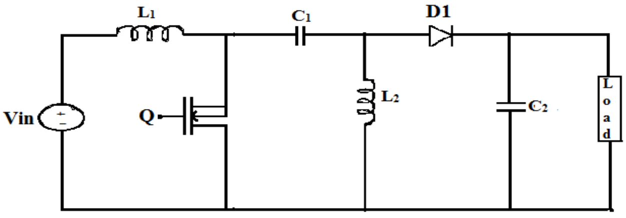

Fig.1 Circuit diagram of SEPIC Converter

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).

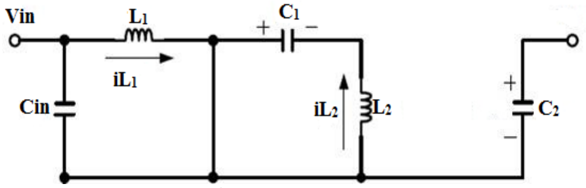

Fig.2 (a) Equivalent circuit of the SEPIC converter when the switch is ON.

Applying KVL,

Considering $L_{1,}$

$$i_{L1} = \frac{V_{in}}{L_1}T_{on} \quad (1)$$

Considering $L_{2,}$

$$i_{L2} = \frac{V_{C1}}{L_2}T_{on} \quad (2)$$

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

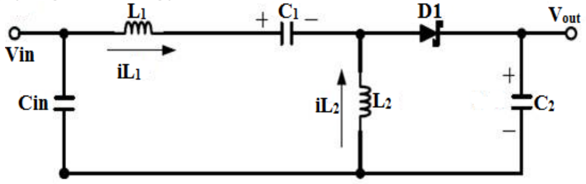

Fig.2 (b) Equivalent circuit of the SEPIC converter when the switch is OFF

Applying KVL,
Considering $L_{1,}$
We know that, V_0=V_{C2}

$$i_{L1} = \frac{V_{in} - V_{C1} - V_o}{L_1}T_{off} \, (3)$$

Considering $L_{2,}$

$$i_{L2} = \frac{-V_o}{L_2}T_{off} \quad (4)$$

Average Voltage across L_1& L_2 is Zero. So,

$$V_{in} - V_{C1} - V_{L1} - V_{L2} = 0. \quad (5)$$

$$V_{in} = V_{c1} \, (6)$$

Equation (6) becomes,

$$i_{L1} = \frac{-V_o}{L_1}T_{off} \quad (7)$$

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

$$\frac{V_{in}}{L_1}T_{on} - \frac{V_o}{L_1}T_{off} = 0 \quad (8)$$

We Know that,

$T_{on} = dT$ and $T_{off} = (1-d)T$

By simplifying the above expression we get,
The average output Voltage is

$$V_0 = \frac{d}{1-d}V_{in} \, (9)$$

For the lossless Circuit,

$$I_{out} = \frac{1-d}{d}I_{in} \, (10)$$

The peak-to-peak ripple current in the inductor L_1 & L_2

$$\Delta I_{L1\&L2} = \frac{V_{in} * d}{f_s * L_1} \, (11)$$

According to the variation in duty cycle d, this SEPIC converter acts as either buck or boost converter.

III. MODELING 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 thatapproximates 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 topredict 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-dcconverter Bode plot can be used to determine suitablecompensation in feedback loop for desired steadystate and transient response. For this the State SpaceAveraging 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:$(0 < t < dT)$

$\dot{X} = A_1X + B_1V_{in}$(12)

During switch off:$(0 < t < (1-\mathrm{d})\mathrm{T})$

$\dot{X} = A_2X + B_2$(13)

and the output voltage is

$V_o = CX + EV_{in}$(14)

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

$\dot{X} = [A_1d + A_2(1-d)]X + [B_1d + B_2(1-d)]V_{in}$(15)

Where,

'd' is the duty cycle of the switch.

$\dot{X}$ is the electric charge.

A is thesystem matrix of the converter

B is the input matrix of the converter

C is the Output matrix of the converter.

E is the direct transmission matrix of the converter

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 high or low 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 of Conventional SEPIC Converter*

The state space equations for SEPIC converter during switch ON and OFF are

During switch ON:

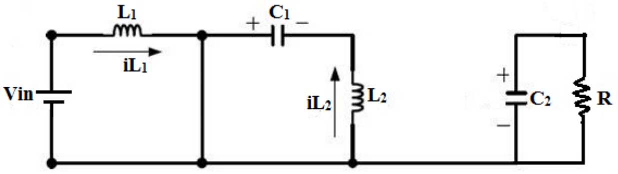

Fig.3 (a) State Space equivalent circuit of SEPIC during switch ON

$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}$(16)

$\frac{dV_{C1}}{dt} = -\frac{i_{L2}}{C_1}$(17)

$\frac{di_{L2}}{dt} = \frac{V_{C1}}{L_2}$(18)

$\frac{dV_{C2}}{dt} = -\frac{V_{C2}}{RC_2}$(19)

During Switch OFF:

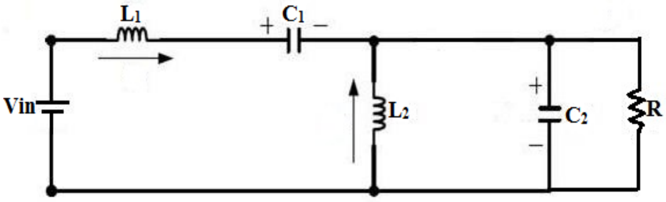

Fig.3 (b) State Space equivalent circuit of SEPIC during switch OFF

$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1} - \frac{V_{C1}}{L_1} - \frac{V_{C2}}{L_1}$(20)

$\frac{dV_{C1}}{dt} = \frac{iL_1}{C_1}$(21)

$\frac{di_{L2}}{dt} = -\frac{V_{C2}}{L_2}$(22)

$\frac{dV_{C2}}{dt} = \frac{i_{L1}}{C_2} + \frac{i_{L2}}{C_2} - \frac{V_{C2}}{RC_2}$(23)

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.

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{C_1} & 0 \\ 0 & -\frac{1}{L_2} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{RC_2} \end{bmatrix} (24)$$

$$A_2 = \begin{bmatrix} 0 & -\frac{1}{L_1} & 0 & -\frac{1}{L_1} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_2} & 0 & \frac{1}{C_2} & -\frac{1}{RC_2} \end{bmatrix} (25)$$

$$B_1 = B_2 = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} (26)$$

B. *State Space Averaging of Proposed SEPIC Converter*

The state space equations for SEPIC converter during switch ON and OFF are

During switch ON:

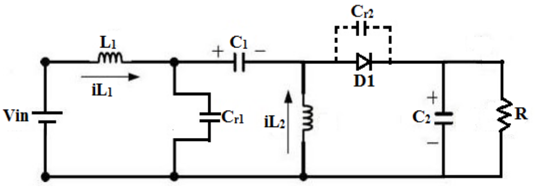

Fig. 4(a) State Space equivalent circuit of SEPIC during switch OFF

$$\frac{di_{L1}}{dt}=\frac{V_{in}}{L_1}\quad(27)$$

$$\frac{dV_{C1}}{dt}=-\frac{i_{L2}}{C_1}\quad(28)$$

$$\frac{di_{L2}}{dt}=\frac{V_{C1}}{L_2}\quad(29)$$

$$\frac{dV_{C2}}{dt}=-\frac{V_{C2}}{RC_2}\quad(30)$$

$$\frac{dV_{cr1}}{dt}=0\quad(31)$$

$$\frac{dV_{cr2}}{dt}=\frac{iL_2}{C_{r2}}\quad(32)$$

During switch OFF:

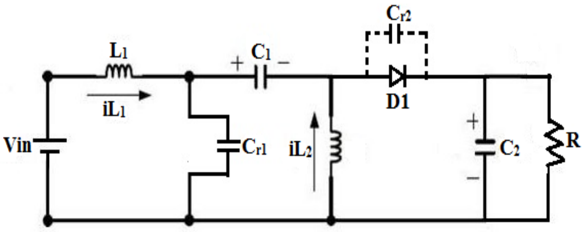

Fig. 4(b) State Space equivalent circuit of SEPIC during switch OFF

$$\frac{di_{L1}}{dt}=\frac{V_{in}}{L_1}-\frac{V_{cr1}}{L_1}\quad(33)$$

$$\frac{dV_{C1}}{dt}=-\frac{i_{L2}}{C_1}\quad(34)$$

$$\frac{di_{L2}}{dt}=-\frac{V_{C1}}{L_2}\quad(35)$$

$$\frac{dV_{C2}}{dt}=\frac{i_{L1}}{C_2}+\frac{i_{L2}}{C_2}-\frac{V_{C2}}{RC_2}\quad(36)$$

$$\frac{dV_{cr1}}{dt}=-\frac{iL_1}{C_{r2}}\quad(37)$$

$$\frac{dV_{cr1}}{dt}=0\quad(38)$$

i_{L1}, i_{L2}, V_{C1}, V_{C2}, V_{Cr1}, V_{Cr2} are the state variables of SEPIC converter. The averaged matrices for the steady-state and linear small-signal state-space equations can be written according to above equations.

$$A_1=\begin{bmatrix}0&0&0&0&0&0\\0&0&-\frac{1}{C_1}&0&0&0\\0&-\frac{1}{L_2}&0&0&0&0\\0&0&\frac{1}{C_2}&-\frac{1}{RC_2}&0&0\\0&0&0&0&0&0\\0&0&0&\frac{1}{C_{r2}}&0&0\end{bmatrix}\quad(39)$$

$$A_2=\begin{bmatrix}0&0&0&0&-\frac{1}{L_1}&0\\0&0&-\frac{1}{C_1}&0&0&0\\0&0&0&-\frac{1}{L_2}&0&0\\\frac{1}{C_2}&0&\frac{1}{C_2}&-\frac{1}{RC_2}&0&0\\-\frac{1}{C_{r1}}&0&0&0&0&0\\0&0&0&0&0&0\end{bmatrix}\quad(40)$$

$$B_1=B_2=\begin{bmatrix}\frac{1}{L_1}\\0\\0\\0\\0\\0\end{bmatrix}\quad(41)$$

C. Transfer Function Evaluation

With the state space matrices defined above, the transfer function is given by,

$$G_{vv}=C(SI-A)^{-1}B\quad(42)$$

$$X=A^{-1}B\,V_{in}\quad(43)$$

Where,

$$A=[A_1d+A_2(1-d)]\quad(44)$$

$$B=[B_1d+B_2(1-d)]$$

$$C=[0\quad 0\quad 0\quad 1]\quad(45)$$

For Conventional SEPIC
and

$$C=[0\quad 0\quad 0\quad 0\quad 0\quad 1]$$

(46)
for Proposed resonant SEPIC

$$E=[0]\quad(47)$$

After discovering the values of A, B, C & E evaluate them toobtain the transfer function. Compute K_p, Ki&K_d parameters to tune the controller.
Where,
G_{vv} – Transfer function.

K_p- Proportional gain; of the controller.
K_i – Integral gainof the controller.
K_d- Derivative gain; of the controller.

D. Controller Tuning

PID controllers use a 3 basic behaviour types or modes:

P - Proportional, I - Integral and D - Derivative. While proportional and integral 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.

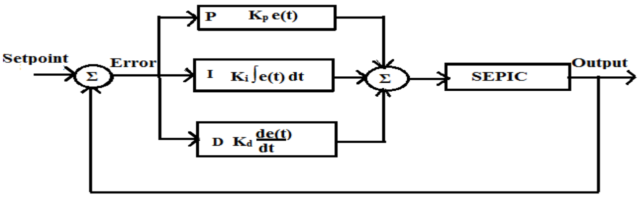

Fig. 5 .Design of PID controller

- 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 modelof 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,paper Cohen-Coon tuning method is used which is duly used for stiff system.

E. Cohen-Coon Tuning Method

This technique was proposed by G.H.Cohen and G.A.Coon. 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 changehad a sigmoidal shape and it is shown in Fig.5.

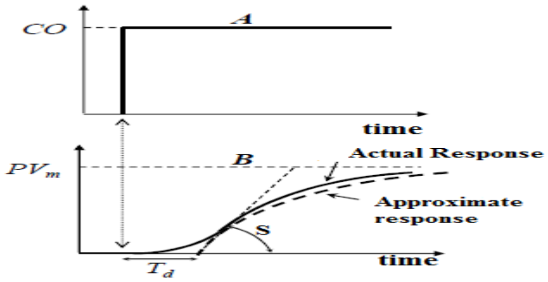

Fig. 6. Cohen-Coon Tuning

Where, the transfer function is given by

$G_{fpm} = \frac{PV_m}{CO} = \frac{Ke^{-T_d s}}{\tau s+1}$ in which

$$K = \frac{B}{A}$$

$\tau = \frac{B}{S}$, S is the slope of the sigmoidal response of the Inflection.

T_d = Time elapsed until the system responded.

From the obtained steady state response we have to compute the parameters K_p,K_i&K_d using these expressions given below.

$$K_p = \frac{1}{K}\frac{\tau}{T_d}\left[\frac{4}{3} + \frac{T_d}{4\tau}\right] \quad (48)$$

$$T_i = T_d \frac{32+6T_d/\tau}{13+3T_d/\tau} \quad (49)$$

$$T_D = T_d \frac{4}{11+2T_d/\tau} \quad (50)$$

The Transfer function of PID controller is given by:

$$G(s) = K_p\left(1 + T_D s + \frac{1}{T_i s}\right) \quad (51)$$

Where,
K_p = Proportional gain.
T_D = Derivative time constant.
T_i = Integral Time Constant.
K = the output steady state divided by the input step change,
τ = the effective time constant of the first order response,
T_d = the dead time(time elapsed until thesystem responded).

By this above mentioned method initial tuning was done and to get a well-tuned controller output, fine tuning must be done manually as a further progress.

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 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_{r1} along with coupling capacitor C_s to achieve ZVS condition. Combination as Quasiresonant and multi resonant technique ensures fixed frequency and duty ratio operation which 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,

a. L_{r1} and C_{r1}
b. L_{r2} and C_{r2}

$$L_{r1} = \frac{1}{16\pi^2 f_{sw}^2 C_{r1}} \quad (52)$$

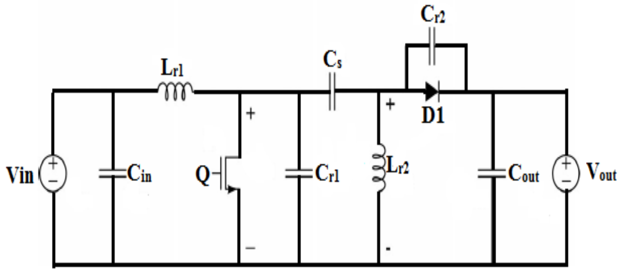

Fig.7 Proposed Resonant SEPIC converter

Resonant inductor L_{r2} and Capacitance C_{r1} and C_{r2} are tuned approximately to deliver the output. First, design the open loop SEPIC converter and find all the parameters required. Further for achieving resonant condition introduce capacitance in parallel with diode and switch and tune them particularly to get a specified output.

V. SIMULATION RESULTS

` In order to verify the proposed topology of the resonant switching of the SEPIC converter the simulation results have been analyzed by open loop and closed loop model of SEPIC converter and also 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 simulations have been done by MATLAB/Simulink.The parameters are

For Conventional SEPIC:

V_{in} or V_{dc} =3.6V, L1=L_2=64.89μH,

C_1=10μF, C_2=39.144nF, D_{max} =56%.

For resonant SEPIC:

L_{r1}=L_{r2}= 64.89μH, C_{r1}= 3.8pF; C_{r2}=20nF, C_S=10μF and it is well tuned for better response.

A. *Open LoopModelfor SEPIC Converter*

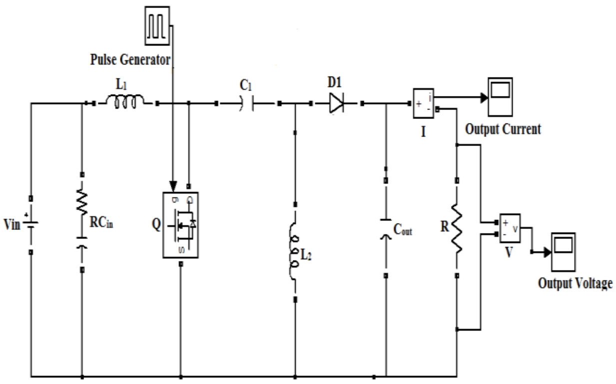

Fig.8 Simulink model for open loop of SEPIC converter

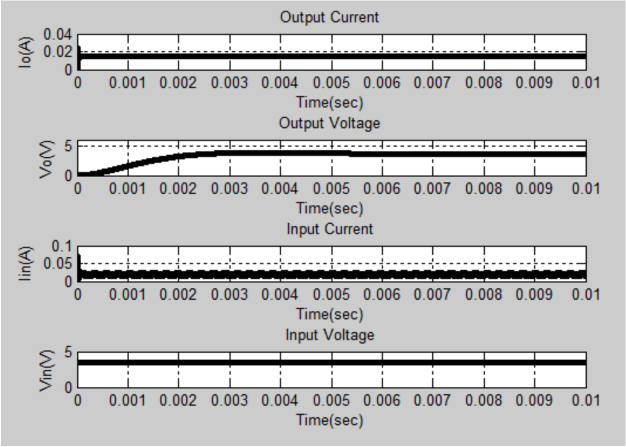

Fig. 9 Simulation result for open loop SEPIC converter

B. Closed Loop Modelfor SEPIC Converter

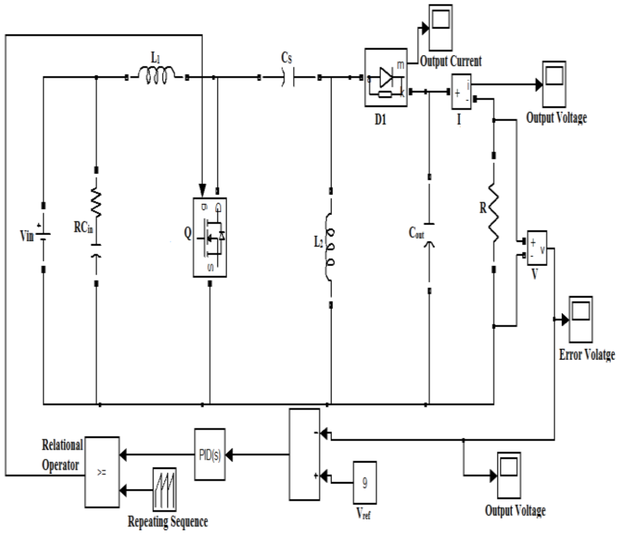

Fig.10 Simulink model for closed loop model for SEPIC converter

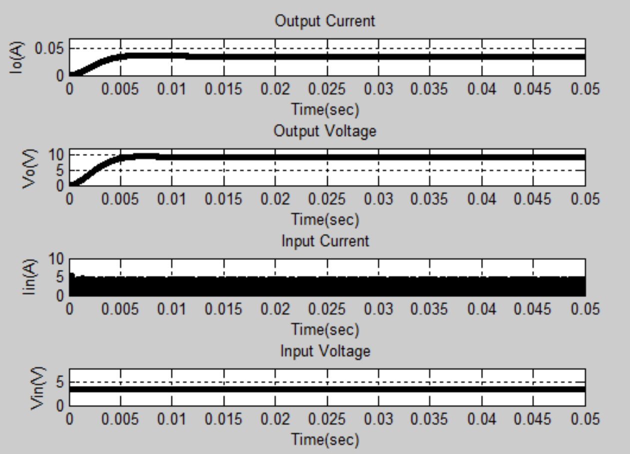

Fig.11 Simulation result for closed loop of SEPIC converter using PID control

C. Proposed Resonant SEPIC Converter Model

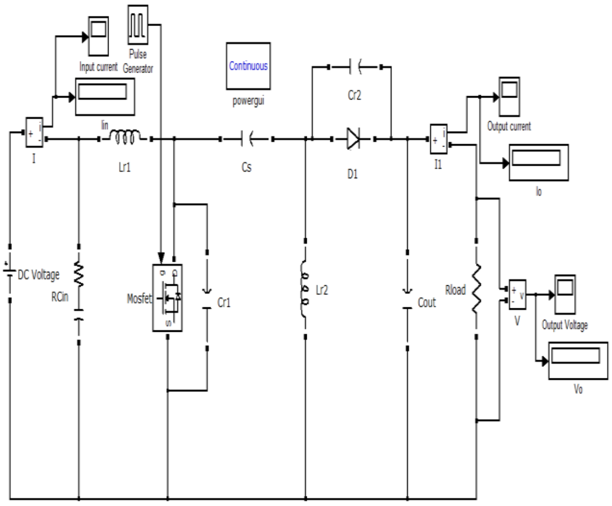

Fig. 12 Simulink model for proposed resonant SEPIC converter model

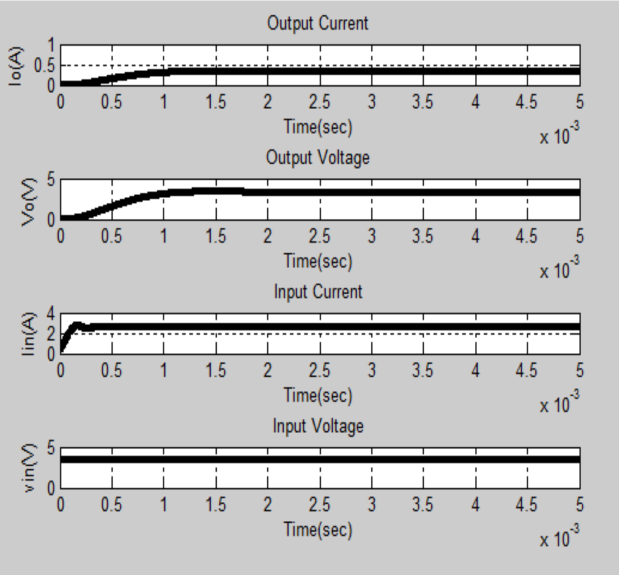

Fig.13 Simulation result for proposed resonant SEPIC converter

D. Proposed Closed loop ofResonant SEPIC converter

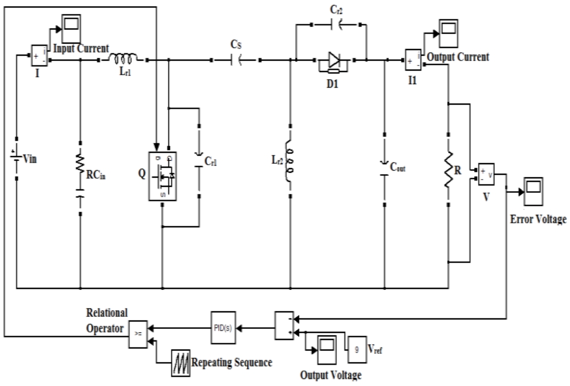

Fig. 14 Simulink model for proposed closed loop resonant SEPIC converter model

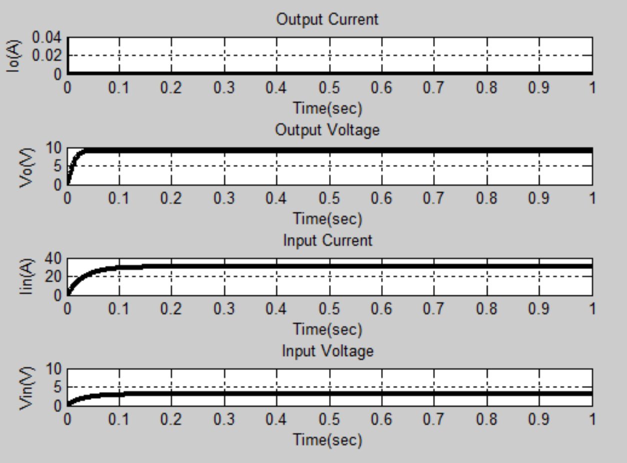

Fig.15 Simulation result for proposed resonant SEPIC converter

E. Comparative Efficiency Analysisof SEPIC Converter

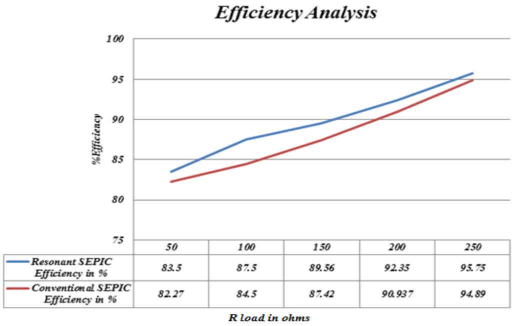

Fig.16Comparative Efficiency analysis of SEPIC Converter

From the abovesimulation 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 resonantSEPIC 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. The variations are compared as shown in Table1.

Table1: Comparison between Conventional and Proposed SEPIC Converter

Transient response Specification	Conventional SEPIC	Proposed Resonant SEPIC
Rise Time(t_r)	0.0025 S	0.00089 S
Peak Time(t_p)	0.0035 S	0.0015 S
Settling Time(t_s)	0.0063 S	0.0019 S
Delay Time (t_d)	0.0015 S	0.0010 S
Maximum Peak overshoot(M_p)	5.12%	2.15%

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 MHz.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.

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