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SIMULATION OF CLOSED LOOP VOLTAGE CONTROL OF SEPIC CONVERTER

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Abstract— **In this study, a robust output SEPIC DC-DC converter is designed and simulated. The studied single ended primary inductor converter (SEPIC) output voltage is regulated to a constant value regardless of its input. A double loop PI controller is designed and tuned for the voltage and current control which yields a control technique that results in simple implementation by reducing complexity. The multiloop control technique is used to improve converter behavior in case of wide system parameter variations. The controller parameters and design procedure are provided for the SEPIC converter for non zero current operation mode. The proposed implementation of the controlled SEPIC converter has been simulated in Matlab/Simulink environment. The simulations have been done with various operating conditions. Results show that the PI-controlled SEPIC rejects the disturbances and provides good tracking performance.**

Keywords— **DC-DC converter, multiloop control, PI control, SEPIC converter**

I. INTRODUCTION

DC-DC converters have a spread use of industrial application areas such as motor drives, computer peripherals, communication devices, switch mode power supplies, medical equipment, etc.

DC-DC converter changes its dc input voltage to a dc output voltage at another level. Lots of study in this field has produced different converter topologies [1].

SEPIC is one of these DC-DC converters and is used in applications where a wide range of input voltage is required such as electrical vehicles, UPS, medical and telecom devices, etc. [2].

It has unique features among the DC-DC converters that the converter can produce an output voltage that is either greater than, equal to, or less than the input supply voltage without change of polarity. It has a nonlinear output characteristic. Its nonlinearity resulting from repeated switching cause SEPIC to have complex dynamic behavior.

Converter circuits require control arrangements to have an accurate tracking performance and quick response with high precision. Closed loop control structures [3] are employed to converters for better performance including transient and steady state regimes because of the inherent capability of the feedback control system that its parameters can be adjusted to change its transient and steady state behavior [4]. Lots of research works have been done for control converters. Besides the traditional control algorithms, modern technologies have been also used in the control of DC-DC converters. Most popular of these techniques include fuzzy logic control [5,6], sliding mode control [7-9], and the combination of these two, fuzzy sliding mode control [10-11]. Artificial neural network [12-13]. Control of the DC-DC converters needs to provide stability in all operating conditions. Good steady state and transient responses insensitive to load, input, and parameter change are also required for a control method.

Despite the modern controllers, the traditional controllers (PID, PI) are widely in use with simplicity in the closed loop control systems [14-15]. One of the most commonly used conventional controllers for the control of DC-DC converters is the proportional-integral PI controller [16]. The basic aim behind the use of PI controller is to obtain a good voltage regulation in the case of parameter variation and external disturbances [17].

As it is the fact that a PI controller is simple and presents a good dynamic response [18], it is one of the control methods for DC-DC converters [19]. Therefore, a double loop [20] PI controlled SEPIC converter operated in continuous conduction mode (CCM) is studied in this paper to have a good static and dynamic performance operating with input, load, and component value changes.

Double loop control can be used with the converters which have right half plane zero, as in the cases of boost and buck–boost converters [21].

The performance of the SEPIC is presented in terms of output voltage regulation under different operating conditions such as startup transients, input voltage variations, load variations and steady state conditions.

II. METHODS

A SEPIC converter whose circuit diagram is given in Fig. 1, has a dc voltage source V_i, two inductors L_1 and L_2, two capacitors C_1 and C_2, an IGBT switch, a diode and a load resistance.

The dynamics of the SEPIC converter can be mathematically modeled by fourth-order differential equations due to the inclusion of two inductors and two capacitors in its circuit diagram. Its dynamic behavior can be represented by four first order differential equations dependent on each other in state space model.

The input and output relationship can be obtained by the switch ON and OFF states assuming ideal components and CCM which assumes the inductor currents never be zero. The two stages of the operation are when the switch is ON the diode is OFF and when the switch is OFF the diode becomes ON.

The equivalent circuits of the SEPIC converter corresponding to the operation modes that are ON and OFF states of the switch are given in Fig. 2.

When the switch is closed the diode becomes nonconducting, the energy is transferred from the supply to the inductor L_1, the voltage across this inductor is equal to the supply voltage, while the stored energy in the coupling capacitor C_1 is transferred to the output inductor L_2. The energy stored by the output capacitor; C_2 is used to feed the load.

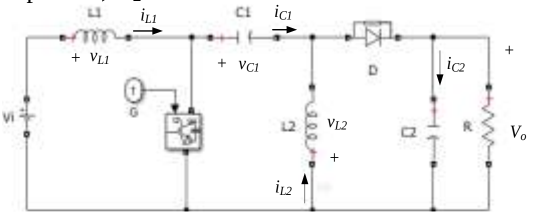

Fig. 1. A SEPIC converter circuit diagram

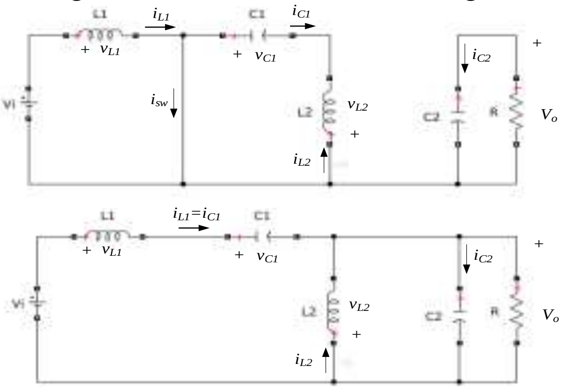

Fig. 2. Circuit with switch ON and OFF states

When the switch S is OFF, the diode is ON. The energy stored in the inductor L_1 and L_2 is transferred to C_1 and L_2 discharges through the capacitor C_1 and, C_2. Capacitor C_1 is get charged. The diode D is forward biased and the input voltage is directly transferred to the load. The corresponding waveforms of current through and the voltage across each element are shown in Fig. 3.

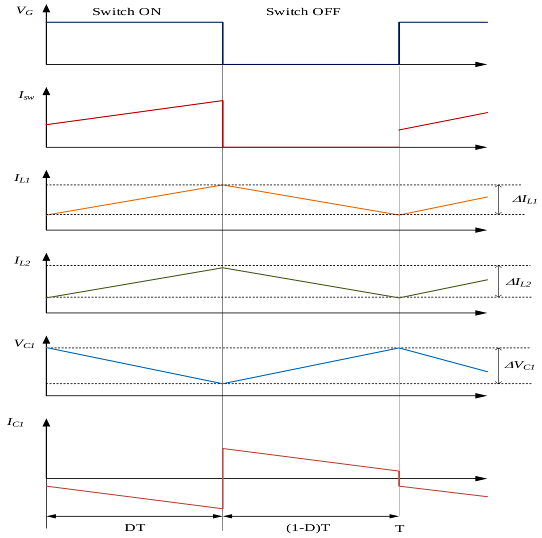

Fig. 3. Current and voltage waveforms of SEPIC components

In continuous conduction mode, some energy remains in the inductors causing currents not to be zero in the inductors. As the input inductor is always in series with the input supply during switch ON and OFF, the input current ripple becomes low.

A. Design of SEPIC Converter –

The design of SEPIC converter parameters is made by assuming continuous conduction mode. In this mode inductor current is not allowed to fall zero. Using Kirchhoff's voltage law for the loop including V_i, L_1, C_1, and C_2 the following equation is obtained.

$-V_i+v_{L1}+v_{C1}-v_{L2}=0$ (1)

Assuming average inductor voltages and the average capacitor currents are zero in the steady state operation, voltage across C_1 is

$v_{c1}=V_i$ (2)

When the switch is ON the diode is OFF, the corresponding SEPIC circuit is given in Fig.2 (a). The voltage across L_1 for during the time DT is

$v_{L1}=V_i$ (3)

When the switch is OFF, the diode becomes ON, this time the corresponding circuit is shown in Fig.2 (b). Kirchhoff' s voltage law around the loop is

$-V_i+v_{L1}+v_{C1}+V_o=0$ (4)

The voltage across C_1 does not change and remains at the value when the switch is ON which is V_i, then for the interval (1-D)T

$v_{L1}= -V_0$ (5)

Because the average inductor voltage is zero, by combining Eq. 3 and Eq. 5 the following expression is obtained.

$v_{L1}DT+v_{L1}(1-D)T=0$ (6)

replacing the v_{L1} values for the intervals DT and (1-D)T which are the intervals corresponding to the switch ON and switch OFF times,

$V_iDT-V_o(1-D)T=0$ (7)

The output voltage of the SEPIC converter without incorporating losses due to the parasitic elements such as the diode voltage drop can be expressed as

Vo=D/(1-D)Vi (8)

The value of the inductor L_1 is determined by the allowed input current ripple Δi_{L1}

$L_1=D/(f_{sw}\ \Delta i_{L1})V_i$ (9)

where f_{sw} is the switching frequency of the switch.

The second inductor value L_2 is determined using the permitted output current ripple Δi_{L2}

$L_2=((1-D))/(f_{sw}\Delta i_{L2}))V_0$ (10)

The value of the coupling capacitor C_1 is determined by using input ripple voltage Δv_{C1} and is given by

$C_1=(D/(f_{sw}\Delta v_{C1}))I_i$ (11)

and the output dc-link capacitor value is determined using the output voltage ripple as [22]

$C_2=D/(f_{sw}(\Delta v_{C1}/v_0)R)$ (12)

B. Controller Design –

A PI controller is designed to reach the specified operation of SEPIC. The controller has to regulate the SEPIC output so that it tracks the reference command even in the cases of sudden disturbances, reference variations, line variations, and components variations.

The designed PI controller checks the error between the converter reference and the actual output voltage and corrects the converter operating error to provide the desired system response.

The determination of PI controller parameter values for obtaining the desired system performance from the controlled system is known as tuning. This is the key point of the controller design for closed loop system. Several techniques are used to obtain the PI controller parameters proportional and integral gain constants (KP, KI). These techniques include Zeigler – Nichols tuning method [23-25], root locus method [26-27], and frequency response data [28].

Ziegler-Nichols method uses transient response characteristics of a given control system for tuning PID parameters. The PID controller design using Ziegler-Nichols technique is based on a few linearized transfer function models of the converter operating at a desired equilibrium point. The PID controller parameters are obtained by applying the step test to the step response of the converter.

The root locus technique is a graphical tool which uses the open loop transfer function to find the locus of the roots of the closed loop characteristic equation with variation in the controller gain. A suitable value of the controller gain is then selected from the root locus plot. The closed-loop roots need to be inside the unit circle in order to achieve closed-loop stability. Matlab control system toolbox can be a useful tool to get the root locus plot of a given system. Root locus plot presents the information of dependence of system response on the open loop poles and zeros. This information is used to perform the system performance specifications.

The key to applying the PID control design based on the frequency response data approach is to get the Bode diagram of the system which does not necessitate the mathematical model of the system. The gain and phase margins are used to obtain the controller parameters.

Trial and Error Method:

The trial and error technique is the simple technique of tuning a PID controller. This tuning technique is based on guess-and-check technique. When the effects of the PID parameters are clearly well understood, then this method becomes relatively easy.

The effect of PID parameters on the closed loop control system response is detailed in Table 1.

Table -1 Effect of PID parameters on system response [29].

	K_P	K_I	K_D
Rise Time	Decrease	Decrease	Small Change
Overshoot	Increase	Increase	Decrease
Settling Time	Small Change	Increase	Decrease
Steady State Error	Decrease	Decrease	No Change

In this technique, the proportional control action is taken as a main control, and the integral and derivative actions are used to refine it.

When designing a PID controller for a given system the following steps should be applied to obtain the desired response. First, the open loop response is obtained to see which performance criteria need to be improved. The controller parameter is adjusted with the integral and derivative actions held at a minimum until the desired response is reached. The flowchart given in Fig. 4 summarizes the trial and error tuning method.

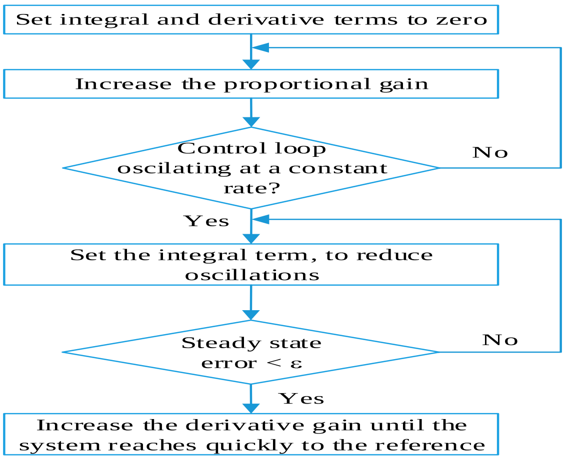

Fig. 4. Flowchart of trial and error method

As seen in the table adding a proportional term improves the rise time, the derivative term reduces the overshoot and the integral term reduces the steady state error. Each of the gains K_P, K_I, and K_D are adjusted until the desired response is obtained.

Using trial and error technique for tuning of the controller parameters should meet system performance specifications and the final controlled system need to be reliable and economical.

The block diagram of a typical PI controller is shown in Fig. 5 and its transfer function is

$$C(s)=K_p+(K_I/s) \quad (13)$$

The signal e(t) is the tracking error resulting from the difference between the given reference and the measured output signal. This error is used as input to the PI controller which produces the integral of the signal at its input. The output of the PI controller u(t) is equal to the sum of proportional gain (K_P) times the error and the integral gain (K_I) times the integral of the error signal. Time domain expression of the signal u(t) applied to the plant is given by

$$u(t)=K_p\, e(t)+K_I \int e(t)dt \quad (14)$$

This control signal is applied to the plant. The plant produces an output voltage with the control signal u(t). This output voltage is again compared with the reference command until the desired level is reached. This repetition forms a closed loop system.

In this study, voltage regulation of SEPIC converter is achieved using PI controller. To improve converter performance, PI controller parameters are tuned using the trial and error method. Using a PI controller with appropriate proportional and integral gains the dynamic response of SEPIC converter is improved and the steady-state error is reduced.

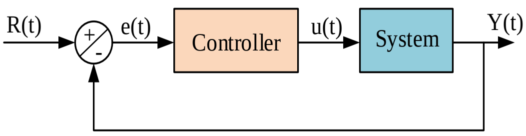

Fig. 5. Block diagram of a controlled system

III. RESULTS AND DISCUSSION

The aim in this study is to regulate the output voltage of a SEPIC that has an invariant dynamic performance under various operating conditions.

A cascade PI control technique is realized to ensure the disturbance rejection and tracking performance. Both the output voltage loop controller and the inner current loop controller are linear PI type controllers.

The system performance is tested for the cases of input voltage variations, load variations, and also components variations.

Simulations have been done on SEPIC converter circuit with parameters tabulated in Table 2.

Table -2 Circuit parameters.

Parameter	Value
L_1 , L_2	325□ H
C_1, C_2	75□ F, 100□ F
f_{sw}	20000Hz
K_{P_V} , K_{P_I}	0.02 , 1
K_{I_V} , K_{I_I}	25 , 100
R	50□

Eq. (9) - Eq. (12) are used to obtain the SEPIC component values. Intensive simulations have been done on SEPIC to determine the PI controller parameters to obtain the desired performance. The system is implemented and simulated in Matlab/Simulink.

Simulink block of the PI controlled SEPIC system is shown in Fig. 6. It is seen that the error between the reference command voltage and measured output voltage of the converter is used as the PI control input for the outer voltage loop.

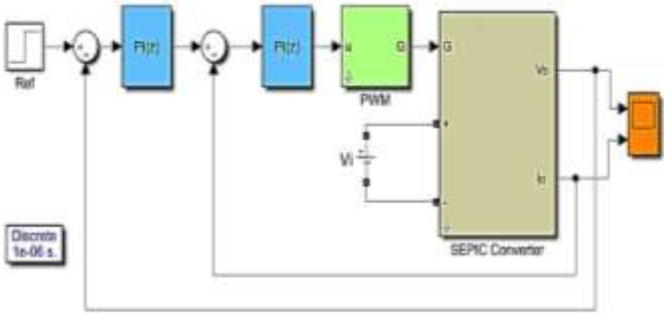

Fig. 6. Simulink block of the controlled SEPIC converter

The output of the voltage controller is taken as a reference current. The error between this reference current and measured converter current is used as input for the current loop controller of PI type. The output of the current controller is used as a switching signal for the power switch.

Figure 7 presents the output voltage of SEPIC in the transient region. The input voltage is 10V and the reference voltage is 12V. It can be seen that the converter output voltage has a small overshoot and settled at the time of 0.02s.

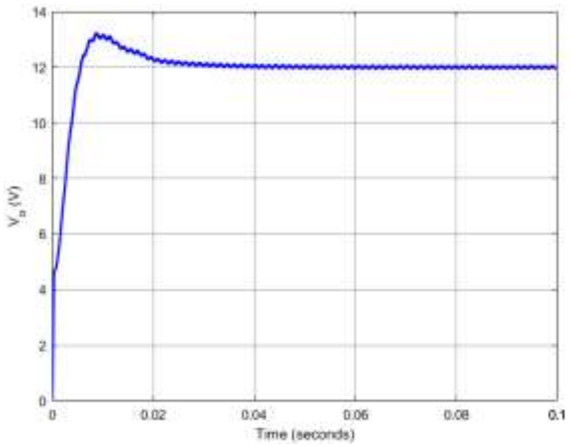

Fig. 7. Output voltage

The variation of output voltage and current waveforms in case of step changes in the input voltage from 12V to 15V at t=0.05s and from 15V to 8V at t=0.1s. is shown in Fig. 8.
It is seen that the output voltage has a maximum of 13 V and 0.02s settling time at starting.15.4V maximum and 0.02s settling time for the first step change and 6.7V maximum and 0.03s settling time for the second step change. The input voltage during these reference voltage changes stays the same with a value of 10V.
The simulink block that performs the input voltage change while the converter is running is implemented as in Fig 9.
To see the input voltage variations on the output voltage, the supply voltage is increased 50% from 10V to 15V at t=0.05s, and then the supply voltage is decreased from 15V to 8V at t=0.1s. During these changes, the reference voltage is maintained constant at 12V.

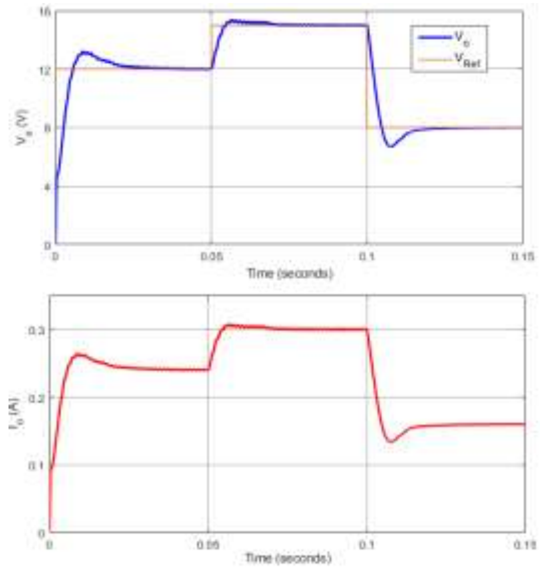

Fig. 8. Output voltage and current waveforms in case of step changes in the input voltage

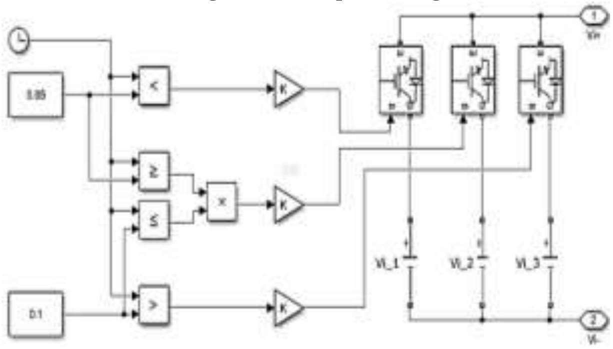

Fig. 9. Implementation of input voltage change while simulation is running

Figure 10 shows the input voltage, output voltage, and output current when changes occur in the input supply voltage.
It could be seen that the output voltage is robust to the input voltage variations.
Figure 11 shows the output voltage waveform when sudden changes in load from 50Ω to 60Ω at t=0.05s and 60Ω to 40Ω at t=0.1s occur.
In both cases the input voltage is kept constant with a value of 10V and the reference voltage is 12V. The load value is scaled with a factor of 10 for clear visualization in the same figure. As it is clear from the waveforms the output voltage tracks the reference voltage being insensitive to the load variations.

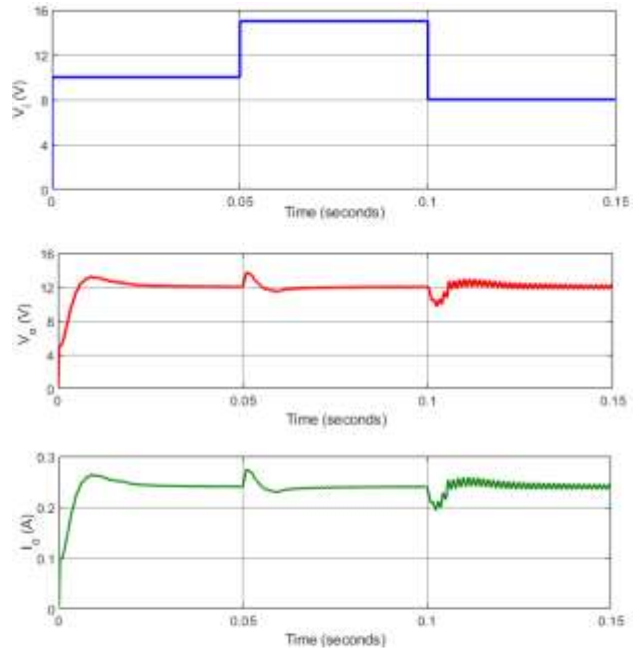

Fig. 10. Input, output voltage, and output current waveforms with changes in input voltage

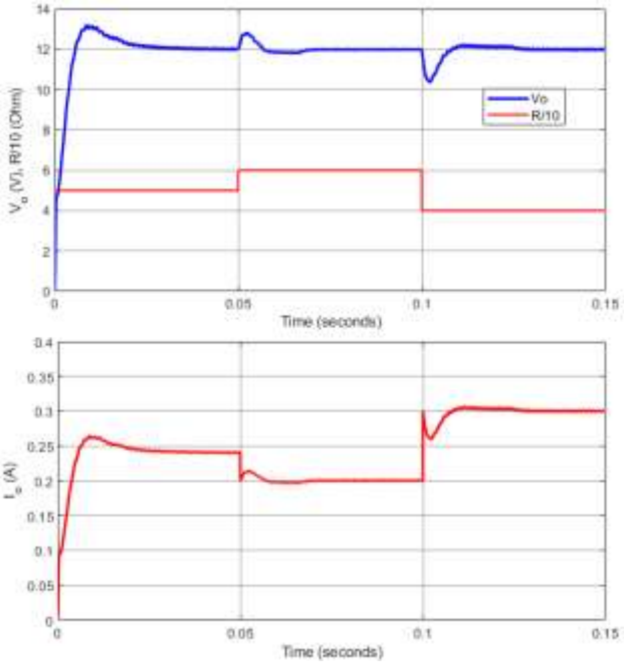

Fig. 11. Output voltage waveforms with changes in load

The load change is realized using the simulink implementation as shown in Fig. 12.

The output voltage presented in Fig. 13, shows the response for the variation in capacitor values from 100µF to 500µF. The value of the capacitor is changed from 100µF to 500µF at t=0.05s. The designed controller successfully suppressed the effect of capacitance variation on the output voltage.

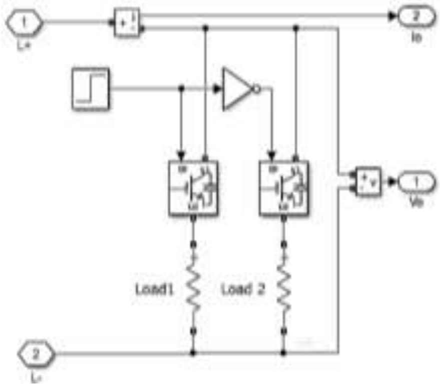

Fig. 12. Implementation of load change while simulation is running

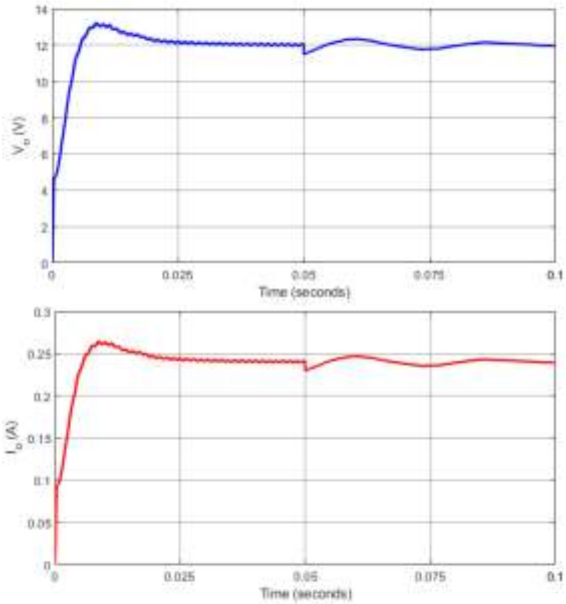

Fig. 13. Output voltage waveforms with changes in capacitor capacitance

IV.CONCLUSION

The SEPIC does the voltage conversion from the positive supply voltage to positive output voltage in a wide range both less than and greater than the input source voltage.

This study has successfully demonstrated the application of PI controlled SEPIC converter. The classical PI control technique is provided advantages such as stability, robustness, good performance, and simple implementation. It resulted in simple and improved performance compared to other control methods.

The simulation based performance analysis of a PI controlled SEPIC converter has been presented. The PI control technique has proved to be robust in the cases of line and load changes and circuit component variations. The simulation results demonstrated the effectiveness and feasibility of the double loop PI control scheme.

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