Design of State Feedback Controller for positive output elementary super-lift DC-DC Luo converter for Low Power Applications

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This paper focuses on modeling, simulation and hardware implementation of Positive Output Elementary Super-Lift (POESL) DC-DC Luo converter based on State Feedback Controller (SFC) for low power applications. POESL DC-DC Luo converter is widely used due to their simpler design, high voltage transfer gain, ease of use and cost effectiveness. The converter output voltage is enhanced stage by stage in arithmetic progression. To improve the dynamic response of the converter and to accomplish the voltage regulation against load and line fluctuations, a closed loop control technique is presented using inner SFC and outer proportional integral (PI) controller. The results obtained are compared with the conventional PI controller in both inner and outer loop to show the effectiveness of the proposed method. The simulation studies are carried out using MATLAB/ SIMULINK software tool. In addition, an experimental prototype model controlled by C2000 Piccolo TMS320F28027 MCU digital controller is set up to validate the simulation results. Results revealed that the proposed control scheme (inner SFC and outer PI control) based POESL DC-DC Luo converter offer constant output voltage for wide line and load variations and also achieve the servo operation effectively.

Keywords: Positive Output Elementary Super-Lift (POSEL) DC-DC Luo converter, State Feedback Controller (SFC), Voltage regulation, Closed loop control, Proportional integral (PI) controller.

1. Introduction

Nowadays, power conversion is one of the major concerns in all the industrial and consumer applications. Among the various power conversion techniques, DC - DC conversion has superior importance in modern applications such as computers, cellular phones, electric vehicles, solar powered equipment, telecom and wireless which are powered from batteries to reduce its size and to increase the efficiency. All these electronic devices have number of sub-circuits which involves unique voltage level. The DC - DC converters offer a voltage of different level thereby producing multiple controlled voltages from a single variable battery voltage which reduces the requirement of many batteries with different voltage level. The existing both basic and derived DC - DC converters are designed in such a way to suit the requirements of certain applications only. The different types of basic DC-DC converters such as buck, boost, buck-boost and derived DC-DC converters like cuk and SEPIC converter are used for load voltage regulation. The buck converter provides lower ripples in the output voltage but the output voltage is lower than the input voltage and also needs an input filter. Moreover, one of the major problems with buck converter is the isolation. [1, 2].

On the other side, the boost converter boost up the output voltage and eliminates the need of input filter but cannot perform the buck operation and has significant ripples in the output voltage [3, 4].These drawbacks were overcome by the buck-boost converter which can either increase or decrease the output voltage though it needs a filter at the input and the output sides [5]. Whereas the derived cuk converter performs both buck or boost operation with polarity inversion however the output voltage is affected by parasitic capacitance effect [6, 7]. The output voltage is less affected by parasitic effect in case of elementary super lift Luo converter compared to the aforementioned converters and also more efficient than other converters. The POESL DC-DC Luo converter have the following characteristics such as high voltage transfer gain, high power density, reduced ripple in output voltage and current [8-12]. The researchers in [13,14] presented the voltage regulation of a zero-voltage switching quasi-resonant-positive output super lift Luo converter with low switching losses for industrial applications using dedicated analog resonant controller UC3861 operating under resonant switching conditions.

The design of SFC for voltage lifting technique using POESL DC – DC Luo converter was not yet implemented and it is based on state feedback control law. Theoretically, the design of SFC or pole placement method (PPM) is to set the desired pole location by moving the pole location of the system to get the desired response of the system. Thus SFC results in the desired dynamic response and excellent disturbance rejection [15]. Hence in this work, an attempt has been made to design SFC for POESL DC - DC Luo converter to attain the required regulated output voltage even in the presence of line and load variations.

This paper is structured as follows: Section 2 describes the design and analysis of POESL DC - DC Luo converter. Section 3 explains the design of closed loop analysis of Luo converter with inner SFC and outer PI controller. Section 4 and 5 discusses the closed loop response and dynamic response such as load and line variation respectively, with the hardware validation presented in section 6. Finally, the conclusion was made in the last section of this paper.

2. Design of POESL DC - DC Luo Converter

Fig.1 shows the proposed POESL DC - DC Luo converter. It provides high voltage gain and when cascaded, the gain rises stage by stage in arithmetic progression. The specifications used for the design of the proposed converter are given as follows: Switching frequency, f_s: 50 kHz, Supply voltage, V_{in}: 12V, Output voltage, V_o :30V,Output resistance, R:100Ω, Ripple in inductor current, $\Delta I_L 1$:1.6% of output current, Ripple in the capacitor voltage ΔV_C : 0.48% of output voltage (V_O). By using the above specifications, the values of input inductor L, capacitor C_1 and C_2 are calculated as follows:

$$L = \frac{V_{in} d}{\Delta I_L f} = 5\text{mH}$$

$$C = C_1 = C_2 = \frac{V_0}{\Delta V_C f R} = 1250\ \mu\text{F}$$

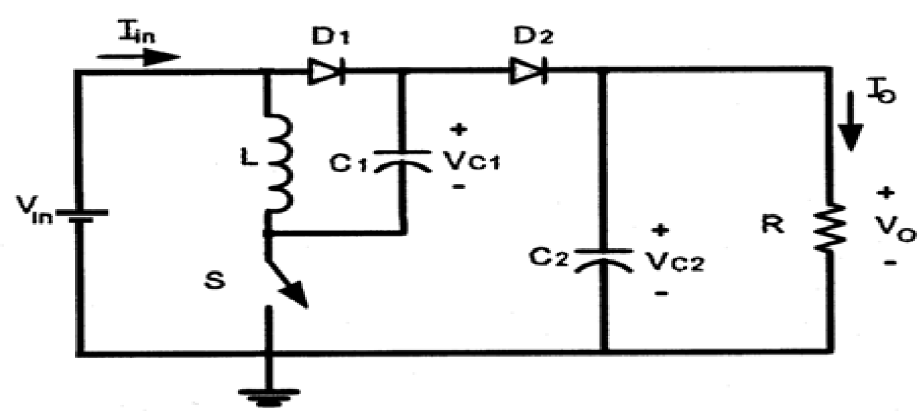


Fig.1.POESL DC - DC Luo converter

2.1. Mathematical Modeling of POESL DC - DC Luo Converter

To obtain the state space model of POESL DC - DC Luo converter, the state space equations is obtained by switching ON and OFF of the converter. Fig. 2 illustrates the equivalent circuit of the POESL DC

- DC Luo converter for the ON stage. For the equivalent circuit shown in Fig. 2, the KVL equations are given as follows;

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \quad (1)$$

$$\frac{dV_{C_2}}{dt} = \frac{-V_{C_2}}{R\,C_2}\ [V_0 = V_{C_2}] \quad (2)$$

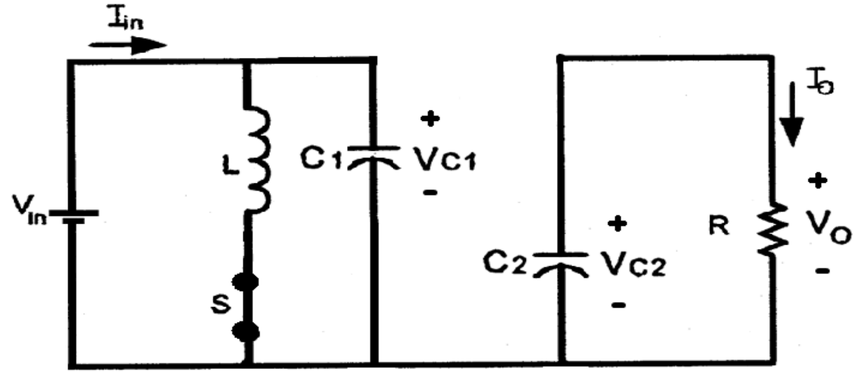


Fig.2. Equivalent circuit of the POESL DC - DC Luo converter for the ON stage

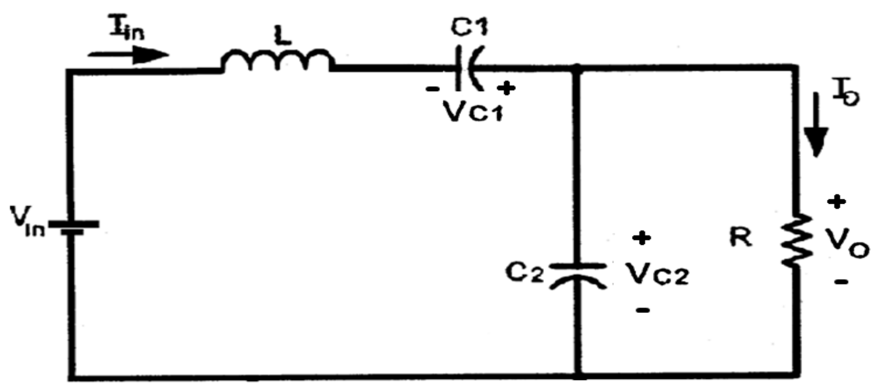


Fig.3. Equivalent circuit of the POESL DC - DC Luo converter for the OFF stage

Fig.3 presents the equivalent circuit of the POESL DC - DC Luo converter for the OFF stage. For the equivalent circuit revealed in Fig. 3, the KVL equations are given as follows;

$$\frac{d\,i_L}{dt} = \frac{2\,V_{in}}{L} - \frac{V_{C_2}}{L} \quad (3)$$

$$\frac{dV_{C_2}}{dt} = \frac{i_L}{C_2} - \frac{V_{C_2}}{RC_2}\ [\,V_0\ =\ V_{C_2}\,] \quad (4)$$

Using the state Eqs. (1) and (2), the state matrix during switch ON stage is given by

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_{C_2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC_2} \end{bmatrix} \begin{bmatrix} i_L \\ V_{C_2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{5}$$

The Eq.(5) is of the form

$$\dot{X} = A_1X + B_1U \tag{6}$$

Using state Eqs.(3) and (4), the state matrix during the switch OFF stage is given by

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_{C_2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C_2} & \frac{-1}{RC_2} \end{bmatrix} \begin{bmatrix} i_L \\ V_{C_2} \end{bmatrix} + \begin{bmatrix} \frac{2}{L} \\ 0 \end{bmatrix} V_{in} \tag{7}$$

The Eq.(6) is of the form

$$\dot{X} = A_2X + B_2U \tag{8}$$

Here A_1, B_1 represents the state matrix and input matrix for the switch 'S' is in ON stage and A_2, B_2 represents the state matrix and input matrix for the switch 'S' is in OFF stage. For the proposed POESL DC - DC Luo converter, the output equation is given by

$$Y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_{C_2} \end{bmatrix} + [0] \tag{9}$$

For one time period 'T', 'd' is the duration for which the switch 'S' is ON and '(1-d)' is the duration for which the switch 'S' is OFF. Now, by using the matrices A_1, B_1, A_2, B_2 the state matrix 'A', input matrix 'B' is calculated as follows,

$$A = A_1d + A_2(1 - d) = \begin{bmatrix} 0 & \frac{-(1-d)}{L} \\ \frac{(1-d)}{C_2} & \frac{-1}{R\,C_2} \end{bmatrix} \tag{10}$$

$$B = B_1d + B_2(1 - d) = \begin{bmatrix} \frac{2-d}{L} \\ 0 \end{bmatrix} \tag{11}$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} \text{ and for the given system } \quad D = [0] \tag{12}$$

3. Closed Loop control of *POESL DC - DC Luo Converter*

This section presents the closed loop control of proposed POESL DC - DC Luo converter with outer loop consisting of PI controller and inner loop with SFC to regulate the output voltage as depicted in Fig.4.

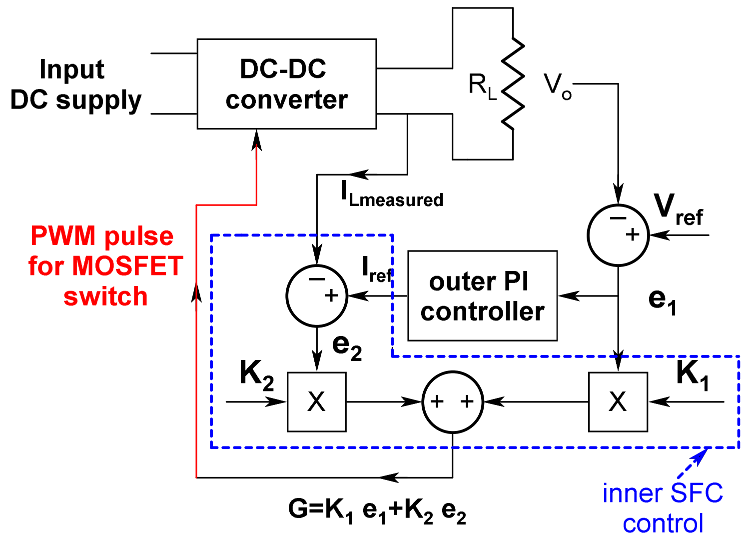


Fig.4. Closed loop control of DC-DC Luo converter

3.1. Proportional Integral controller

In the proposed system, the outer PI controller is designed using Z-N method of tuning to obtain the parameters of K_p and K_i as discussed in [7]. The function of PI controller is to provide the reference inductor current for the inner loop. For the proposed system, the proportional constant K_p and the integral constant K_i are considered as 0.2 and 2 respectively.

3.2 Design of SFC

SFC design is a method in which the determination of closed loop system poles location on the complex plane (preferably left half of the complex plane) is done by setting a controller gain 'K'. System poles describe the behavior of linear dynamic systems. The design of SFC is attainable if and only if the system is completely state controllable.

Steps involved in the design of the SFC are as follows:

Step 1: Check the controllability of the system. If the given system is controllable, it ensures that the design of SFC is possible.
Step 2: To design an SFC, obtain the state model of the system.
Step 3: Assume δ (damping ratio), ω_n (natural frequency of oscillations), to get the desired poles and the desired characteristic equation.
Step 4: Relate the desired characteristic equation with characteristic equation obtained using state model to get the controller gain 'K'.
Step 5: Develop an SFC, u = - K x using the state feedback gain 'K'.

For the proposed system, the controllability matrix $M = [B \quad AB]$ is found to be

$$M = \begin{bmatrix} 333.4 & 0 \\ 0 & 177902.24 \end{bmatrix} \tag{13}$$

The Rank of controllability matrix 'M' is 2, since its determinant is a non-zero number.

$|M| = 59.312 \times 10^6$ (14)

The system is completely state controllable and hence controller design using arbitrary pole placement is possible. The general equation for the formation of the desired closed loop poles is

$$-\delta\omega_n \pm j\omega_n\sqrt{1-\delta^2} \quad (15)$$

Using the values of δ, ω_n and by using the Eq. (15), the required closed loop poles are found as

$S_1, S_2 = -3.9 \pm j4$

The desired characteristic equation is

$$(s - 3.9 - j4)\,(s - 3.9 + j4) = 0$$

$$s^2 - 7.8s + 31.21 = 0 \quad (16)$$

Comparing the Eq. (16) with the general 2nd order equation $s^2 + \alpha_1 s + \alpha_2 = 0$

α_1 , α_2 are found to be

$$\alpha_1 = -7.8 \quad , \quad \alpha_2 = 31.21 \quad (17)$$

The characteristic equation for the proposed system using the state matrix 'A' is

$$|sI - A| = \begin{vmatrix} s & 133.4 \\ -533.6 & s+8 \end{vmatrix} = 0$$

$$s^2 + 8s + 71182.24 = 0 \quad (18)$$

Comparing the Eq. (18) with the general 2nd order equation $s^2 + a_1 s + a_2 = 0$, a_1 and a_2 are determined as $a_1 = 8$, $a_2 = 71182.24$

And by using the values of α_1 , α_2 , a_1 and a_2 the state feedback gain matrix 'K' is given by

$$K = [\alpha_2 - a_2 \quad \alpha_1 - a_1] \quad (19)$$

$$K = [K_1 \quad K_2] = [-71151.03 \quad -15.8] \quad (20)$$

The control law is $u = -Kx = -(K_1 e_{i_L} + K_2 e_v)$ (21)

$$u = -(-71151.03\, e_{i_L} - 15.8\, e_v) \quad (22)$$

$$u = 71151.03\, e_{i_L} + 15.8\, e_v \quad (23)$$

Here e_v and e_{i_L} represents the voltage and current errors respectively.

4. Simulation Results and discussion

This section discusses the closed loop control of proposed POESL DC-DC Luo Converter employing MATLAB/SIMULINK software tool. The closed loop simulation circuit of the POESL DC - DC Luo converter comprises of DC supply voltage V_{in}, capacitors C_1 and C_2, inductor L, MOSFET switch S, diodes D_1 and D_2, and load resistor R. Fig.5 shows the closed loop simulation circuit of the POESL DC - DC Luo converter, in which the output voltage is sensed and compared with the reference voltage. The resultant error voltage e_v is fed as an input to an outer PI controller and its output is the reference inductor current. The measured input inductor current i_L is compared with the reference inductor current i_{Lref} and the resultant is the current error signal e_i.

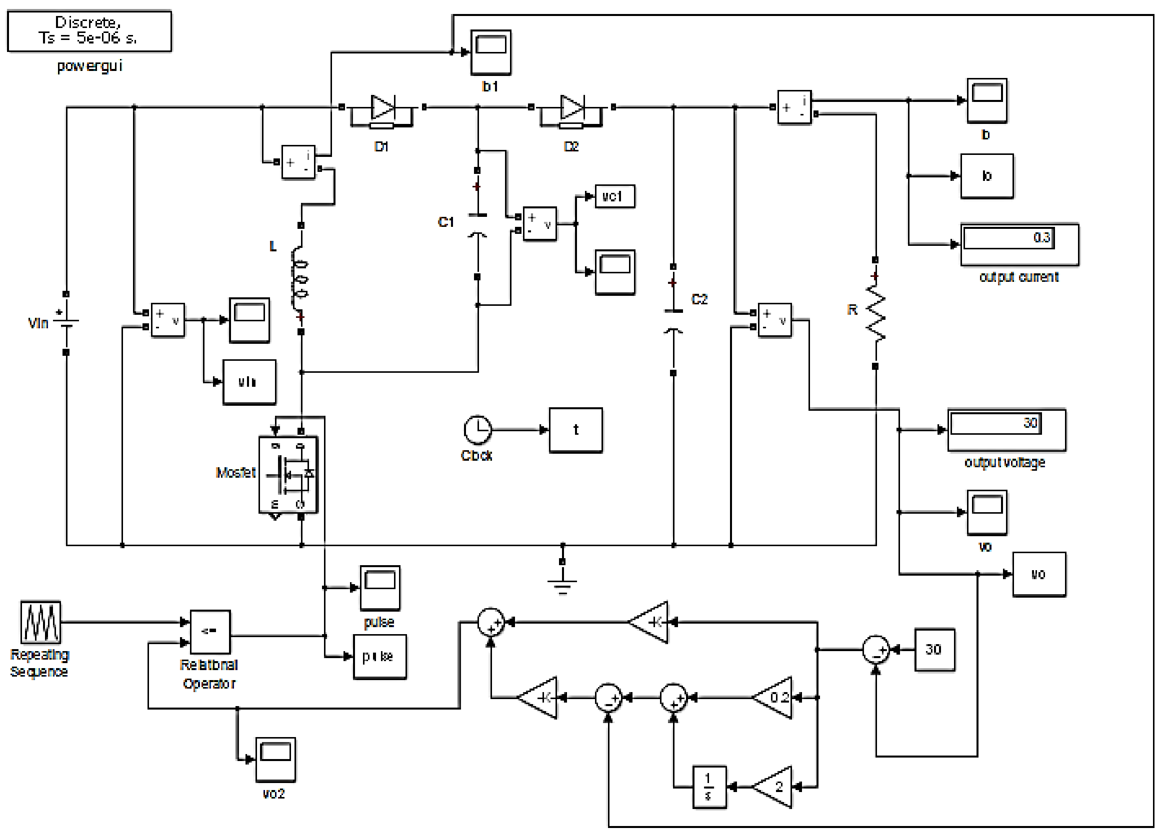


Fig.5. Closed loop simulation circuit of POESL DC - DC Luo Converter

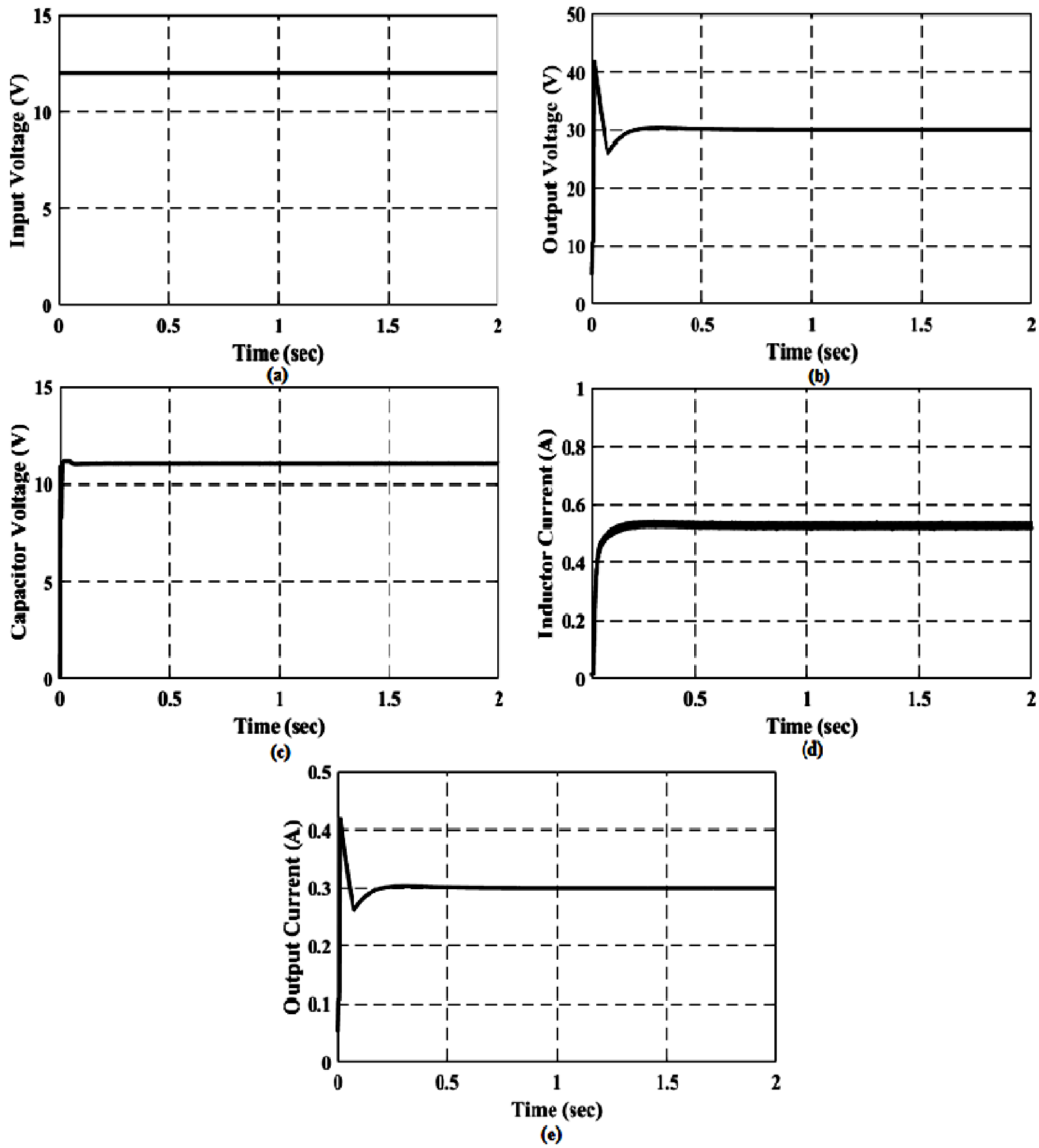


Fig.6. Closed loop simulation results of POESL DC-DC Luo converter using PI controller (outer and inner loop)

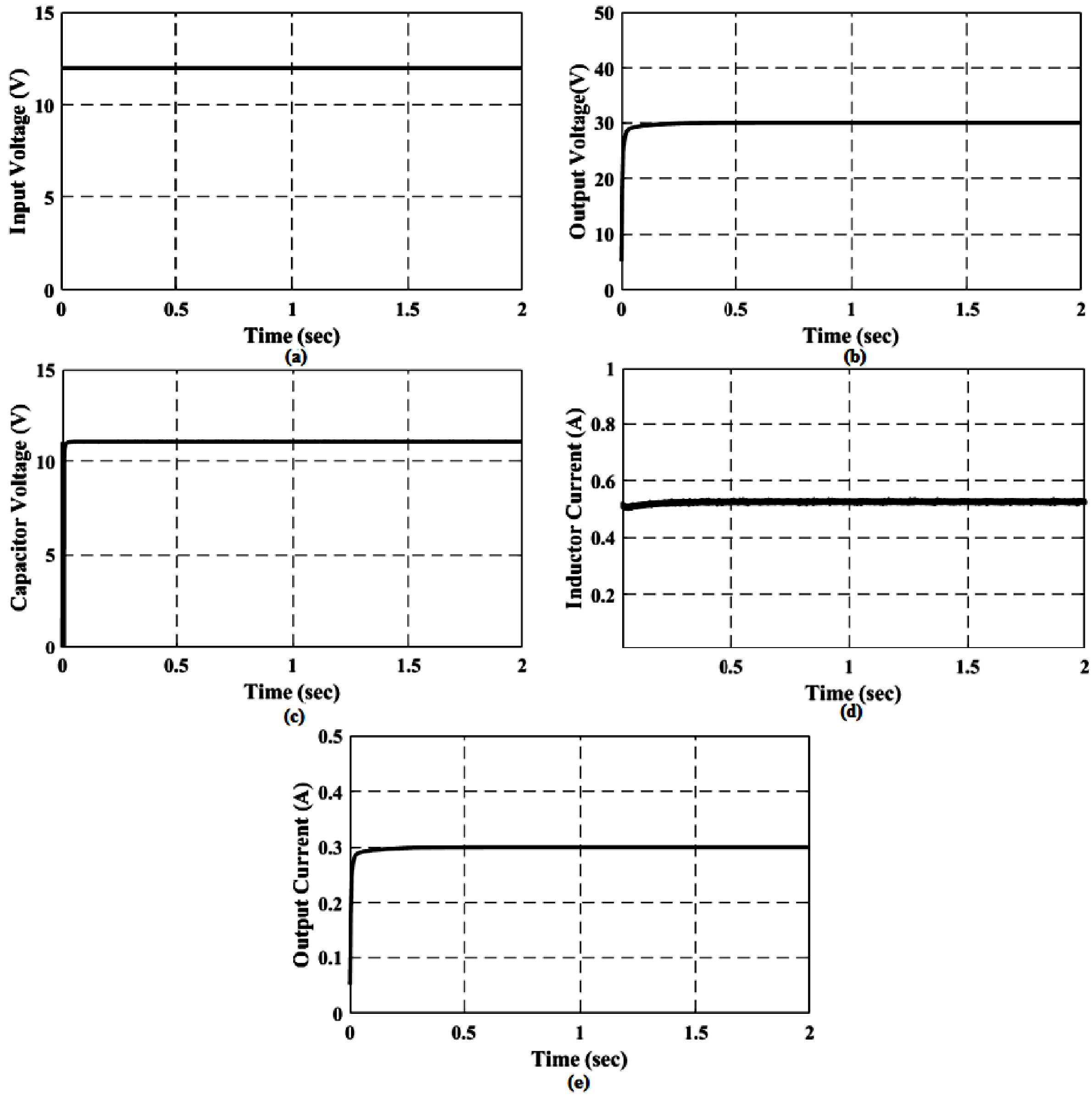


Fig. 7. Closed loop simulation results of POESL DC-DC Luo converter using PI (outer loop) and SFC (inner loop)

The control law for SFC is found to be $u = -(K_1 e_{i_L} + K_2 e_v) = -(-71151.03\, e_{i_L} - 15.8\, e_v)$ with K_1=71151.03, K_2=15.8. K_1, K_2 represents the state feedback gains obtained using SFC as discussed in section 3. The resultant SFC control law 'u' is compared with the carrier wave of desired switching frequency of 50 kHz. The output of the comparator is the PWM pulse used for triggering the MOSFET switch of the POESL DC - DC Luo converter in order to obtain the required DC output voltage.

Fig. 6 and 7 shows the closed loop simulation results of DC-DC Luo converter using PI controller (both inner and outer loop) and proposed control scheme (inner SFC and outer PI control). Fig.6a-6e and Fig.7a-7e represents the input voltage of the converter, output voltage waveform, input capacitor voltage waveform, inductor current waveform and output current waveform using PI controller (inner and outer loop) and the proposed control scheme (inner SFC and outer PI) respectively. The results reveal that the proposed control scheme offer a regulated output voltage without any overshoot at 0.21 sec whereas the PI controller with an overshoot magnitude of 42V settles at 0.45 sec. Moreover, the responses such as inductor current and capacitor voltage are significantly improved using the proposed method of control scheme than the conventional PI control method.

5. Performance Analysis of POESL DC - DC Luo Converter

This section presents the steady state performance analysis of DC-DC Luo converter of proposed control scheme. Fig.8 and 11 shows the load voltage and load current waveforms for 20% decrease in step load variation introduced at 1sec using PI and proposed control scheme. The proposed controller tracks the reference voltage at 0.142 sec whereas the conventional PI controller tracks the reference voltage at 0.353 sec. Fig.9 illustrates the output voltage for input voltage variations, in which at 1.085 sec, the supply voltage is reduced from 12V to 6V (50% decrease), at 2.024 sec the supply voltage is increased from 6V to 18V (50% increase) and at 3.121 sec the supply voltage is reduced from 18V to 12V (50% decrease). The PI controller gives a regulated output voltage within 0.6 sec for all the line variations introduced. Fig.10 portrays the output voltage for reference voltage or set point variation. At 1.1 sec, the reference voltage is reduced from 30V to 25V (20% decrease), at 2.08 sec reference voltage is increased from 25V to 35V (20% increase). PI controller provides a regulated output within 0.5 sec for all the line variations introduced.

Fig.12 illustrates the output voltage for input voltage variations, in which at 1.12 sec, the supply voltage is reduced from 12V to 6V (50% decrease), at 2.0231 sec supply voltage is increased from 6V to 18V (50% increase) and at 3.124 sec, supply voltage is reduced from 18V to 12V (50% decrease). Proposed control scheme offer a regulated output voltage within 0.55 sec for all the line variations introduced. Fig. 13 illustrates the output voltage for reference voltage or set point variation. At 1.09 Sec, reference voltage is reduced from 30V to 25V (20% decrease), at 2.102 sec reference voltage is increased from 25V to 35V (20% increase). Proposed control scheme provide a regulated output within 0.35 sec for all the line variations introduced. The results reveal that the proposed control scheme (inner SFC and outer PI control) able to perform servo and regulator operations effectively. The proposed scheme is tested for parameter variations and the PI controller parameter constants such as K_P and K_I are given for different values. Table I reveals that SFC can provide a regulated output voltage for different values of PI controller parameters such as K_P and K_L. Also, the proposed method is tested for inductance parameter variations (For L=10mH & L=5mh) as shown in Fig.14 and 15. It is observed from the results that the proffered approach provide a regulated output voltage for different values of inductances. Table II represents the efficiency of the Luo converter using proposed scheme is better when compared to conventional PI controller which in turn shows the effectiveness of the propounded controller.

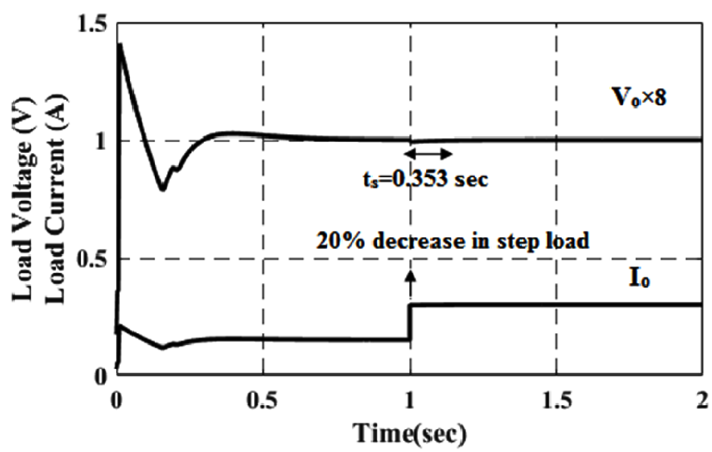


Fig. 8. Load voltage and Load current waveforms for 20% decrease in step load using PI controller (both loop)

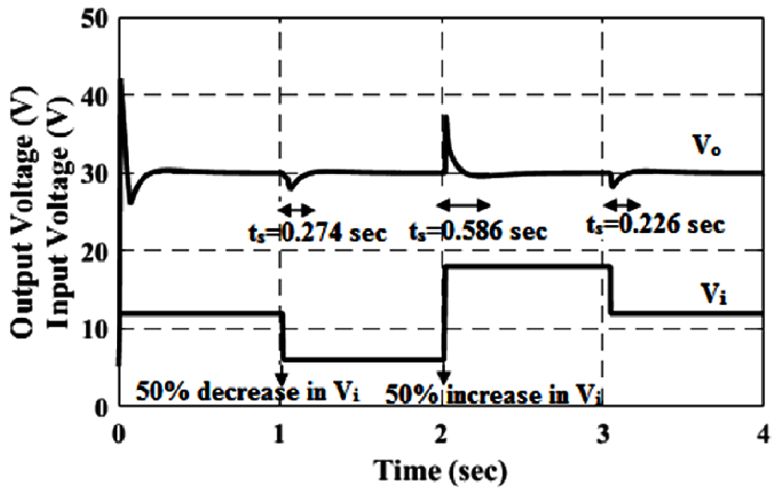


Fig.9.Output Voltage waveform for Line variation using PI controller (both loop)

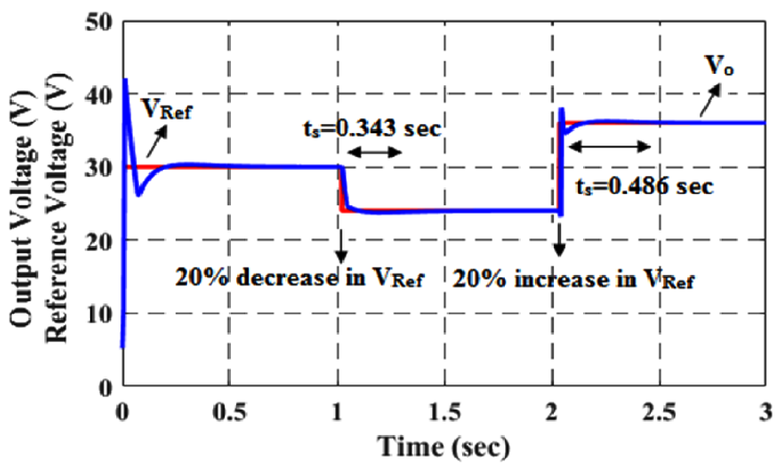


Fig. 10. Output Voltage waveform for Reference voltage variation using PI controller (both loop)

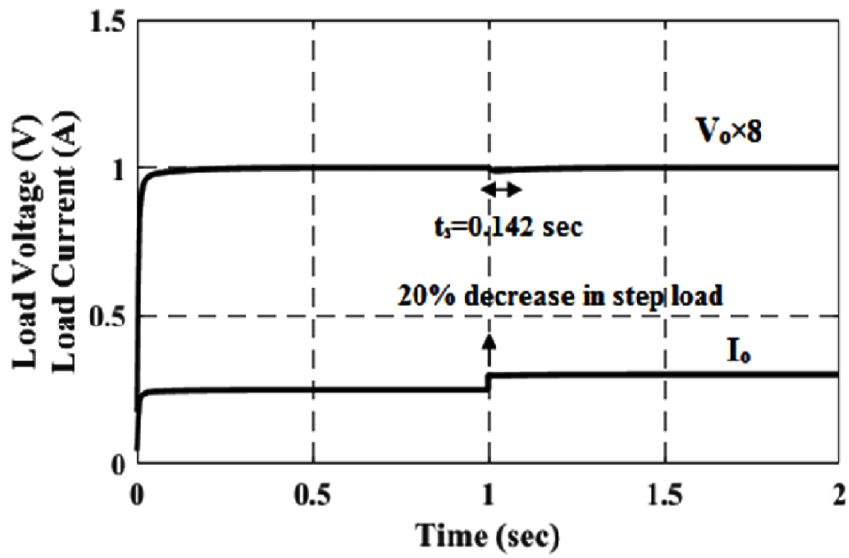


Fig. 11. Load voltage and Load current waveforms for 20% decrease in step load using proposed control method

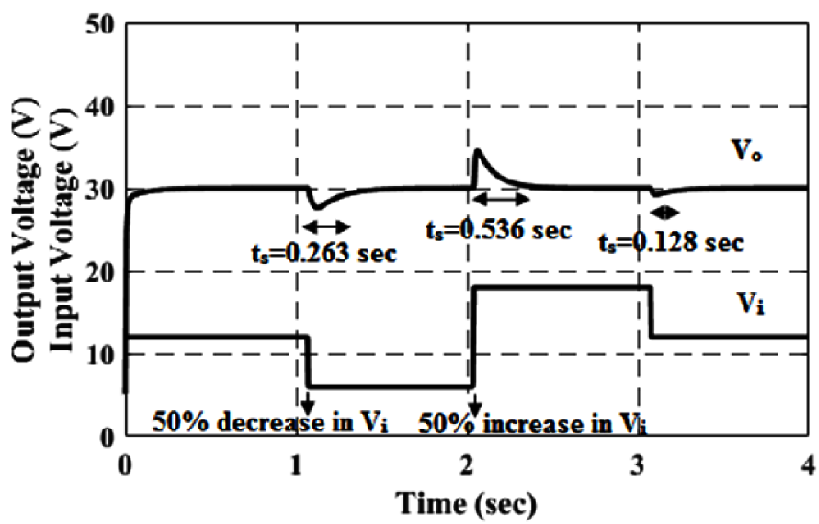


Fig. 12.Output Voltage waveform for Line variation using proposed control method

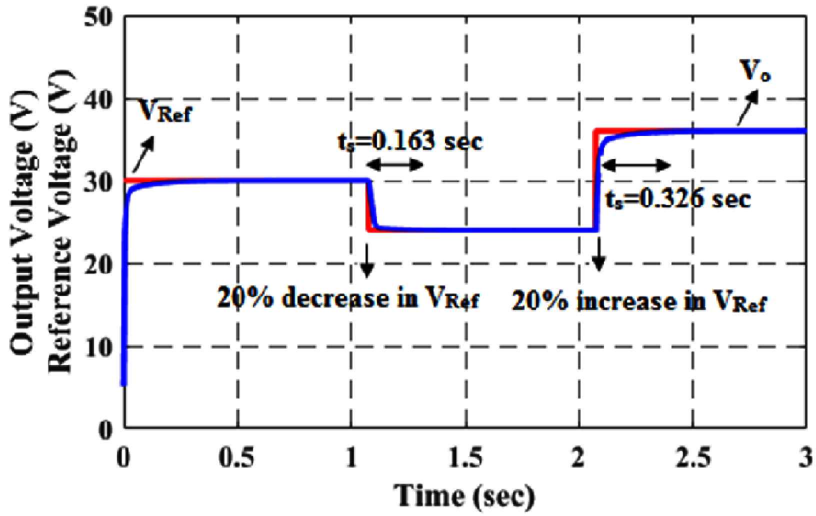


Fig. 13. Output Voltage waveform for Reference voltage variation using proposed control method

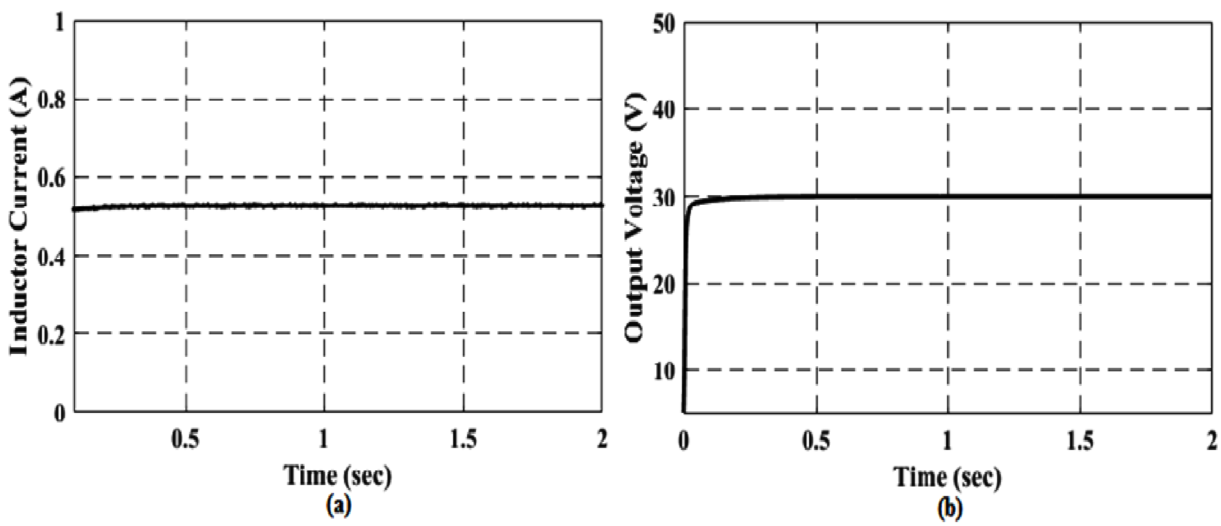


Fig. 14. Inductor Current and Output Voltage waveform for L=10mH using proposed control method

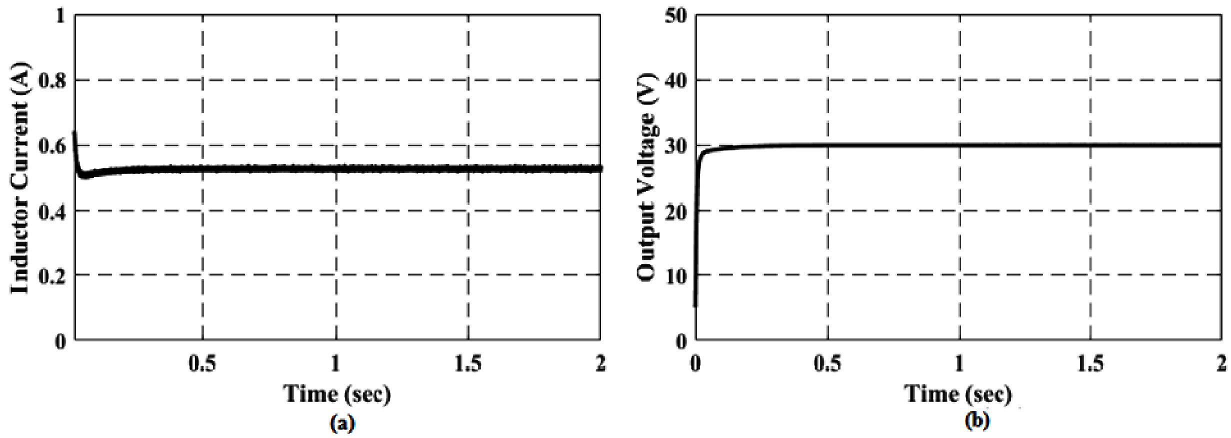


Fig. 15. Inductor Current and Output Voltage waveform for L=5mH using proposed control method

Table I .Output Voltage for the Variation in PI Controller Parameters

PI Controller Parameters		Output Voltage(V)
K_P	K_I	
0.01	0.1	29.86
0.02	0.2	30
0.05	0.5	30
0.1	1	30
0.2	2	30
0.5	5	30
1	10	30
2	20	30

Table II. Efficiency analysis of the system using PI and SFC for load variation

Load variation %	**Efficiency (%)**	
	Proposed control method	**PI control (inner and outer loop)**
Rated Load	85.89	83.62
5%	85.46	83.13
10%	85.12	83.01
15%	84.33	82.48
20%	83.72	81.26
25%	82.48	80.04

6. Hardware Implementation POESL DC - DC Luo Converter

Fig. 16 shows the hardware prototype model of POESL DC-DC Luo Converter, in which the input and output inductors used are of ferrite core type and the capacitors are of plain polyester type. The power MOSFET IRF540N is used as a switch and IN 4007 is used as a diode. IR 2110 is used to drive the power MOSFET. The proposed control scheme (inner SFC and outer PI control) is experimentally tested in the laboratory with the same design specifications as used in simulation as depicted in Table III. The digital controller is particularly designed for the development of high-speed multivariable digital controllers based on the C2000 Launchpad (TMS320F28027) Microcontroller. The output voltage, inductor current are sensed by Hall Effect voltage and current sensors, scaled down to less than + 3.4 V using the signal conditioning circuit and fed-back to the controller through the ADC channels of the TMS320F28027 Microcontroller. The SFC is then designed in SIMULINK and downloaded to the TMS320F28027 Microcontroller which provides the necessary switching signals to the driver circuit which in turn feeds the pulse width modulation (PWM) pulses to the MOSFET switch present in the DC-DC Luo converter.

The hardware results obtained for the DC-DC Luo converter using proposed control scheme is presented in Fig.17 and 18. Fig. 17a depicts the input voltage provided to the proposed converter module. Fig. 17b shows the PWM pulses generated using SFC technique for triggering the MOSFET switch present in the POESL DC-DC Luo Converter. Fig. 18a depicts the output voltage obtained by the proffered converter module and the results reveal that the presented SFC provides the regulated output voltage of 30 V. Fig. 18b shows the inductor current obtained by the proposed converter module.

Table III Hardware Specifications

Specifications/Components name	**Role**	**Rating**
LV 25-P (Voltage sensor)	To sense the output voltage	I_{PN}=10 mA, V_{PN}=10V -500V
LEM HX 03-P (current sensor)	To sense the input current	I_{PN}=3A-50A
IR 2110 (Driver circuit)	To increase the current to the level needed to drive the MOSFET	-
IRF540N (MOSFET)	To provide the switching operation	N-Channel Power MOSFET200V, 30A, 0.075Ω
IN 4007 (Diode)	To provide Freewheeling action	-
TMS320F28027 (Digital controller)	To control the overall system	-

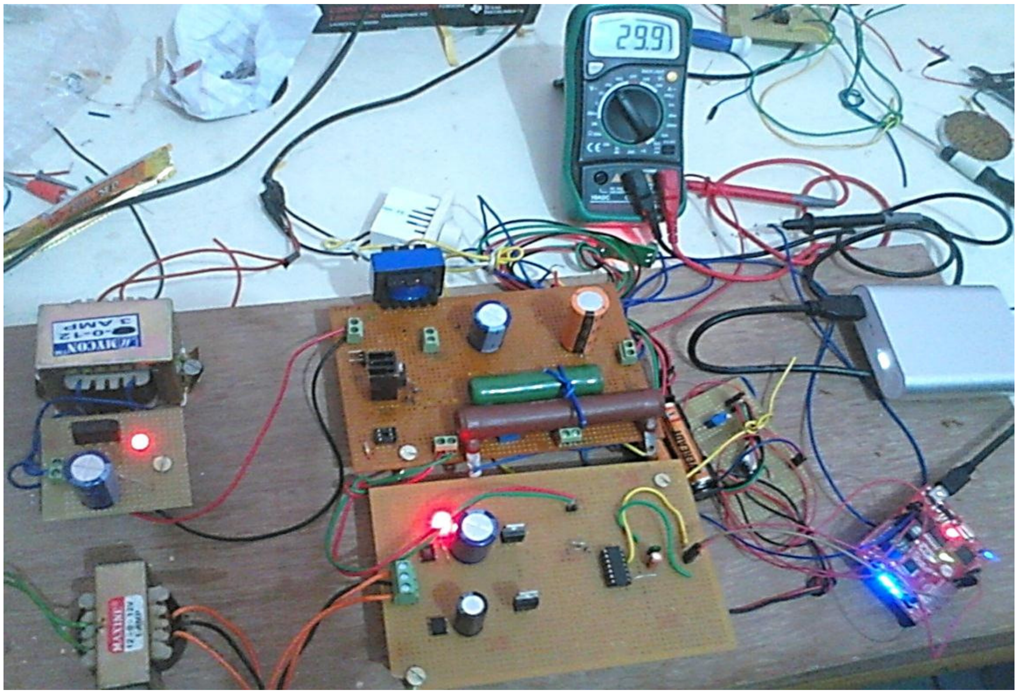
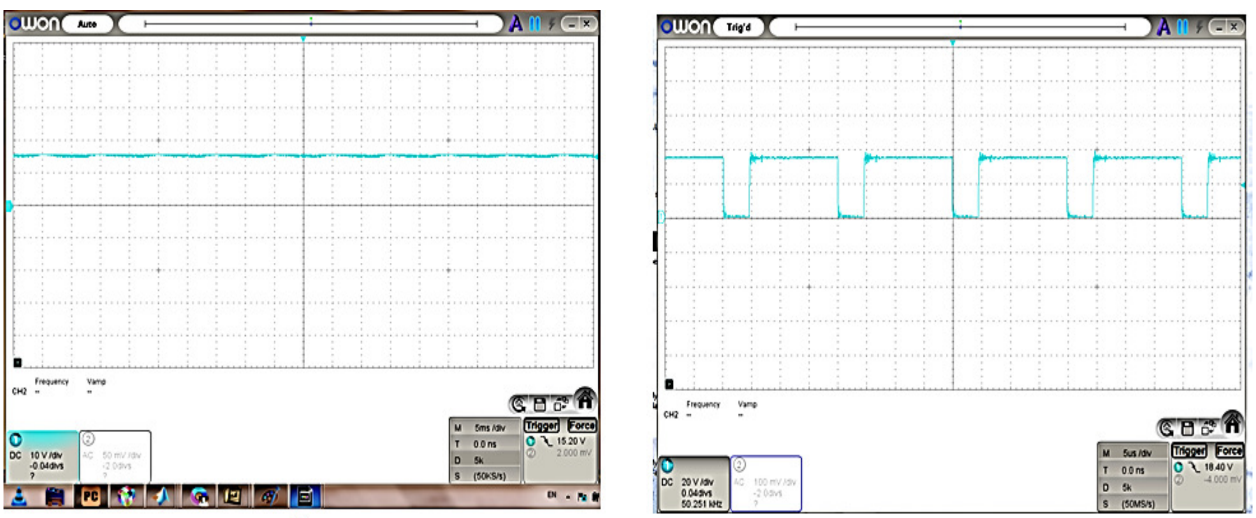
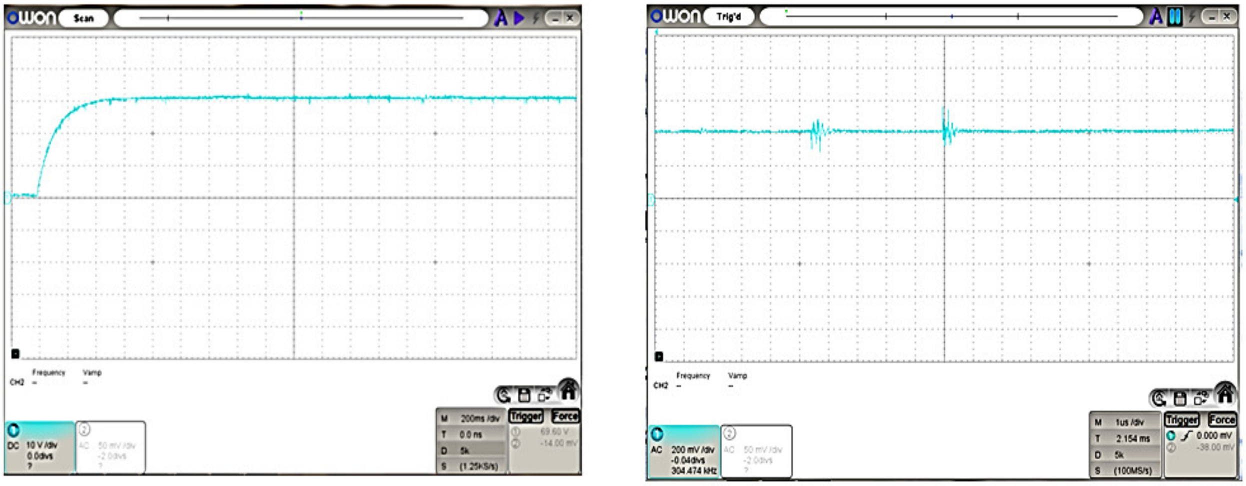


Fig.16. Hardware prototype model of POESL DC-DC Luo Converter



(a) (b)

Fig.17. Input voltage and the PWM Pulses



(a) (b)

Fig.18. Output voltage and Inductor current

7. Conclusion

In this work, closed loop control of POESL DC - DC Luo converter for low power applications has been implemented. To improve the transient and steady state response of POESL DC - DC Luo converter, a closed loop control technique is realized by using the inner SFC and outer PI controller. The results obtained is compared with the conventional PI controller in both the loop. Extensive simulation studies were carried out by using MATLAB/ SIMULINK software tool and the results were presented. The hardware prototype was constructed and SFC was implemented using TMS320F28027 microcontroller. The simulation results were validated with the experimental results in order to analyze the performance of POESL DC – DC Luo converter. Results reveal that the proposed system can provide regulated output voltage for wide line and load variation. Therefore, the closed loop control of POESL DC – DC Luo converter using inner SFC and outer PI provides a regulated output voltage for parameter variation and also can perform servo operation effectively.

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