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PI Control for Positive Output Elementary Super Lift Luo Converter

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***Abstract*—**The object of this paper is to design and analyze a proportional – integral (PI) control for positive output elementary super lift Luo converter (POESLLC), which is the start-of-the-art DC-DC converter. The positive output elementary super lift Luo converter performs the voltage conversion from positive source voltage to positive load voltage. This paper proposes a development of PI control capable of providing the good static and dynamic performance compared to proportional – integral-derivative (PID) controller. Using state space average method derives the dynamic equations describing the positive output elementary super lift luo converter and PI control is designed. The simulation model of the positive output elementary super lift Luo converter with its control circuit is implemented in Matlab/Simulink. The PI control for positive output elementary super lift Luo converter is tested for transient region, line changes, load changes, steady state region and also for components variations.

***Keywords*—**DC-DC converter, Positive output elementary super lift Luo converter (POESLLC), Proportional – Integral (PI) control.

I. Introduction

DC-DC conversion technology has been developing very rapidly, and DC-DC converters have been widely used in industrial applications such as dc motor drives, computer systems and communication equipments. The output voltage of pulse width modulation (PWM) based DC-DC converters can be changed by changing the duty cycle.

The positive output elementary super lift Luo converter is a new series of DC-DC converters possessing high-voltage transfer gain, high power density; high efficiency, reduced ripple voltage and current [1]. These converters are widely used in computer peripheral equipment, industrial applications and switch mode power supply, especially for high voltage-voltage projects [1]-[2]. Control for them needs to be studied for the future application of these good topologies.

The super-lift technique considerably increases the voltage transfer gain stage by stage in geometric progression [3]-[4]. However, their circuits are complex. An approach, positive output elementary super lift Luo converters, that implements the output voltage increasing in geometric progression with a simple structured have been introduced. These converters also effectively enhance the voltage transfer gain in power-law terms [1].

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Due to the time variations and switching nature of the power converters, their static and dynamic behavior becomes highly non-linear. The design of high performance control for them is a challenge for both the control-engineering engineers and power electronics engineers. In general, a good control for DC-DC converters always ensures stability in arbitrary operating condition. Moreover, good response in terms of rejection of load variations, input voltage variations and even parameter uncertainties is also required for a typical control scheme. The static and dynamic characteristics of these converters have been well discussed in the literature [5]. With different state-space averaging techniques, a small-signal state-space equation of the converter system could be derived. The proportional integral derivative (PID) controller's recent tuning methods and design to specification has been well reported in the literature [6]-[7]. The PI control technique offers several advantages compared to PID control methods: stability, even for large line and load variations, reduce the steady error, robustness, good dynamic response and simple implementation.

Intensive research in the area of DC-DC converter has resulted in novel circuit topologies [8]. These converters in general have complex non-linear models with parameter variation. The averaging approach has been one of the most widely adopted modeling strategies for switching converters that yields a simple model [9]. Analysis and control design of paralleled DC-DC converters with master-slave current sharing control has been well reported [10].

In this paper, state-space model for positive output elementary super lift Luo converter (POESLLC) are derived at first. A PI control with zero steady state error and fast response is brought forward. The static and dynamic performance of PI control for positive output elementary super lift Luo converter is studied in Matlab/Simulink. Details on operation, analysis, control strategy and simulation results for positive output elementary super lift Luo converter (POESLLC) are presented in the subsequent sections.

II. Converter Operation and Modeling of POESLLC

For the purpose of optimize the stability of positive output elementary super lift Luo converter dynamics, while ensuring correct operation in any working condition, a PI control is a more feasible approach.

The PI control has been presented as a good alternative to the control of switching power converters [11]. The main advantage PI control schemes is its insusceptibility to plant/system parameter variations that leads to invariant dynamics and static response in the ideal case.

A. Circuit Description and Operation

The positive output elementary super lift Luo converter is shown in Fig. 1. It includes dc supply voltage V_{in}, capacitors C_1 and C_2 , inductor L_1, power switch (n-channel MOSFET) *S,* freewheeling diodes D_1 and D_2 and load resistance *R*.

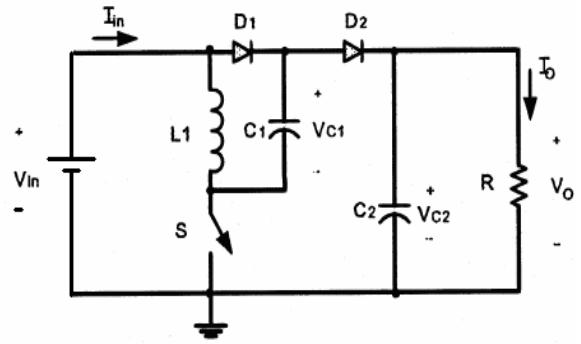

Fig. 1 The positive output elementary super lift Luo converter

The principle of the sliding mode controller is to make the capacitor voltages V_{C1} and V_{C2} follow as faithfully as possible capacitor voltage references.

In the description of the converter operation, it is assumed that all the components are ideal and also the positive output elementary super lift Luo converter operates in a continuous conduction mode. Figs. 2 and 3 shows the modes of operation of the converter [1].

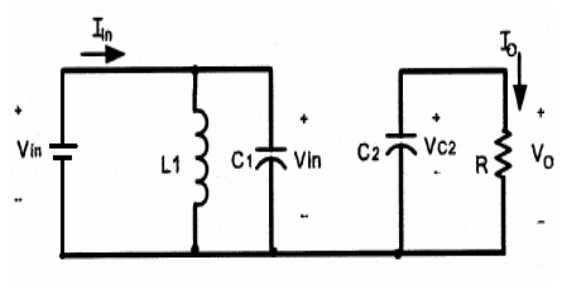

Fig. 2 Mode 1 operation

In Fig. 2 when the switch *S* is closed, voltage across capacitor C_1 is charged to V_{in} The current i_{L1} flowing through inductor L_1 increases with voltage V_{in}.

In Fig. 3 when the switch *S* is closed, decreases with voltage (V_o - *2* V_{in}). Therefore, the ripple of the inductor current i_{L1}

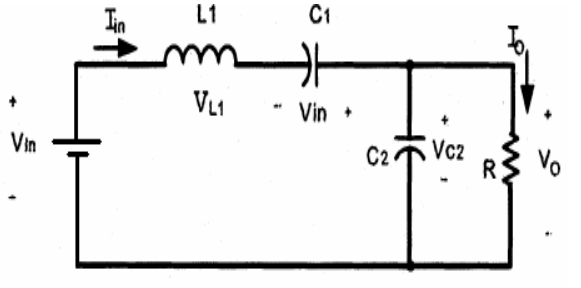

Fig. 3 Mode 2 operation

$$\Delta_{iL1}=\frac{V_{in}}{L_1}dT=\frac{V_O-2V_{in}}{L_1}dT \tag{1}$$

$$V_O=\frac{2-d}{1-d}V_{in} \tag{2}$$

The voltage transfer gain is

$$G=\frac{V_O}{V_{in}}=\frac{2-d}{1-d} \tag{3}$$

The input current i_{in} is equal to (i_{L1} + i_{C1}) during switching-on and only equal to i_{L1} during switching-off. Capacitor current i_{C1} is equal to i_{L1} during switching-off. In steady state, the average charges across capacitor C_1 should not change. We have the following relations:

$$i_{in-off}=i_{L1-off}=i_{C1-off}\ ,\ i_{in-on}=i_{L1-on}+i_{C1-on}$$
$$dT\,i_{C1-on}=(1-d)Ti_{C1-off}$$

If inductance L_1 is large enough, i_{L1} is nearly equal to its average current i_{L1}. Therefore

$$i_{in-off}=i_{L1}=i_{C1-off}\ ,\ i_{in-on}=i_{L1}+\frac{1-d}{d}\frac{i_{L1}}{d}$$

$$i_{C1-on}=\frac{(1-d)}{d}i_{L1}$$

and average input current

$$I_{in}=di_{in-on}+(1-d)i_{in-off}=i_{L1}+(1-d)i_{L1}=(2-d)i_{L1} \tag{4}$$

Considering $T=\frac{1}{f}$ and

$$\frac{V_{in}}{I_{in}}=\left(\frac{(1-d)}{(2-d)}\right)^2\frac{V_o}{I_o}=\left(\frac{(1-d)}{(2-d)}\right)^2R$$

The variation ratio of inductor current i_{L1} is

$$\xi=\frac{\Delta_{iL1/2}}{i_{L1}}=\frac{d(2-d)TV_{in}}{2L_1I_{in}}=\frac{d(1-d)^2}{2(2-d)}\frac{R}{fL_1} \tag{5}$$

The ripple voltage of output voltage V_o is

$$\Delta_{vo}=\frac{\Delta Q}{C_2}=\frac{I_o(1-d)T}{C_2}=\frac{(1-d)}{fC_2}\frac{V_o}{R} \tag{6}$$

Therefore, the variation ratio of output voltage V_o is

$$\xi=\frac{\Delta_{vo}/2}{V_o}=\frac{(1-d)}{2RfC_2} \tag{7}$$

B. State space modeling

The state variables v_1, v_2 and v_3 are chosen as the current i_{L1}, the voltage V_{C1} and voltage V_{C2} respectively. In Fig. 2 When the switch is closed, the state space equation POESLLC is given as (8) [9]-[10],

$$\begin{cases} \dot{v}_1 = \dfrac{V_{in}}{L_1} \\ \dot{v}_2 = \dfrac{V_{in}}{C_1 R_{in}} - \dfrac{v_1}{C_1} \\ \dot{v}_3 = -\dfrac{v_3}{RC_2} \end{cases} \quad (8)$$

In Fig. 3 when the switch is open, the state space equation of POESLLC is given as (9) [9]-[10]

$$\begin{cases} \dot{v}_1 = \dfrac{V_{in}}{L_1} - \dfrac{v_2}{L_1} - \dfrac{v_3}{L_1} \\ \dot{v}_2 = \dfrac{v_1}{C_1} \\ \dot{v}_3 = \dfrac{v_1}{C_2} - \dfrac{v_3}{RC_2} \end{cases} \quad (9)$$

By using state-space averaging method, the state-space averaging model of the POESLLC is given as (10) [9]

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{dV_{C1}}{dt} \\ \frac{dV_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{R_{in}L_1} & \frac{d-1}{L_1} & \frac{d-1}{L_1} \\ \frac{1-2d}{C_1} & \frac{-d}{R_{in}C_1} & 0 \\ \frac{1-d}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{d}{R_{in}C_1} \\ -\frac{i_{L1}}{C_2} \end{bmatrix} u \quad (10)$$

$$\dot{v} = Av + Bu$$

Its output equation is given as

$$V_O = v_4 \quad (11)$$

Where R_{in} is internal resistance of source which is not shown in the circuit but it is very small value, u is input variable, d is duty cycle or the status of the switches, υ and ύ are the vectors of the state variables (i_{L1}, V_{C1} , V_{C2}) and their derivatives respectively.

III. Design Of PI Control

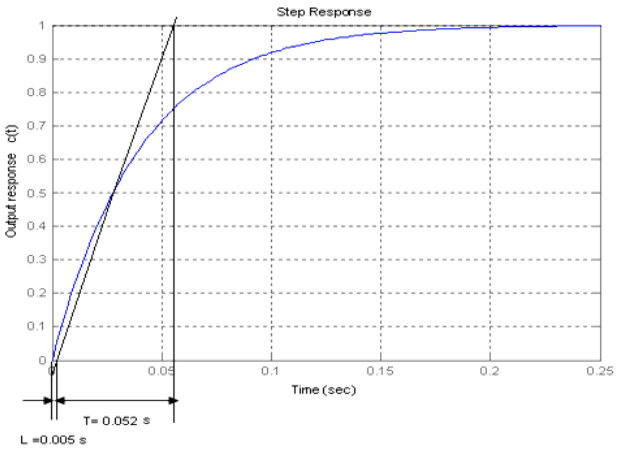

Fig. 4 S- shaped curve of step response of POESLLC

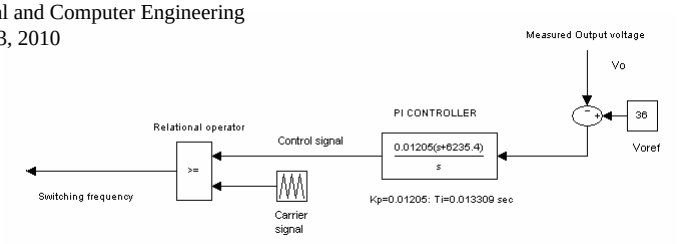

Fig. 5 Simulink simulation model of PI control

The PI control is designed to ensure the specifying desired nominal operating point for POESLLC, then regulating POESLLC, so that it stays very closer to the nominal operating point in the case of sudden disturbances, set point variations, noise, modeling errors and components variations.

The PI control settings proportional gain (*Kp*) and integral time (*Ti*) are designed using Zeigler – Nichols tuning method [6]-[7], [11] by applying the step test to (10) and (11) to obtain S – shaped curve of step response of POESLLC as shown in Fig. 4. From the S-shaped curve of step response of POESLLC may be characterized by two constants, delay time L = 0.005s and time constant T = 0.052s. The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersections of the tangent line with the time axis and line output response *c(t)* as shown in Fig. 4. Ziegler and Nichols suggested to set the values of *Kp* = 9.36 and *Ti* = 0.016s according to the Table I.

The PI control optimal setting values (*Kp* and *Ti*) for POELC are obtained by finding the minimum values of integral of square of error (ISE), integral of time of square of error (ITAE) and integral of absolute of error (IAE), which is listed in Table II. The simulink model of block of PI control section and its transfer function model are shown in Fig. 5. Error in output voltage and change in duty cycle of the power switch *S* (n- channel MOSFET) is respectively the input and output of the PI control.

TABLE I
ZIEGLER-NICHOLS TUNING RULES

Type of controller	*Kp*	*Ti*	*Td*
P	*T/L*	∞	0
PI	0.9*T/L*	*L*/0.3	0
PID	1.2T/*L*	*2L*	0.5*L*

TABLE II
SIMULATED RESULTS OF MINIMUM VALUES OF ISE, IAE, ITAE AND OPTIMAL SETTING VALUES OF KP AND TI

ISE	IAE	ITAE	Kp	Ti (s)
2.377	0.1935	0.001557	0.01205	0.0133

IV. Simulation Study

The validation of the system performance is done for five regions viz. transient region, line variations, load variations, steady state region and also components variations. .Simulations has been performed on the positive output elementary super lift Luo converter circuit with parameters listed in Table III. The static and dynamic performance of PI control for the positive output elementary super lift Luo converter is evaluated in Matlab/Simulink. The

Matlab/Simulink simulation model is depicted in Fig. 6. It can be seen that error in output voltage of the power switch (n – MOSFET) of PI control input is obtained by the difference between feedback output voltage and feedback reference output voltage, and output of PI control, change in duty cycle of the power switch (n - channel MOSFET).

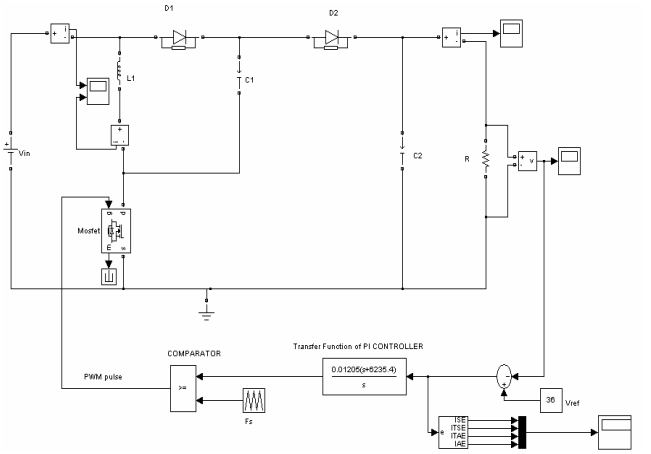

Fig.6 Simulation model of PI control with positive output elementary super lift Luo converter

A. Transient Region

TABLE III
PARAMETERS OF POSITIVE OUTPUT SUPER LIFT LUO CONVERTER

Parameters name	Symbol	Value
Input Voltage	*Vin*	12V
Output Voltage	*Vo*	36V
Inductor	L_1	100µH
Capacitors	C_1, C_2	30 µF
Nominal switching frequency	*Fs*	100kHz
Load resistance	*R*	50 Ω
Output power	*Po*	25.92W
Input power	*Pin*	28.236W
Input current	*Iin*	2.353 A
Efficiency	η	91.79%
Range of duty cycle	*d*	0.3 to 0.9
Desired duty cycle	*d*	0.5

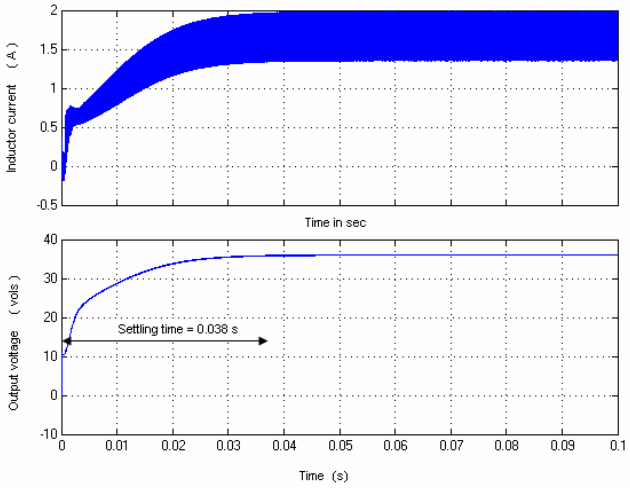

Fig. 7 Output voltage and inductor current in a transient region

Fig. 7 shows the output voltage and the inductor current of PI with POESLLC in the transient region. It can be found that the converter output voltage and inductor current has a negligible overshoot and settled at time of 0.038 s in this region with designed PI control.

B. Line Variations

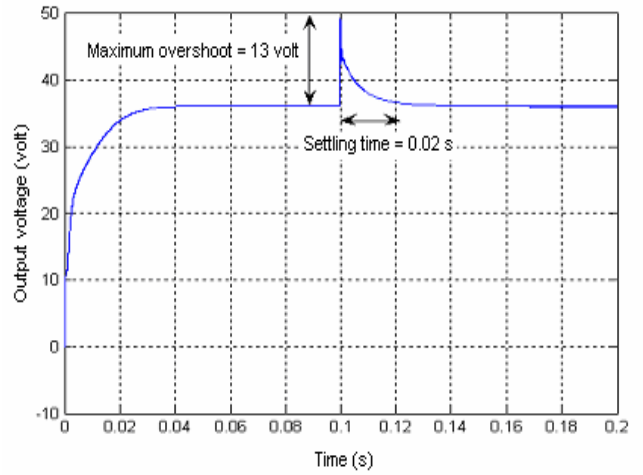

Fig. 8 Output voltage when input takes a step change from 12V to 15V

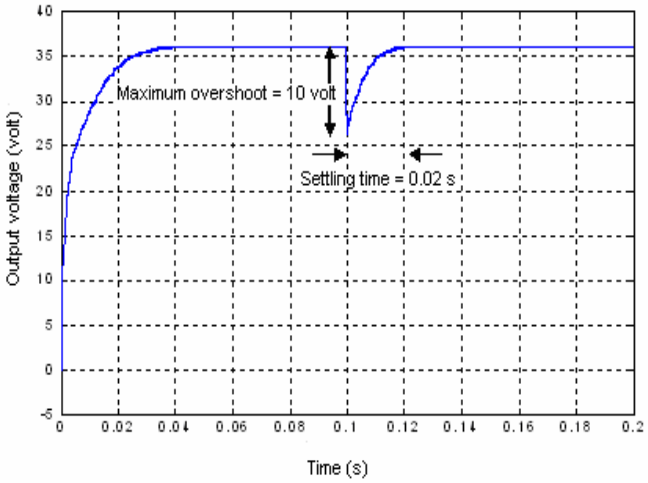

Fig. 9 Output voltage when input takes a step change from 12V to 9V

In Fig. 8 shows the variation of output voltage of PI control with positive output elementary super lift Luo converter for the input voltage step change from 12 V to 15 V (+ 30 % line disturbance). It can be found that converter output voltage has a maximum overshoot of 13 V and 0.02 s settling time with designed PI control. In Fig. 9 shows the output voltage variation for another input voltage step change from 12 V to 9 V (- 30 % line disturbance). It can be seen that the converter output voltage has a maximum overshoot of 10 V and 0.02 s settling time.

C. Load Variations

Fig. 10 shows the variation of output voltage with the step change in load from 50 Ω to 60 Ω (+ 20% load disturbance). It could be seen that there is a small overshoot of 0.5V and steady state is reached with a very less time 0.018 s.

In Fig. 11 shows another variation of output voltage with step change in load from 50 Ω to 40 Ω (- 20 % load disturbance). It could be seen that there is a small overshoot

of 0.5V and steady state is reached with a very small time 0.018 s.

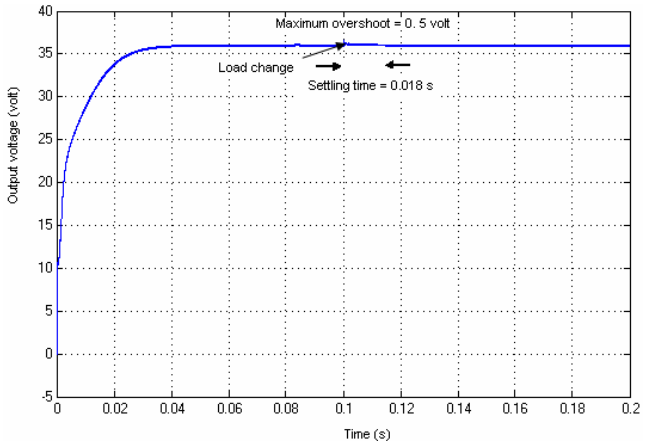

Fig.10 Output voltage when load resistance makes a step changes from 50 Ω to 60 Ω

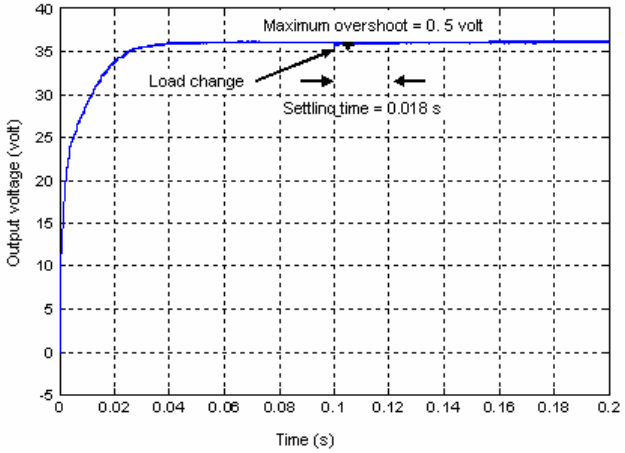

Fig.11 Output voltage when load resistance makes a step changes from 50 Ω to 40 Ω

D. Steady State Region

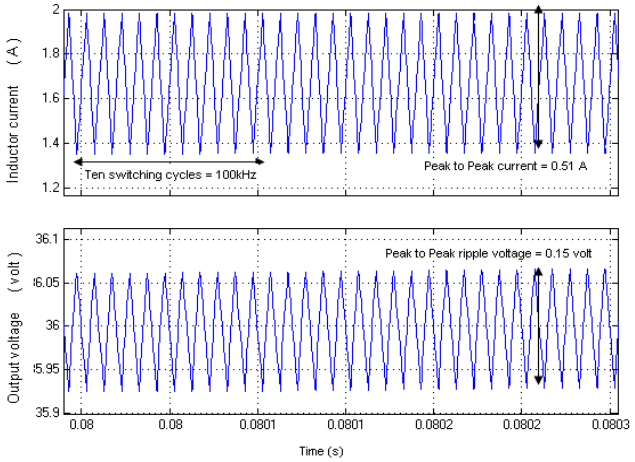

Fig.12 Output voltage and inductor current in steady state region

Fig. 12 shows the instantaneous output voltage and current of the inductor current in the steady state. It is evident from the figure that the output voltage ripple is very small about 0.15V and the peak to peak inductor current is 0.51A while the switching frequency is 100 kHz.

E. Circuit Components Variations

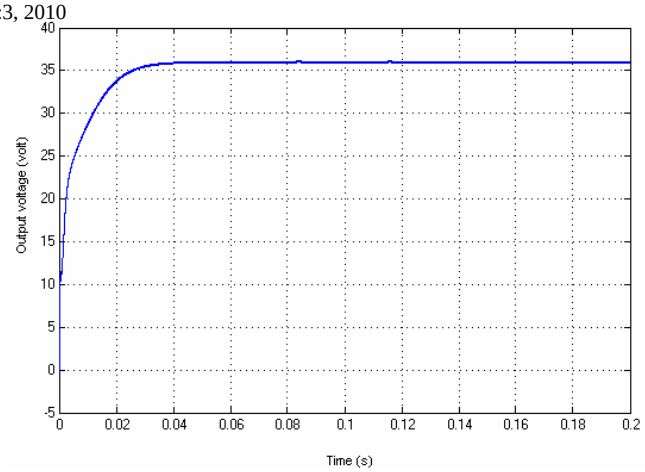

Fig.13 Output voltage when capacitors variation from 30 µF to 100 µF

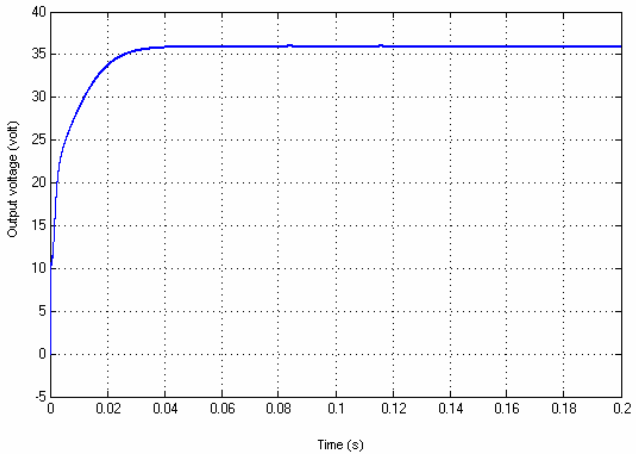

Fig.14 Output voltage when inductor varies from 100µH to 500µH

An interesting result has been illustrated in Fig. 13, which shows response for the variation in capacitor values 30 µF to 100 µF. The PI control is very successful in suppressing effect of capacitance variation effect that a minute output ripple voltage. The capacitor change has no severe effect on the value of inductor current. In Fig. 14 shows the output voltage for inductor variation from 100 µH to 500 µH and the change has no severe effect on the converter behavior due to the efficient developed PI control.

Figs. 15 and 16 show the average input current and average output current respectively. It is showed that the average input current is 2.307A and average output current is 0.72A which is closer to theoretical value in Table III. Using simulation analysis computes that the input and output power values are 28.236W and 25.92W respectively, which is closer to the calculated theoretical value listed in Table III.

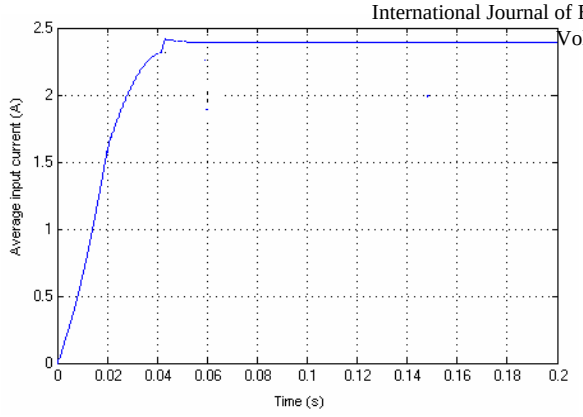

Fig.15 Average input current

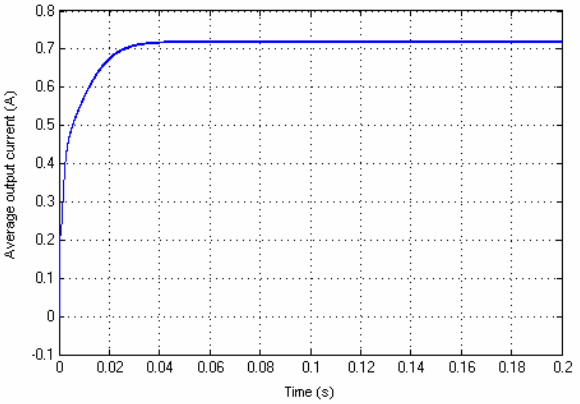

Fig.16 Average output current

V. Conclusions

The positive output elementary super lift Luo converter (POESLLC) performs the voltage conversion from positive source voltage to positive load voltage. Due to the time variations and switching nature of the power converters, their dynamic behavior becomes highly non-linear. This paper has successfully demonstrated the design, analysis, and suitability of PI controlled positive output elementary super lift Luo converter. The simulation based performance analysis of a PI controlled positive output elementary super lift Luo converter circuit has been presented along with its state space averaged model. The PI control scheme has proved to be robust and its triumph has been validated with transient region, line and load regulations, steady state region and also with circuit components variations. The positive output elementary super lift Luo converter with PI control thus claims its use in applications such as computer peripheral equipment, switch mode power supply, medical equipments and industrial applications, especially for high voltage projects etc.

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He has made a significant contribution to the PWM theory through his publications and has developed close ties with the international research community in the area. He has authored more than 50 papers published in international and national conference proceedings and professional journals. Dr.S.Jeevananthan regularly reviews papers for all major IEEE TRANSACTIONS in his area and AMSE periodicals (France). He is an active member of the professional societies, IE (India), MISTE, SEMCE and SSI.