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PI Control of Split Inductor Type Elementary Additional Series Positive Output Super Lift Converter

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Abstract: Super lift converter is a new series of DC/DC converter possessing high voltage transfer gain, high efficiency, reduced ripple voltage and current. Super lift technique armed by split inductors increases the output voltage in higher geometric progression. This paper focuses on splitting the input side inductor of the additional series positive output super lift converter in order to obtain a high voltage transfer gain. The proposed super lift converter is modeled using state space averaging technique. A suitable PI controller has been designed to regulate the converter against audio susceptibility and output impedance variation. Simulation study of the proposed converter along with the controller has been carried out in MATLAB/SIMULINK to investigate the static and dynamic response of the converter.

Key words: Split type elementary additional series positive output super lift converter (SEPOSLC) · proportional · Integral (PI) control · DC to DC Converter (DC/DC)

INTRODUCTION

Super lift converter for a given input voltage, the output voltage increases stage by stage in geometric progression. Voltage conversion from line side to load side output voltage V_0. Positive Output Super Lift Converter (POSLC) is a new series of DC to DC converter possessing high voltage transfer gain, high power density, high efficiency, reduced ripple voltage and current. It effectively increases the voltage transfer gain in higher proportion [1-4]. Split inductor type positive output super lift converter splits the energy storage element inductor into α part, effectively increases the energy storage in each capacitor. The stored energy in the inductor and capacitor is pumped to the load.

Split stage in POSLC converter is defined as α stage, if $\alpha = 2$ the input inductor in the circuit topology is splitted into two inductors in the circuit which is charged to the supply voltage when the switch is in the ON condition. Positive output super lift converter is classified into two series namely main series and additional series, these two series differs from the number of energy storage elements used in their topology.

Proportional Integral (PI) controller has been implemented for the proposed DC-DC converter. PI control techniques offer stability, large line and load variation robustness, good dynamic response. PI control is chosen to ensure fast dynamic response for line side and load side disturbances with output voltage regulation.

In this paper, state-space averaged model for split type elementary additional series positive output super lift luo converter (SEPOSLLC) has been derived. The static and dynamic performance of PI control for split type elementary additional series positive output super lift converter has been studied in Matlab/Simulink. Details on operation, analysis, control strategy and simulation results for split type elementary additional series positive output super lift converter (SEPOSLC) has been presented in the subsequent sections.

Converter Operation and Modeling of Split Type Positive Output Super Lift Converter

Circuit Description and Operation: The circuit diagram of the split inductor type positive output super lift converter is shown in Figure-1. It includes DC supply voltage V_{in}, inductors L_1 to L_2, C_1, C_2, C_{11}, C_{22} capacitor, power switch (n-channel MOSFET) S, freewheeling diodes D_1 to D_7 and load resistance R.

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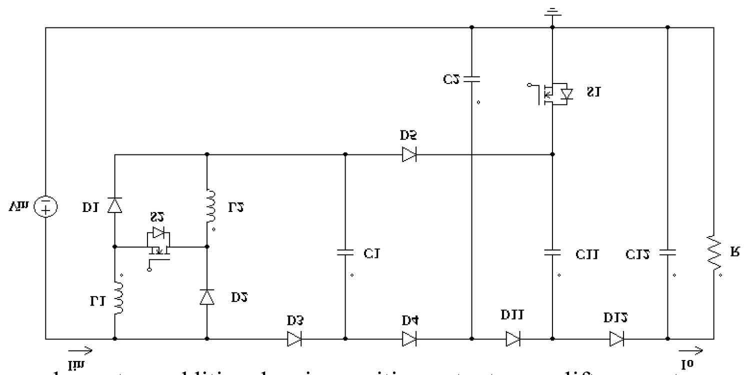

Fig. 1: Split inductive type elementary additional series positive output super lift converter.

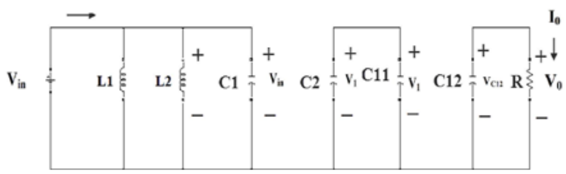

Fig. 2: Mode1 operation.

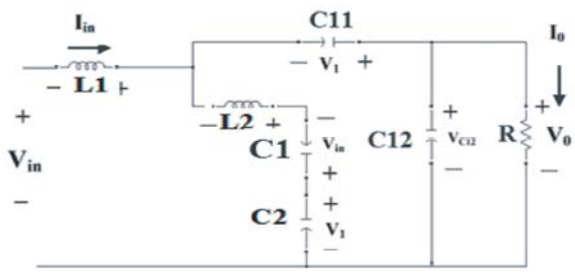

Fig. 3: Mode 2 operation.

In the description of the converter operation, it is assumed that all the components are ideal and also split inductor type elementary additional series positive output super lift converter operates in a continuous conduction mode. Figure 2 and 3 shows the modes of operation of the converter. The voltage across the inductors L_1 and L_2 are charged to V_{in} during the on state of the switch under the steady state condition.

The current i_L flowing through inductor L increases with voltage V_{in} during switching-on period kT.

Inductor L decreases with voltage - $[V_O - V_1 - V_{in}]$ during switching-off period (1 - k) T. The inductor current increases during switch S on and decreases during switch S off. The peak to peak current ripple in the inductor is the same during steady state operation and it is given as:

$$\Delta_{iL} = \frac{V_{in}}{L} kT = \frac{V_o - V_1 - V_{in}}{L}(1-k)T \tag{1}$$

$$V_0 = \left(\frac{3+k}{1-k}\right)V_{in} \tag{2}$$

The voltage transfer gain is:

$$G = \frac{V_O}{V_{in}} = \left(\frac{3+k}{1-k}\right) \tag{3}$$

The input current i_{in} is equal to $(i_{L1} + i_{L2} + i_{C1})$ during switching-on and only equal to i_L during switching-off. Inductor current i_{L1} and i_{L2} is equal to i_{C1} during switching-off. In steady state, the voltage across the inductor L_1, L_2 is equal to V_{in}. The following relations are obtained [5].

$$i_{in\text{-}off} = i_{C\text{-}off} = i_{L1\text{-}off} + i_{L2\text{-}off}$$
$$i_{in\text{-}on} = i_{C1\text{-}on} + i_{L1\text{-}on} + i_{L2\text{-}on}$$
$$i_{L1\text{-}on} = \frac{I_O}{k} \tag{4}$$

If inductance L_1 is large enough, i_L is nearly equal to its average current I_L. Therefore

$$i_{in\text{-}off} = I_L = i_{L1\text{-}off} + i_{L11\text{-}off}$$
$$i_{L1\text{-}off} = i_{L2\text{-}off} = i_{L3\text{-}off}$$
$$i_{in\text{-}off} = I_L = \frac{2I_O}{(1-k)}$$
$$i_{L1\text{-}off} = i_{L2\text{-}off} = \frac{I_O}{(1-k)} \tag{5}$$

And average input current:

$$I_{in} = ki_{in\text{-}on} + (1-k)i_{in\text{-}off} = \frac{4I_o}{(1-k)} \tag{6}$$

The variation ratio of inductor current i_L is:

$$? = \frac{?\ i_L/2}{i_L} = \frac{k\,(1-k)^2 R}{8\,(4-2k)\,L_1 f} \quad (7)$$

The ripple voltage of output Vo is:

$$?\,V_o = \frac{?\,Q}{L_{12}} = \frac{(1-k)T\,I_o}{L_{12}} = \frac{(1-k)V_o}{fL_{12}\,R} \quad (8)$$

Therefore, the variation ratio of output voltage V_o is:

$$? = \frac{?\,V_o/2}{V_o} = \frac{(1-k)}{2RfL_{12}} \quad (9)$$

State Space Modeling: State variables x1, x2, x3, x4, x5, x6 are chosen as the current i_{L1}, the voltage V_{L1}, V_{L2}, V_{L3}, V_{C1}, V_{C2}, respectively. From Figure-2 When the switch is closed, the state space equation is given as:

$$\begin{cases} \dot{X}_1 = \frac{U_1}{L_1} \\ \dot{X}_2 = \frac{U_1}{L_2} \\ \dot{X}_3 = \frac{U_1}{R_{in}} - \frac{X_1 + X_2}{C_1} \\ \dot{X}_4 = \frac{A * U_1}{R_{in}} - X_1 \\ \dot{X}_5 = \frac{B * U_1}{R_{in} * C_1} - \frac{B * (X_1 + X_2)}{C_1} \\ \dot{X}_6 = -\frac{X_6}{RC_4} \end{cases} \quad (10)$$

In Figure-3 when the switch is open, the state space equation of split inductor type elementary additional series positive output super lift converter is given as

$$\begin{cases} \dot{X}_1 = \left(\frac{C * U_1}{(1-k) * L_1}\right) - \frac{X_2}{L_2} \\ \dot{X}_2 = X_1 - C_3 * B * X_2 \\ \dot{X}_3 = \frac{X_1}{C_1 * C_3 * B} \\ \dot{X}_4 = D * X_1 \\ \dot{X}_5 = E * X_1 \\ \dot{X}_6 = \frac{C_3 * C_1}{C_4} - \frac{X_6}{RC_4} \end{cases} \quad (11)$$

where the A, B, C, D, E, F are constants. They are given below:

$$\begin{cases} A = (3 + k/1 - k) * (C_3/C_1C_2) \\ B = (3 + k/1 - k) \\ C = (1 + 3k/1 - k) \\ D = (C_1(1 + k)/(C_2 * C_1(1 + k) + C_2 * C_3(3 + k)) \\ E = (C_3(3 + k)/(C_3 * C_1(1 + k) + C_3^2(3 + k)) \end{cases} \quad (12)$$

By using state space averaging method [6, 9], the state space averaged equation in matrix form of the split inductor type elementary additional series positive output super lift converter is given as:

$$V = AV + BU \quad (13)$$

Its output equation is given as:

$$V_0 = V_{L12} \quad (14)$$

where R_{in} is internal resistance of source, u_1 is input variable, k is duty cycle or the status of the switches, X_1, X_2, X_3, X_4, X_5 and X_6 are the vectors of the state variables (i_{C1}, V_{L1}, V_{L2}, V_{C1}, V_{C11}, V_{C12}) and their derivatives respectively.

Design of Pi Control: The PI control is designed to ensure the specified desired nominal operating point, to regulate the voltage for split inductor type elementary additional series positive output super lift converter, so that it stays very closer to the nominal operating point in the case of sudden disturbances and components variations.

The PI control settings proportional gain (K_P) and integral time (T_i) are designed using Zeigler - Nichols tuning method. Values of L and T obtained from open loop of split inductor for enhanced positive output super lift luo converter are as follows:

L = 0.0002s and time constant T = 0.004s. 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 [7]. Ziegler and Nichols suggested to set the values of $K_P = 1.8$ and $T_i = 0.0066$ s [8].

The PI control optimal setting values (Kp and Ti) 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) [10], which is listed in Table-1.

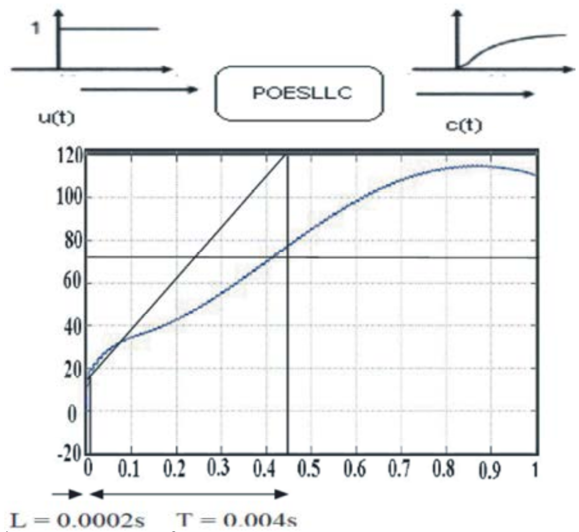

Fig. 4: S- Shaped curve of open loop response of SEPOSLC.

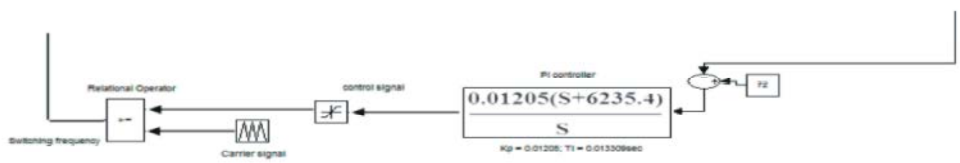

Fig. 5: Simulink simulation model of PI control.

Table 1: Simulated results of minimum values of ISE, IAE, ITAE and optimal setting values of Kp and T_i.

ISE	IAE	ITAE	K_p	T_i (s)
0.00124	0.0134	0.4059	0.01205	0.0133

Table 2: Parameters of split inductor type elementary additional series positive output super lift converter

Parameters Name	Symbol	Value
Input voltage	V_{in}	12V
Output voltage	V_o	84V
Inductor	L_1 and L_2	100µH
Capacitors	C_1,C_2, C_{11},C_{22},	30µF
Nominal switching frequency	Fs	100kHz
Load resistance	R	50O
Range of duty cycle	k	0.3 to 0.9
Desired duty cycle	k	0.5

Simulation Results: The validation of the system performance is done for five regions viz. transient region, line variations, load variations, steady state region and also component variations. Simulations have been performed on the split inductor type elementary additional series positive output super lift converter circuit with parameters listed in Table 2. The static and dynamic performance of the converter has been studied using MATLAB/SIMULINK model as depicted in Figure-6. It can be seen that error is computed by comparing the output voltage of converter with the reference voltage. Output of the PI controller is change in duty cycle of the power switch (n - channel MOSFET).

Transient Region: Figure-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 0.02 s in this region with designed PI control.

Line Variations: Figure-8 shows the variation of output voltage of PI control with split inductor type positive output elementary additional series positive output super lift converter for the input voltage step change from 12 V to 9V (-30% line disturbance). It can be found that converter output voltage has a maximum overshoot of 20 V and 0.02 s settling time with designed PI control. Figure-9 shows the variation of output voltage of PI control with split inductor type elementary additional series positive output super lift converter for the input voltage step change from 12 V to 15V (+30% line disturbance). It can be found that converter output voltage has a maximum overshoot of 26 V and 0.02 s settling time with designed PI control.

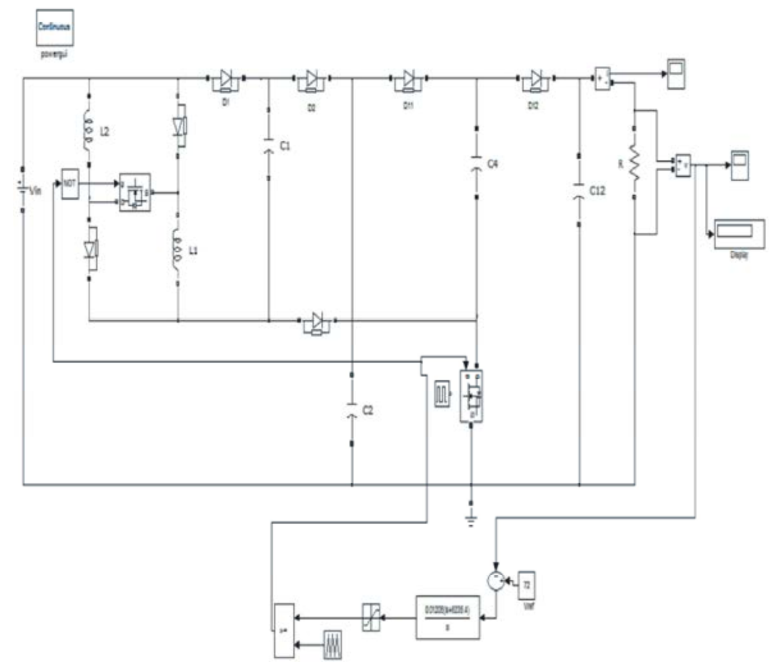

Fig. 6: Simulation model of PI control with split inductor type elementary additional series positive output super lift converter.

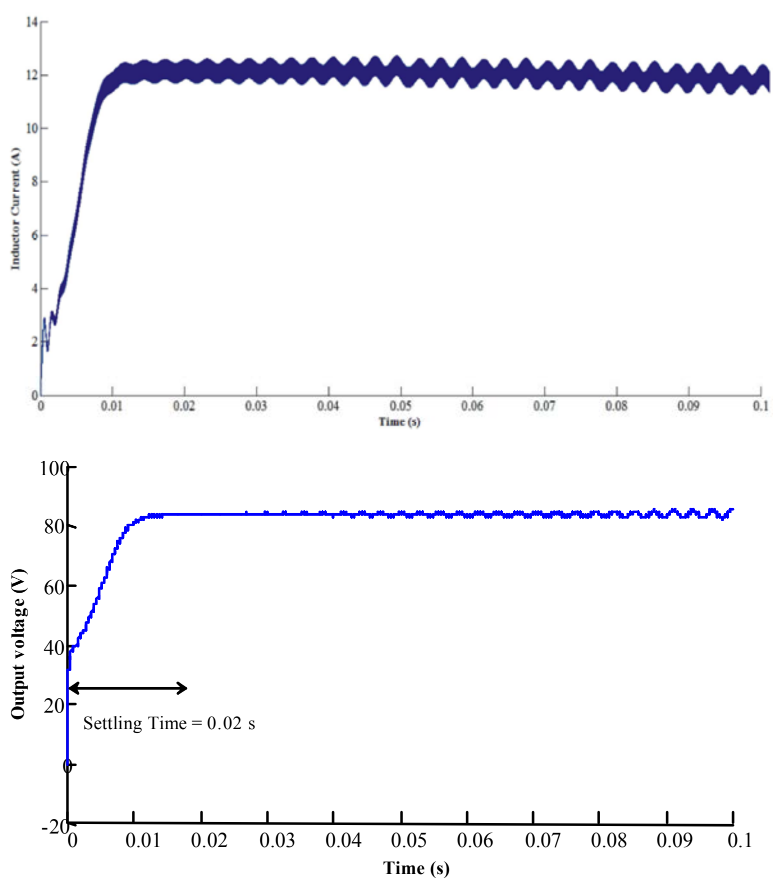

Fig. 7: Inductor current and output voltage in a transient region.

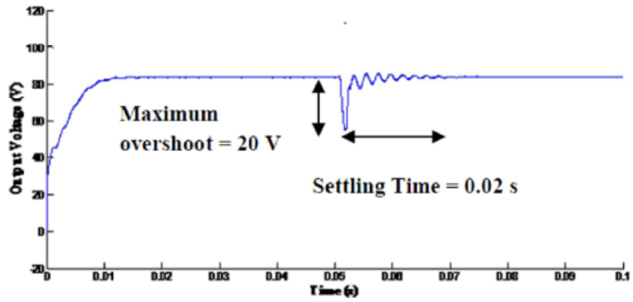

Fig. 8: Output voltage when input takes a step change from 12 V to 9 V.

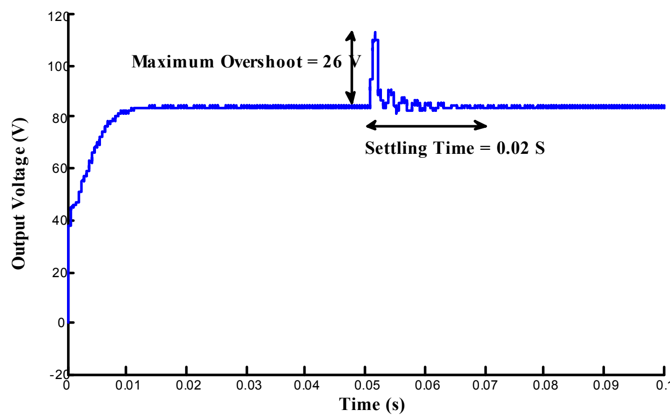

Fig. 9: Output voltage when input takes a step change from 12 V to 15 V.

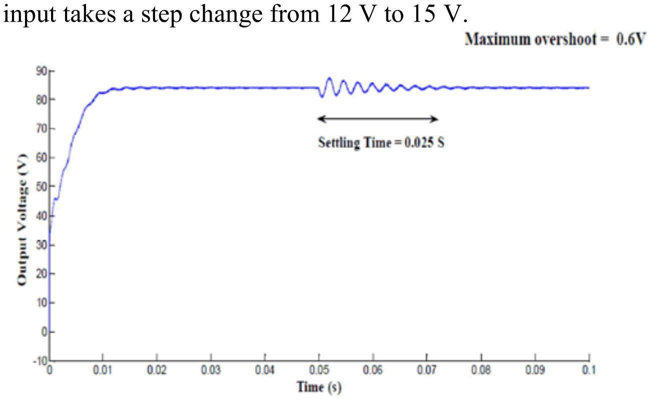

Fig. 10: Output voltage when load resistance makes a step changes from 50 Ω _to 60 Ω.

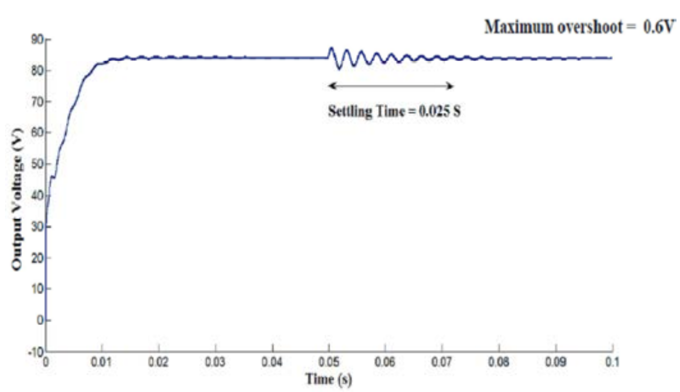

Fig. 11: Output voltages when load resistance makes a step changes from 50 Ω _to 40 Ω.

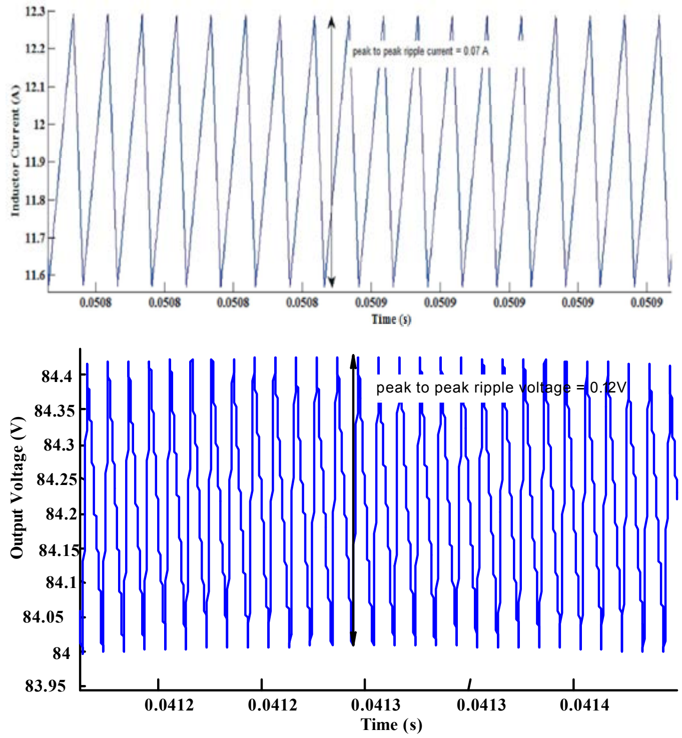

Fig. 12: Inductor current and Output voltage in steady state region.

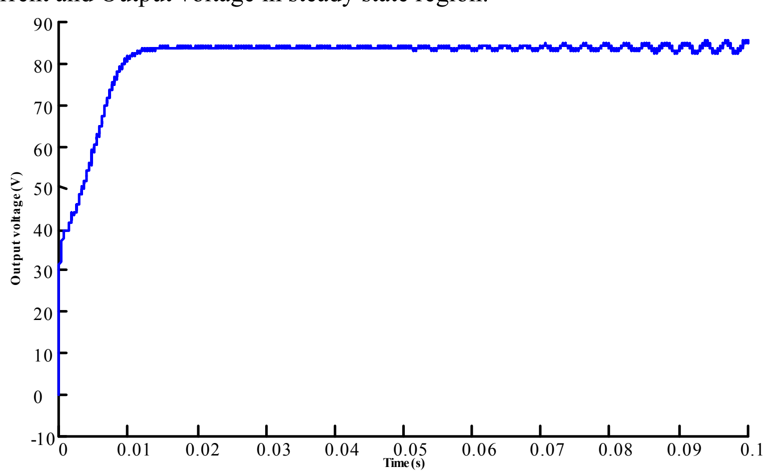

Fig. 13: Output voltage when inductor variation from 30 μF to 120μF.

Load Variations: Figure-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 0.6 V and steady state is reached with a very less time of 0.025 s.

Figure-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 0.6 V and steady state is reached with a very small time of 0.025 s.

Steady State Region: Figure-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 0.12V and the peak to peak inductor current is 0.07A while the switching frequency is 100 kHz.

Circuit Components Variations: An interesting result has been illustrated in Figure-13, which shows response for the variation in capacitor value from 30 μF to 120 μF. There is no wide variation in the output peak overshoot

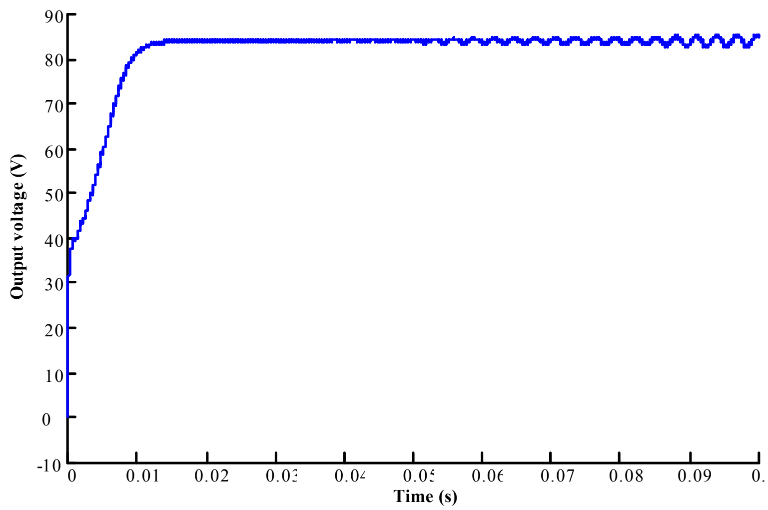

Fig. 14: Output voltage when inductor varies from 100 µH to 300 µH.

Table 3: Comparison of voltage transfer gain in various topologies of DC/DC converters

	Duty cycle				
Types of converters	0.5	0.6	0.7	0.8	0.9
Boost converter	2	2.5	3.33	5	10
Positive output super lift elementary main series converter	3	3.5	4.33	6	11
Positive output super lift elementary additional series converter	5	6	7.66	11	21
Split inductor type positive output elementary additional series super lift converter	6	7	8.66	12	22

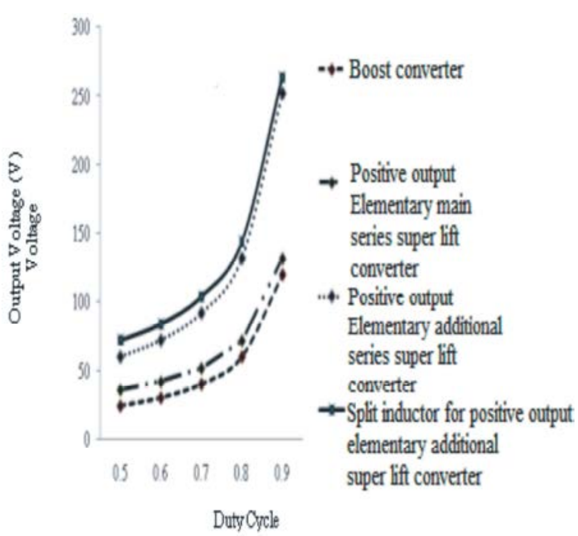

Fig. 15: Graphical representation of output voltage Vs duty cycle in various topologies of DC/DC converters.

and settling time. The inductor change has no severe effect on the steady state voltage across the load. Figure-14 shows the output voltage for inductor variation from 100 µH to 300 µH and the change has no severe effect on the converter behavior due to the efficient developed PI control.

Comparision of Output Voltage Transfer Gain in Various Topologies of Dc/dc Converters: Table-3 shows the comparison of voltage transfer gain for different topologies of DC / DC converter with a varying duty cycle for an input voltage of 12 V. Graphical representation of output voltage versus duty cycle for different topology of DC / DC converter are shown in Figure-15.

CONCLUSIONS

This paper has successfully illustrated the design, analysis and suitability of PI controller for split inductor type elementary additional series positive output super lift converter. The splitting of the input inductor in elementary additional series positive output super lift converter (SEPOSLC) increase the voltage, transfer gain in higher proportion. Due to the time variations and switching nature of the power converters, their dynamic behavior becomes highly non-linear. The simulation based performance analysis of a PI controlled split inductor type elementary additional positive output super lift converter circuit has been presented along with its state space averaged model. The PI control scheme has been studied for transient region, line and load regulations and steady state region and also with circuit component variations and it is found that it is proved to be robust.

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