Parametric variation analysis of CUK converter for constant voltage applications

Rheesabh Dwivedi[1], Vinay Kumar Dwivedi[2], Rahul Sharma[3]

Assistant Professor, Department of Electrical Engineering, Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India[1,2]

Lecturer, Department of Electrical Engineering, Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India[3]

Abstract: This paper presents an optimized controller for non-isolated DC-DC CUK converter for constant voltage applications. CUK converter has inverted voltage polarity at the output, however, it operates on the principle of capacitive energy transfer and uses inductors on both sides of the switch to reduce current ripple. MOSFETs are used as a switching device in low power and high frequency switching applications. It may be noted that, as the turn-on and turn-off time of MOSFETs are lower as compared to other switching devices, which reduces the switching losses. High frequency operation of MOSFET reduced size of filters components. These converters are now being used for various applications, such as Switched Mode Power Supply (SMPS) etc. The paper attempts to present parametric variation analysis of buck-boost converters for constant voltage output.

Keywords: CUK Converter, Duty cycle, PI Controller, PWM

I. INTRODUCTION

The basic non-isolated Cuk converter shown in Fig.1. It is one of the best basic DC-DC converters because its output voltage is negative and the output voltage may be higher or lower than the input voltage. It is widely used in electrical power system, communication, instruments and meters etc. The advantage of the basic non isolated Cuk converter over the standard buck–boost converter is to provide regulated DC output voltage at higher efficiency and this also reduce ripple currents and reduced switching losses. The basic non isolated Cuk converter is a switching power supply with two inductors, two capacitors, a diode, and a transistor switch. The transfer capacitor C_i stores and transfers energy from the input to the output.
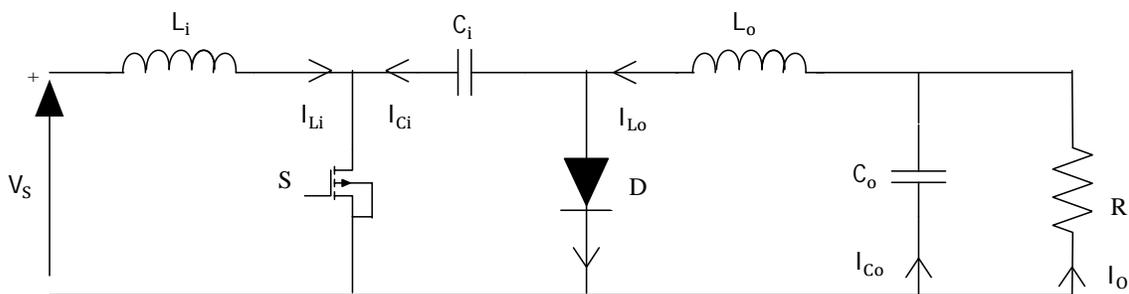

Fig. 1 Schematic diagram of non-isolated Cuk converter

II. OPERATING MODES OF CUK CONVERTER

The converter circuit is divided into two parts as shown in fig.2 and fig.3. During mode 1, when transistor switch is closed then current through inductor L_i rises. At the same time the voltage of capacitor C_i reverse biases diode D and turns it off. The capacitor C_i discharges its energy to the circuit formed by C_i, C_O, L_O and the load.
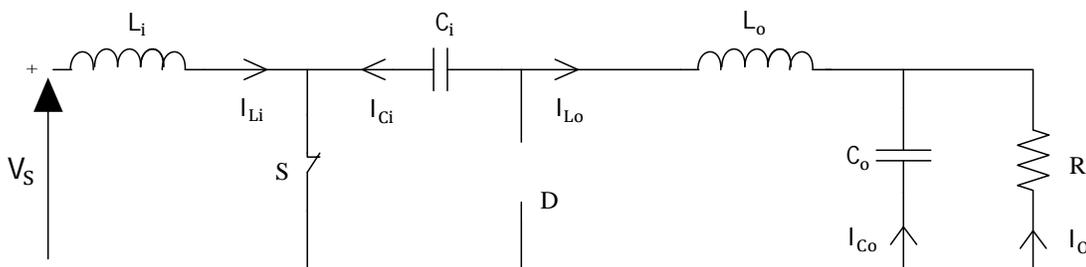
Fig.2 Mode 1: Switch Closed

During mode 2, when the input voltage is turned on and switch S is open then diode D is forward biased and capacitor C_i is charged through L_i, D and the input supply V_S. The energy which is stored in the inductor L_O is transferred to the load. The diode D and the switch S provide a synchronous switching action.
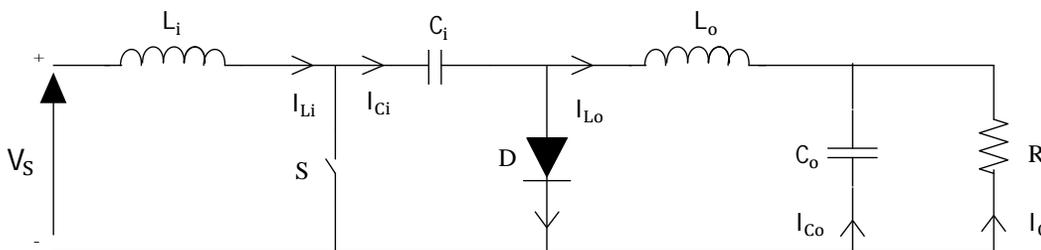

Fig.3 Mode 2: Switch Open

The Cuk converter can step the voltage either up or down, depending on the duty cycle. The Cuk converter contain the series inductors at both input and output, hence it has much lower current ripple in both circuits. The average output voltage can be calculated in term of the switch duty cycle.

D = on time duration of switch/ total switching time period

Duty cycle $= -\dfrac{V_o}{V_S - V_o}$

Output voltage $(V_o) = -V_S \left[\dfrac{D}{1-D}\right]$ (Where the negative sign indicates voltage inversion)

Control schematic of CUK converter output voltage is assumed to be 400V. A simple CUK converter model realize in MATLAB Simulink is shown in fig.5
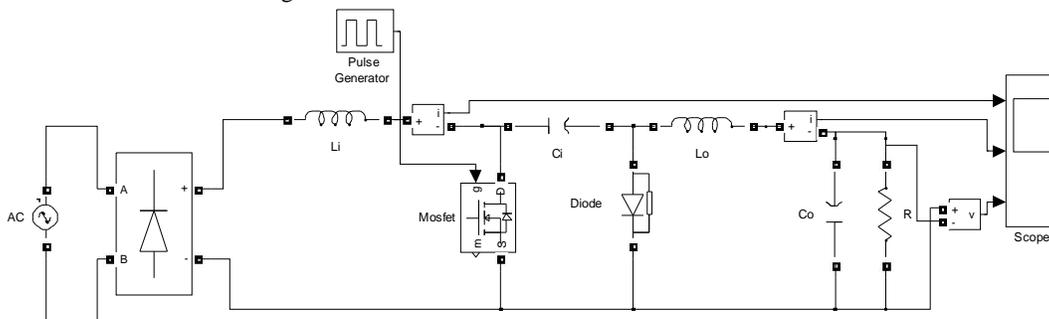

Fig. 4 Simulink model of open loop non- isolated Cuk converter

Design parameter and equations for non-isolated Cuk converter:

$V_O = DV_{in}/(1-D)$

$L_i = DV_{in}/(\Delta I_{Li})\,f_s$

$L_O = V_O(1-D)/(\Delta I_{LO})f_s$

$C_i = D/\{(Rf_s)(\Delta V_{Ci}/V_O)\}$

$C_O = (1 - D)/\{(8L_0f_s{}^2)(\Delta V_{Co}/V_o)\}$

Where

f_s = switching frequency

ΔI_{Li} = peak to peak ripple current I_{Li} (assuming 10% of I_{Li})

ΔI_{Lo} = peak to peak ripple current I_{Lo} (assuming 10% of I_{Lo})

ΔV_{Ci}= voltage ripple (assuming 5% of V_O)

D = duty cycle

Calculated value of design variables are D=0.562, L_i= 54.47×10^{-3} H, L_o= 70×10^{-3} H, C_i= 1.125×10^{-6} F and C_o= 0.025×10^{-6} F
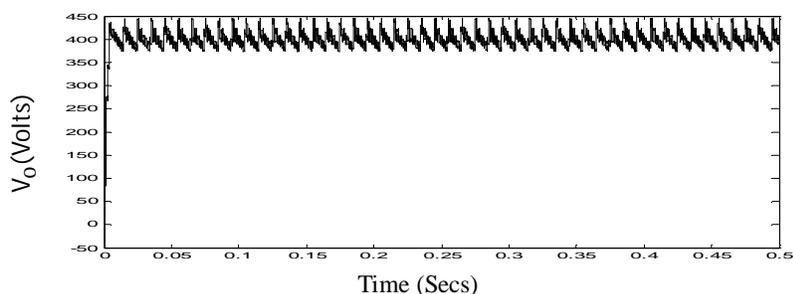

Fig.5 Open loop response of non-isolated Cuk converter

The results of open loop CUK converter is shown in fig.7, which depicts peak to peak ripple voltage (ΔVo) is 54 Volt and maximum overshoot of 10%. Since the design equations assume constant input voltage and constant load under steady state conditions, the variation of input voltage shall result in fluctuation in output Therefore, a closed loop controller is required with optimized parameters to suit the constant voltage output as per requirement of load.

III.   CLOSED LOOP CUK CONVERTER

The Simulink Schematic of CUK converter with analog PI controller is shown in fig. 8
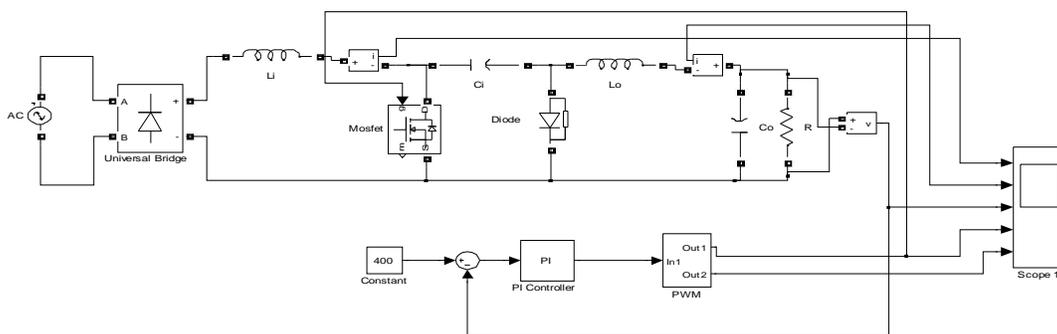
Fig. 6 Simulink model of closed loop Cuk converter

The output voltage is sensed V_{out} and compared with the input voltage V_{ref} .An error signal is produced which is processed through PI controller to generate a control voltage. The control voltage is used to feed to the PWM generator for control of switch. The PI controller has two parameters namely K_P and K_I.

PI controller has transfer function: $C(s) = K_P + \dfrac{K_i}{s}$

Where, K_P=Proportional gain and K_i= Integral gain
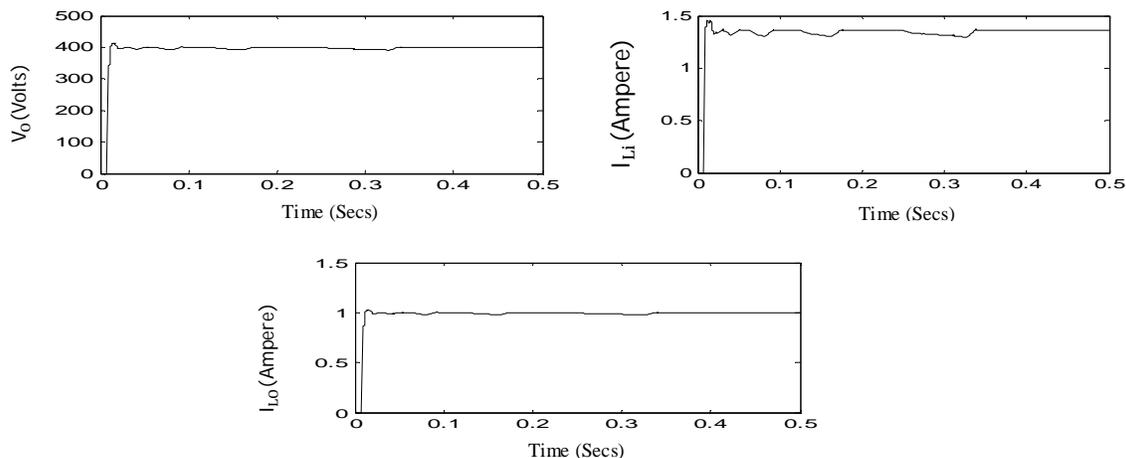
Fig. 7 Closed loop response of Cuk converter

The results of closed loop CUK converter is shown in fig.9 which has maximum overshoot of 3.2%, settling time 0.0116 sec and rise time 0.0107 sec.

TABLE I AND FIG 8-10 SHOWS VARIATION OF PERFORMANCE PARAMETERS FOR VARIATION OF BOOST INDUCTOR (L_i) VALUE IS VARIED.

TABLE I RESULTS OF BOOST INDUCTOR (L_i) VARIATION.

L_i (mH)	Voltage(V_O)			Current (I_{Li})			Current (I_{Lo})		
	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time
34.47	3.2	0.0113	0.0107	7.94	0.01	0.01	3.2	0.0107	0.0107
44.47	3.125	0.0113	0.01075	7.4	0.01	0.01	3.1	0.01073	0.0107
54.47	3.072	0.0113	0.0108	7.2	0.01	0.01	3	0.0108	0.0108
64.47	3.075	0.0114	0.0108	7.46	0.01	0.01	3.07	0.0109	0.01085
74.47	3.125	0.0114	0.0109	7.5	0.01	0.01	3.12	0.0109	0.0109
84.47	3.25	0.0115	0.011	8.25	0.01	0.01	3.25	0.011	0.011
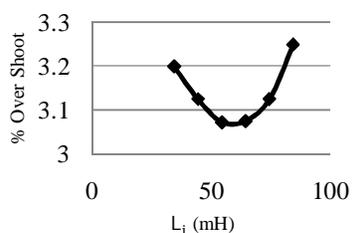
Fig.8.1 Effect on overshoot due to variation in boost inductor (L_i)
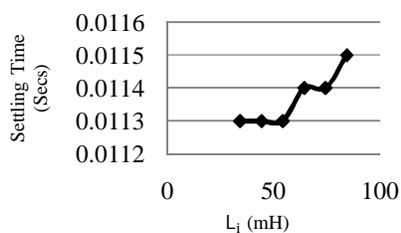
Fig.8.2 Effect on settling time due to variation in boost inductor (L_i)
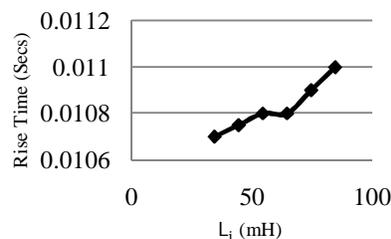
Fig.8.3 Effect on rise time due to variation in boost inductor (L_i)

Fig.8 Effect on output voltage (V_O) due to variation in boost inductor (L_i)

When the value of boost inductor (L_i) increases up to two times of the designed value then output voltage (V_O) overshoot, settling time and rise time continuously increases. If the value of boost inductor (L_i) decreases from its designed value then output voltage (V_O)overshoot increases continuously, settling time remains constant and rise time continuously decreases.
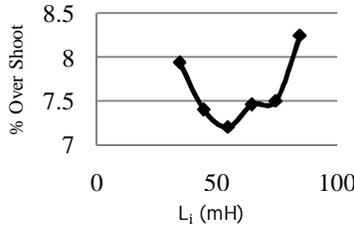
Fig.9.1 Effect on overshoot due to variation in boost inductor (L_i)
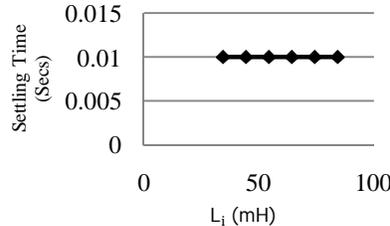
Fig.9.2 Effect on settling time due to variation in boost inductor (L_i)
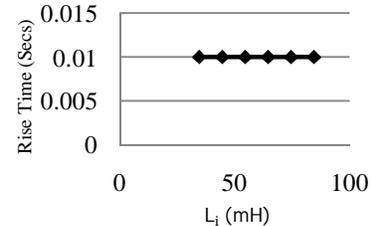
Fig.9.3 Effect on rise time due to variation in boost inductor (L_i)

Fig.9 Effect on inductor current (IL_i) due to variation in boost inductor (L_i)

When the value of boost inductor (L_i) increases up to two times of the designed value then boost inductor current (I_{Li}) overshoot continuously increases, settling time and rise time remains constant. If the value of boost inductor (L_i) decreases from its designed value then boost inductor current (I_{Li}) overshoot continuously increases, settling time and rise time remains constant.
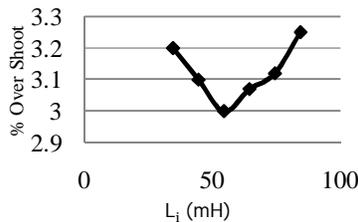

Fig.10.1 Effect on overshoot due to variation in boost inductor (L_i)
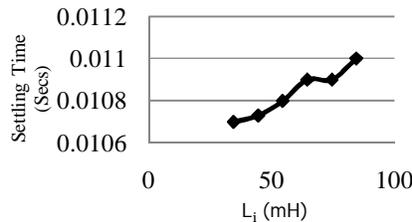
Fig.10.2 Effect on settling time due to variation in boost inductor (L_i)
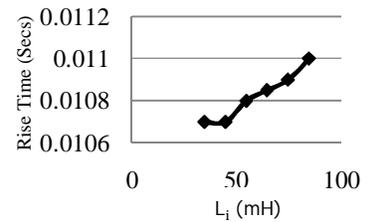
Fig.10.3 Effect on rise time due to variation in boost inductor (L_i)

Fig.10 Effect on inductor current (IL_o) due to variation in boost inductor (L_i)

When the value of boost inductor (L_i) increases up to two times of the designed value then filter inductor current (I_{Lo}) overshoot, settling time and rise time continuously increases. If the value of boost inductor (L_i) decreases from its designed value then filter inductor current (I_{Lo}) overshoot increases continuously, settling time and rise time continuously decreases.

TABLE II AND FIG 11-13 SHOWS VARIATION OF PERFORMANCE PARAMETERS FOR VARIATION OF FILTER INDUCTOR (L_O) VALUE IS VARIED.

TABLE II RESULTS OF FILTER INDUCTOR (L_O) VARIATION.

L_O (mH)	Voltage(V_O)			Current (I_{Li})			Current (I_{Lo})		
	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time
10	3.2	0.0112	0.0106	9.4	0.01	0.01	3.2	0.0106	0.0106
40	3.125	0.0112	0.0107	7.3	0.01	0.01	3.1	0.0107	0.0107
70	3.072	0.0113	0.0108	7.2	0.01	0.01	3	0.0108	0.0108
110	3	0.0115	0.0109	6.5	0.01	0.01	3	0.011	0.0109
140	2.95	0.0116	0.011	6.22	0.01	0.01	2.95	0.0112	0.011
170	2.95	0.0117	0.012	6.21	0.01	0.01	2.94	0.0113	0.012
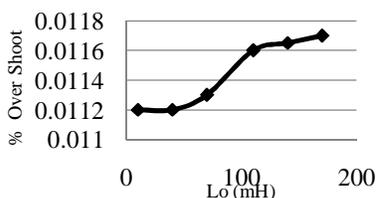
Fig.11.1 Effect on overshoot due to variation in filter inductor (L_O)
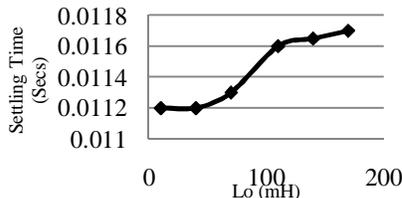
Fig.11.2 Effect on settling time due to variation in filter inductor (L_O)
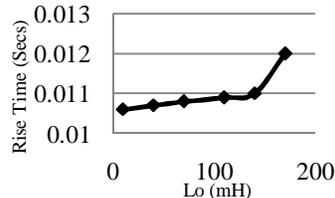
Fig.11.3 Effect on rise time due to variation in filter inductor (L_O)

Fig.11 Effect on output voltage (V_O) due to variation in filter inductor (L_O)

When the values of ripple filter inductor (L_O) increases up to two times of the designed value then output voltage (V_O) overshoot decreases, settling time and rise time continuously increases. If the values of ripple filter inductor (L_O) decreases up to seven times from its designed value then output voltage (V_O) overshoot increases, settling time and rise time continuously decreases.
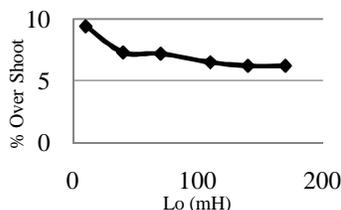
Fig.12.1 Effect on overshoot due to variation in filter inductor (L_O)
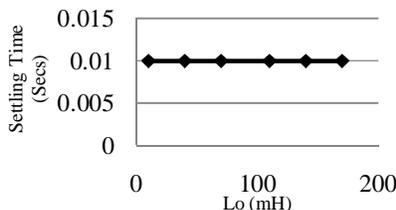
Fig.12.2 Effect on settling time due to variation in filter inductor (L_O)
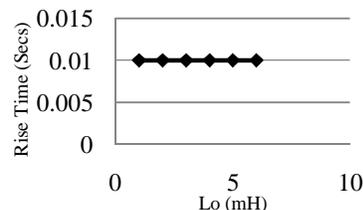
Fig.12.3 Effect on rise time due to variation in filter inductor (L_O)

Fig.12 Effect on inductor current (IL_i) due to variation in filter inductor (L_O)

When the value of ripple filter inductor (L_O) increases up to two times of the designed value then boost inductor current (I_{Li}) overshoot decreases, settling time and rise time remains constant. If the values of ripple filter inductor (L_O) decreases up to seven times from its designed value then boost inductor current (I_{Li}) overshoot increases, settling time and rise time remains constant.
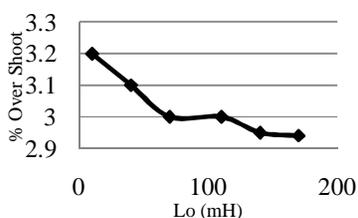
Fig.13.1 Effect on overshoot due to variation in filter inductor (L_O)
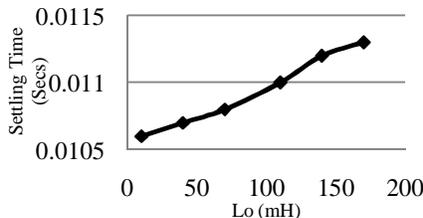
Fig.13.2 Effect on settling time due to variation in filter inductor (L_O)
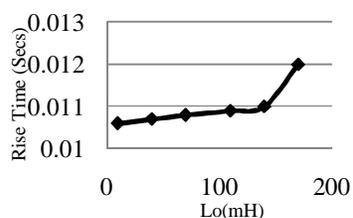
Fig.13.3 Effect on rise time due to variation in filter inductor (L_O)

Fig.13 Effect on inductor current (IL_O) due to variation in filter inductor (L_O)

When the value of ripple filter inductor (L_O) increases up to two times of the designed value then filter inductor current (I_{Lo}) overshoot decreases, settling time and rise time increases. If the values of ripple filter inductor (L_O) decreases up to seven times from its designed value then filter inductor current (I_{Lo}) overshoot increases, settling time and rise time continuously decreases.

TABLE III AND FIG 14-16 SHOWS VARIATION OF PERFORMANCE PARAMETERS FOR VARIATION OF BOOST CAPACITOR (C_i) VALUE IS VARIED.

TABLE III RESULTS OF BOOST CAPACITOR (C_i) VARIATION.

C_i (μF)	Voltage(V_o)			Current (I_{Li})			Current (I_{Lo})		
	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time
0.1125	2.875	0.0113	0.0109	5.93	0.01	0.0105	2.9	0.0108	0.0109
1.125	3.072	0.0113	0.0108	7.2	0.01	0.01	3	0.0108	0.0108
2.125	4	0.0112	0.0107	19.37	0.0127	0.01	4.1	0.01081	0.0107
3.125	7.25	0.0144	0.0108	36.02	0.0131	0.01	7.26	0.01082	0.0104
4.125	10.38	0.0154	0.0109	48.67	0.023	0.01	10.4	0.0141	0.0109
5.125	11.91	0.0162	0.0108	53.9	0.0246	0.01	11.91	0.0152	0.0108
6.125	12.6	0.0169	0.0106	54.41	0.0258	0.01	12.6	0.0158	0.0106
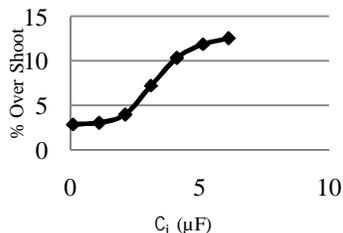
Fig. 14.1 Effect on over shoot due to variation in boost capacitor (C_i)
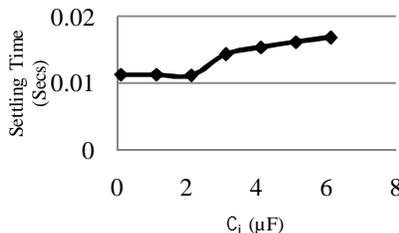
Fig. 14.2 Effect on settling time due to variation in boost capacitor (C_i)
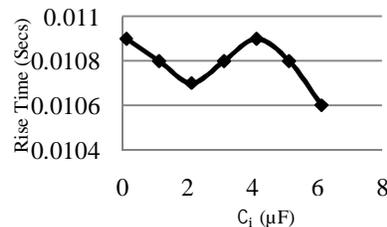
Fig. 14.3 Effect on rise time due to variation in boost capacitor (C_i)

Fig.14 Effect on output voltage (V_O) due to variation in boost capacitor (C_i)

When the value of boost capacitor (C_i) increases up to six times of the designed value then output voltage (V_O) overshoot and settling time increases and rise time decreases. If the values of boost capacitor (C_i) decreases from the designed value then output voltage (V_O) overshoot decreases, settling time remains constant and rise time increases.
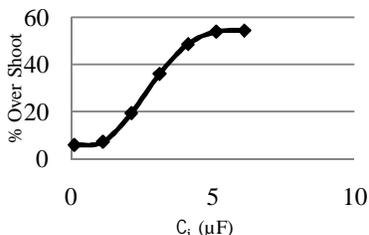

Fig. 15.1 Effect on over shoot due to variation in boost capacitor (C_i)
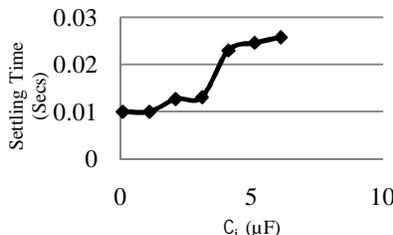
Fig. 15.2 Effect on settling time due to variation in boost capacitor (C_i)
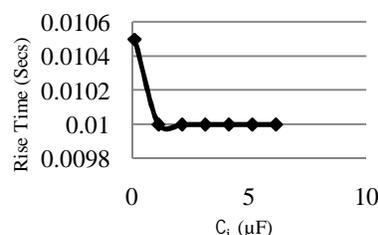
Fig. 15.3 Effect on rise time due to variation in boost capacitor (C_i)

Fig.15 Effect on inductor current (IL_i) due to variation in boost capacitor (C_i)

When the value of boost capacitor (C_i) increases up to six times of the designed value then boost inductor current (I_{Li}) overshoot and settling time continuously increases and rise time remains constant. If the values of boost capacitor (C_i) decreases from the designed value then boost inductor current (I_{Li}) overshoot decreases, settling time remains constant and rise time increases.
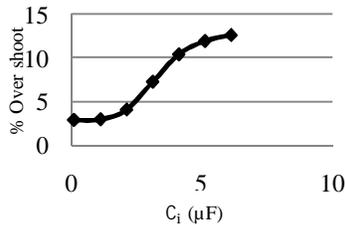
Fig. 16.1 Effect on over shoot due to variation in boost capacitor (C_i)

Fig. 16.2 Effect on settling time due to variation in boost capacitor (C_i)
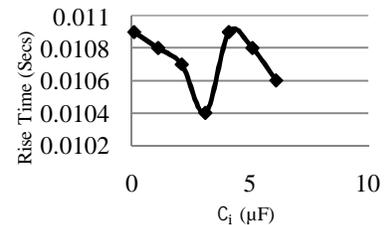
Fig. 16.3 Effect on rise time due to variation in boost capacitor (C_i)

Fig.16 Effect on inductor current (IL_O) due to variation in boost capacitor (C_i)

When the value of boost capacitor (C_i) increases up to six times of the designed value then filter inductor current (I_{Lo}) overshoot and settling time continuously increases and rise time decreases. If the values of boost capacitor (C_i) decreases from the designed value then filter inductor current (I_{Lo}) overshoot decreases, settling time remains constant and rise time increases.

TABLE IV AND FIG 17-19 SHOWS VARIATION OF PERFORMANCE PARAMETERS FOR VARIATION OF FILTER CAPACITOR (C_O) VALUE IS VARIED.

TABLE IV RESULTS OF FILTER CAPACITOR (C_O) VARIATION.

C_o (μF)	Voltage (V_O)			Current (I_{Li})			Current (I_{Lo})		
	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time	O.S (%)	Settling Time	Rise Time
0.00025	3.07	0.0113	0.0108	6.88	0.01	0.01	3	0.0107	0.0108
0.0025	3.071	0.0113	0.0108	6.9	0.01	0.01	3	0.0108	0.0108
0.025	3.072	0.0113	0.0108	7.2	0.0102	0.01	3	0.0108	0.0108
0.25	3.072	0.0113	0.0108	7.79	0.0105	0.01	3.1	0.01081	0.01
2.5	4.5	0.0115	0.0107	16.8	0.013	0.01	6.6	0.0118	0.01
25	34	0.0435	0.01	158.02	0.046	0.01	140	0.042	0.01
50	47.5	0.072	0.01	343.9	0.12	0.01	317	0.118	0.01
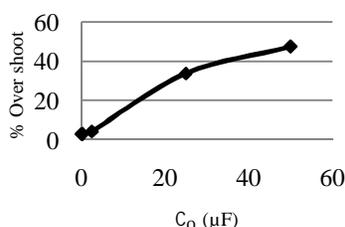
Fig. 17.1 Effect on over shoot due to variation in boost capacitor (C_i)
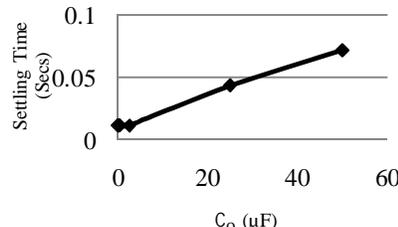
Fig. 17.2 Effect on settling time due to variation in boost capacitor (C_i)
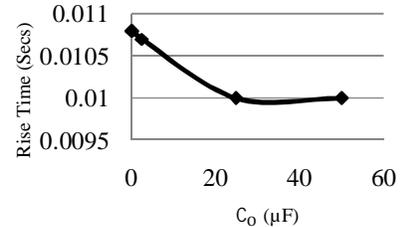
Fig. 17.3 Effect on rise time due to variation in boost capacitor (C_i)

Fig.17 Effect on output voltage (V_O) due to variation in filter capacitor (C_O)

When the value of filter capacitor (C_O) increases up to two thousand times of the designed value then output voltage (V_O) overshoot and settling time continuously increases however rise time decreases and finally attain a constant value. If the values of filter capacitor (C_O) decreases up to hundred times from the designed value then output voltage (V_O) overshoot decreases, settling time and rise time remains constant.

Fig. 18.1 Effect on over shoot due to variation in filter capacitor (C_O)

Fig. 18.2 Effect on settling time due to variation in filter capacitor (C_O)

Fig. 18.3 Effect on rise time due to variation in filter capacitor (C_O)

Fig.18 Effect on inductor current (IL_i) due to variation in filter capacitor (C_O)

When the value of filter capacitor (C_O) increases up to two thousand times of the designed value then boost inductor current (I_{Li}) overshoot and settling time continuously increases however rise time remains constant value. If the values of filter capacitor (C_O) decreases up to hundred times from the designed value then boost inductor current (I_{Li}) overshoot decreases, settling time and rise time remains constant.
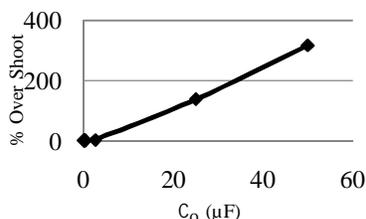

Fig. 19.1 Effect on over shoot due to variation in filter capacitor (C_O)
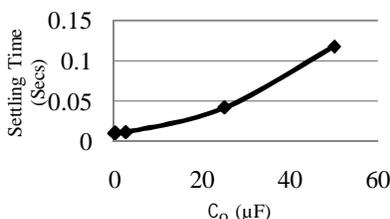
Fig. 19.2 Effect on settling time due to variation in filter capacitor (C_O)
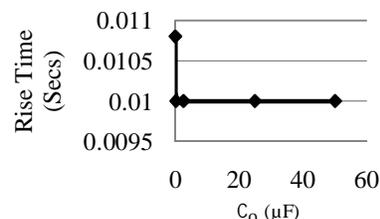
Fig. 19.3 Effect on rise time due to variation in filter capacitor (C_O)

Fig.19 Effect on inductor current (IL_O) due to variation in filter capacitor (C_i)

When the value of filter capacitor (C_O) increases up to two thousand times of the designed value then output filter inductor current (I_{Lo}), settling time continuously increases however rise time decreases and finally attain a constant value. If the values of filter capacitor (C_O) decreases up to hundred times from the designed value then filter inductor current (I_{Lo}) overshoot become constant, settling time slowly decreasing and rise time increased.

IV.   CONCLUSION

The parametric variation analysis of non-isolated CUK converters has been carried out for constant voltage applications considering inductor and capacitor as performance parameters. Non-isolated CUK converter has been designed to deliver 400 volts DC to a 400 watt load. Performance and applicability of this converter is presented on the basis of simulation in MATLAB SIMULINK. The design concepts are validated through simulation and results obtained show that a closed loop system using buck-boost converter will be highly stable with high efficiency. Cuk converter can be used for universal input voltage and wide output power range. The Cuk converter uses capacitive energy transfer. In the Cuk converter overshoot and settling time varies much if there is small change in boost capacitor. The closed loop Cuk converter has an efficiency of 98.69%.

REFERENCES

[1] Sanjeev Singh and Bhim Singh, "A Voltage-Controlled PFC Cuk Converter-Based *PMBLDCM Drive for Air-Conditioners," in Proc.* IEEE TRANS. ON INDUSTRY APPLICATIONS, VOL. 48, NO. 2, Apr. 2012, pp. 832-838.
[2] Sanjeev Singh and Bhim Singh, "Power quality improved PMBLDCM drive for adjustable speed application with reduced sensor buck-boost PFC converter" in proc. IEEE 11th ICETET, 2011, pp.180-184.
[3] Sanjeev Singh and Bhim Singh, "Comprehensive study of single-phase AC-DC power factor corrected converters with high-frequency isolation" IEEE Trans. on Industrial Informatics, vol. 7, no. 4, Nov. 2011, , pp. 540-556.

[4] Boopathy.K and Dr.Bhoopathy Bagan .K, "Buck Boost converter with improved transient response for low power applications" in Proc. IEEE SIEA, Sep 2011, pp. 155-160.

[5] Altamir Ronsani and Ivo Barbi, "Three-phase single stage AC-DC buck-boost converter operating in buck and boost modes" in Proc. IEEE, 2011, pp.176-182.

[6] Sanjeev Singh and Bhim Singh, "An adjustable speed PMBLDCM drive for air conditioner using PFC Zeta converter," *Int. J. Power Electron. (IJPElec)*, vol. 3, no. 2, pp. 171–188, Apr. 2011.

[7] Sanjeev Singh and Bhim Singh, "Power Electronics, Drives and Energy Systems (PEDES)," in Proc. IEEE PEDES'2010.

[8] Sanjeev Singh and Bhim Singh, "Single-phase power factor controller topologies for permanent magnet brushless DC motor drives," in IET Power Electron., 2010, Vol. 3, Iss. 2, pp. 147–175.

[9] Sanjeev Singh and Bhim Singh, "A voltage controlled adjustable speed PMBLDCM drive using a single-stage PFC half-bridge converter," in *Proc. IEEE APEC'10*, 2010, pp. 1976–1983.

[10] Marcos Orellana, Stephane Petibon and Bruno Estibals, "Four switch buck-boost converter for photovoltaic DC-DC ower applications" in proc. IEEE, ISGE, 2010, pp.469-474.

[11] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of single-phase improved power quality ac–dc converters," *IEEE Trans. Ind. Electron.*, vol. 50, no. 5, pp. 962–981, Oct. 2003.

[12] S. M. Ćuk, "Modeling, Analysis, and Design of Switching Converters," Ph.D. dissertation, California Institute of Technology, Pasadena, Nov. 1976.

BIOGRAPHY

Rheesabh Dwivedi received his B.Tech degree in Electrical & Electronics Engineering from Uttar Pradesh Technical University, Lucknow in 2010. He also obtained the M.Tech degree in Instrumentation & Control Engineering from Sant Longowal Institute of Engineering and Technology, Longowal Dist-Sangrur (Punjab) in 2013. He served as assistant professor in Gokaran Narvadeshver Institute of Technology & Management, Lucknow (U.P). His area of interest includes Power Electronics, Control System and Electrical Drives. He is currently an Assistant Professor at the Department of Electrical Engineering in Teerthanker Mahaveer University, Moradabad (U.P), India

Vinay Kumar Dwivedi received his M.Tech degree in Power Electronics & ASIC design from Motilal Nehru National Institute of Technology (MNNIT), Allahabad, U.P. in 2013 and graduated from Uttar Pradesh Technical University, Lucknow, U.P., India in 2008. He was a Faculty member with Dr. K. N. Modi Institute of Engineering & Technology, Ghaziabad, U.P. for about two years and then was with the MIT, Ghaziabad for about one year. His areas of interest are Power electronics, Power Quality, Network and Control System. He is currently an Assistant Professor at the Department of Electrical Engineering in Teerthanker Mahaveer University, Moradabad (U.P), India.

Rahul Sharma completed his B.Tech degree in Electrical Engineering from Uttar Pradesh Technical University,Lucknow in 2011. His area of interest includes Power Electronics, Control System and Electrical Machines. He is currently a Lecturer at the Department of Electrical Engineering in Teerthanker Mahaveer University, Moradabad (U.P), India.