Closed Loop Control of High Voltage Gain IBC with Voltage Multiplier Module

Riyaz K.Kadalgi
P.G. Student, Power Electronics,
Dayananda Sagar College of Engg, Bangalore, India,
riyazkadalgi@gmail.com

Dhanlakshmi.R
Electrical & Electronics Engineering
Dayananda Sagar College of Engg, Bangalore, India,
dhanalaxmisk@gmail.com

Abstract—This paper presents the closed loop control of a high voltage gain IBC. A high voltage gain Interleaved Boost Converter (IBC) with Voltage Multiplier module is suitable for renewable energy system, which requires high step up conversion ratio. In order to obtain high gain, a built-in transformer and a voltage multiplier module inserted into each phase of conventional interleaved boost converter. The voltage multiplier cell is composed of built-in transformer windings, diodes and small capacitors. The Voltage multiplier module is efficient, low cost and simple topology composed of switched capacitors and diodes to obtain high DC output voltage. In order to obtain the controlled output voltage from a DC – DC converter under varying input conditions, it is necessary to regulate the output voltage which is achieved through closed loop control. A PI controller is implemented to improve its performance of the proposed IBC during the disturbances due to renewable energy sources. The closed loop control of the proposed IBC with multiplier module is analyzed and simulated for high voltage gain using MATLAB Simulink.

Keywords*-Interleaved Boost Converter (IBC), High Voltage Gain, Voltage Multiplier, PI controller.*

*****

I. INTRODUCTION

The dc-dc converters with high step up voltage gain is widely used in many applications such as lasers, fuel cell energy conversion systems, X-ray systems, solar cell energy conversion systems, and high intensity-discharge lamp for automobile headlamps. Theoretically, a dc–dc boost converter can achieve a high step up voltage gain with an extremely high duty ratio [1–3].However, in practice, the step-up voltage gain is limited due to the effect of power switches, rectifier diodes, and the equivalent series resistance (ESR) of inductors and capacitors.

The conventional boost converter is used to provide a voltage conversion ratio with low voltage gain. It is hard to provide a large voltage conversion ratio, due to a large duty cycle that brings high conduction loss, and the large peak current may impact the capacitors seriously. Various topologies have been developed to provide a high step up voltage gain without a large duty ratio [4]. The isolated converters will boost the voltage by increasing the turn’s ratio of the high frequency transformer [5-6].

When compared with non-isolated converters for isolated converters it is easy to achieve high voltage gain. It is done by selecting the transformer turns ratio properly; high voltage conversion ratio can be obtained by optimal duty cycle [7]. The switch duty cycle and the transformer turns ratio are controlled to lift the voltage ratio. The main advantage of this converter is switch voltage stress reduction; switch turn-off voltage spikes suppression and diode reverse recovery problem alleviation.

IBC splits the input current based on each phase. Equal current is shared among two converters to minimize the ripple. To overcome the problem of ripples and losses in boost converter, interleaved topology is used [8]. Paper [9] discusses the closed-loop control of interleaved high step up converter to obtain high reliability.The switch voltage stress and the diode peak current are minimized due to the built-in transformer multiplier cells toimprove the conversion efficiency[10-12]. Furthermore there is no reverse-recovery problem for the clamp diodes.

In the proposed paper, a closed loop control is implemented to the IBC with built-in transformer and voltage multiplier module. In order to obtain the controlled output voltage from a DC – DC converter under varying input conditions, it is necessary to regulate the output voltage which is achieved through closed loop control.The closed loop control of the proposed converter is simulated and the results are compared with the open loop control system.

II. IBC WITH VOLTAGE MULTIPLIER MODULE

The circuit configuration of interleaved boost converter with Voltage Multiplier Module for high voltage gain is shown in Fig.1. In the circuit, L_1 and L_2 are the energy storage inductors, S_1 and S_2 are the power switches, C_1,C_2 and C_3,C_4 are the clamp capacitors, Cois the output capacitor, D_1, D_2 and D_3, D_4 are the clamp diodes, and D_5 and D_6 are the rectified diodes. A primary winding N_p, a secondary winding Ns_1, a third winding $Ns_2$and a leakage inductor Lk constitutes the built in transformer. The gate-driving signals of the two power switches are interleaved with a 180° phase shift.

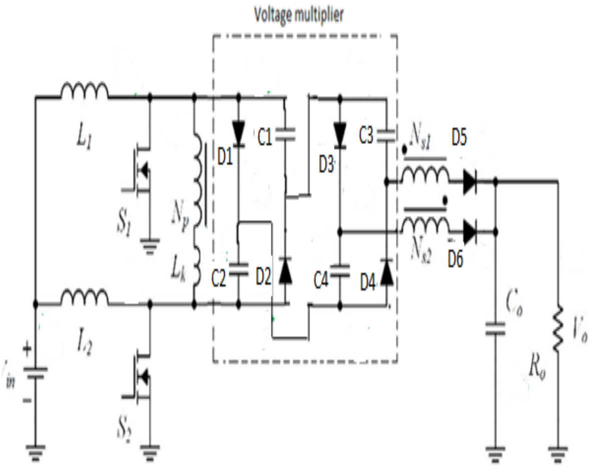

Fig.1.Proposed interleaved boost converter with voltage multiplier

III. CIRCUIT OPERATION

There are totally 10 modes of operation. The analysis and operating principle of the proposed converter modes 1–5 are discussed. Due to the completely symmetrical interleavedtopology, operating modes 6-10 of the proposed converter in second phase are similar to the operating modes 1–5.

Stage 1[t_0, t_1]: In this interval, at t = t_0, both main power switches (S_1 and S_2) turn ON. All thediodes (D_1, D_2, D_3,D_4, D_5, and D_6) are reverse-biased. The path ofcurrent flow in mode 1 is shown in Fig. 2. Inductors L_1 and L_2arecharged by input voltage Vin, and currents though inductorsL_1 and L_2 linearly increase.The inductor currents iL_1 and $iL_2$are respectively, given by

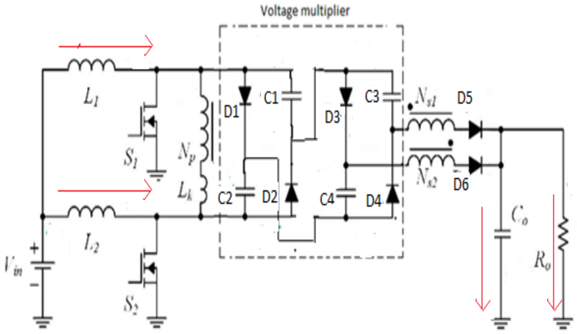

Fig.2. Stage 1 [t_0, t_1] operation of the proposed IBC converter

$$i_{L1}(t) = I_{L1}(t_0) + \frac{Vin}{L_1} t_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$i_{L2}(t) = I_{L2}(t_0) + \frac{Vin}{L_2} t_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (2)$$

Stage2 [t_1, t_2]: In this interval, att = t_1, main power switch S_2 turns OFF, and its parasiticcapacitor is charged by inductor current iL_2. The path ofcurrent flow in mode 2 operation is shown in Fig. 3. The voltage of the parasiticcapacitor is given by

$$V_{DS2}(t) = \frac{I_{L2}(t_1)}{\text{Cds2}} t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (3)$$

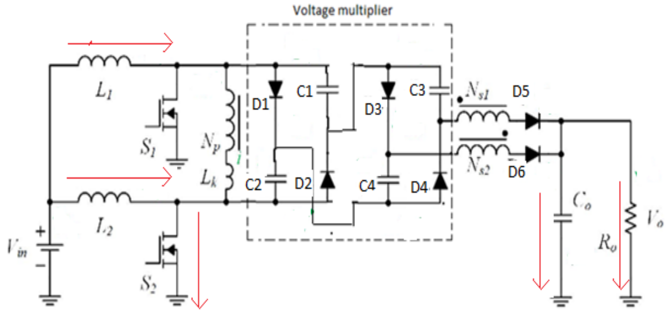

Fig.3. Stage2 [t_1, t_2] operation of the proposed IBC converter

Stage 3 [t_2, t_3]: In this interval, att = t_2, power switch S_2 remains OFF. The voltages of clamp diode D_2, D_4 and rectified diode D_6 decrease; then, D_2,D_4 and D_6begin to turn ON at t = t_2. The path of current flow in mode 3 is shown in Fig. 4. The input voltage V_{in} and the inductor L_2 provide energy to leakage inductor $L_k$and primary winding $N_p$through switch S_1, and to clamp capacitor C_1 through S_1 and D_2 , C_3 through S_1 and D_4.

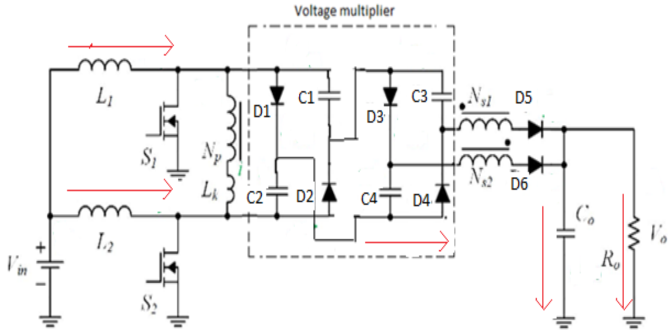

Fig.4. Stage 3 [t_2, t_3] operation of the proposed IBC converter

$$i_{L2}(t) = i_{D2}(t) + i_{D4}(t) + (n+1) i_{D6} \ldots\ldots\ldots\ldots (4)$$

$$i_{Lk}(t) = n * i_{D6}(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$i_{DS1}(t) = i_{L1} + i_{D2}(t) + + i_{D4}(t) + * \, i_{D6} \ldots\ldots . (6)$$

Stage 4 [t_3, t_4]: In this interval, att = t_3, power switch S_2 is still OFF. The diode current iD_2,iD_4 decreases to zero, and the clamp capacitor voltage VC_1 and VC_3 isequal to the drain–source voltage of power switch S_2. The pathof current flow in mode 4 is shown in Fig.5. The rectified diodecurrent iD_6 is proportional to leakage-inductor current iL_k.The currents through L_2, L_k, and S_1 are, respectively, given by

$$i_{L2}(t) = (n+1) * i_{D6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$i_{Lk}(t) = n * i_{D6}(t) \dots\dots\dots\dots\dots\dots\dots\dots\dots\,..(8)$$

$$i_{DS1}(t) = i_{L1} + n * i_{D6}(t) \dots\dots\dots\dots\dots\dots\dots(9)$$

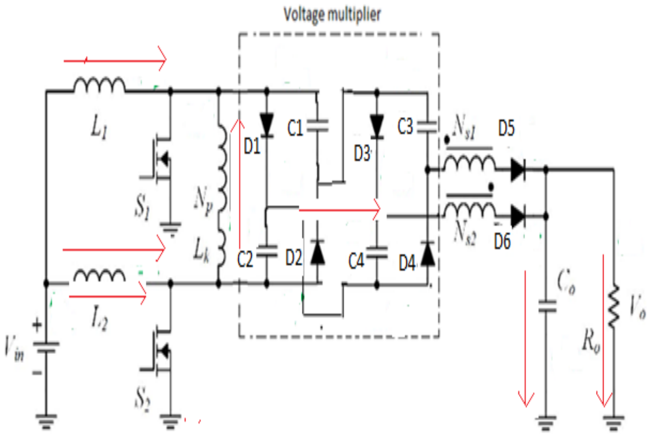

Fig.5. Stage 4 [t_3, t_4] operation of the proposed IBC converter

Stage 5 [t_4, t_5]: In this interval, att= t_4, the power switch S_2 turns ON. The rectified diode D_6 remains forward-biased, because leakage inductor current iL_kstill exists. The path of current flow in mode 5 is shown in Fig.6. The leakage inductor current iL_kdecreases to zero at $t = t_5$, and rectified diode D_6 begins to be reverse-biased. The current through L_2 is given by

$$i_{L2}(t) = i_{Ds2} + (\mathrm{n}+1) * i_{D6} \dots\dots\dots\dots\dots\dots\dots\dots(10)$$

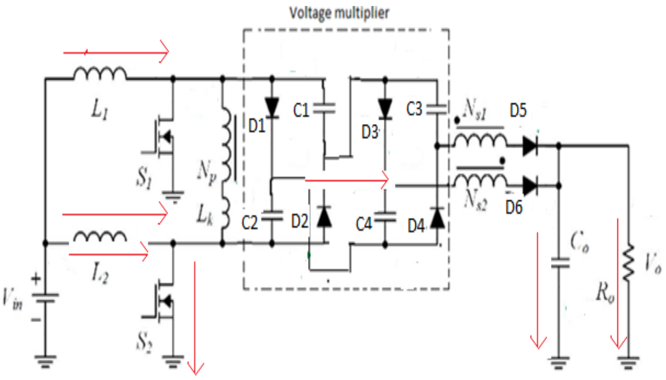

Fig.6. Stage 5 [t_4, t_5] operation of the proposed IBC converter

IV. CLOSED LOOP CONTROL OF PROPOSED IBC

In order to obtain the controlled output voltage from a DC – DC converter under varying input and output conditions, it is necessary to regulate the output voltage which is achieved with the help of concept of negative feedback that is carried out in a closed loop method. The control of the output voltage should be performed in a closed-loop manner through two common closed-loop control methods for PWM dc-dc converters, namely,

- The voltage-mode control.
- The current-mode control.

A. *Voltage Mode Control:*

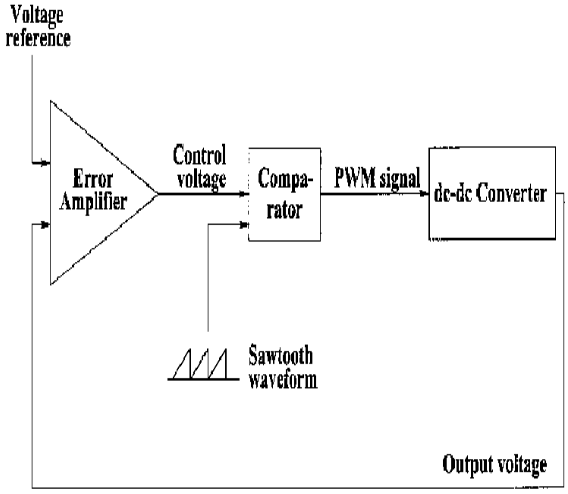

Fig. 7: voltage-mode control

In the voltage-mode control system shown in Fig 7, the converter output voltage is sensed and subtracted from an external reference voltage in an error amplifier. The error amplifier produces a control voltage that is compared to a constant-amplitude saw tooth waveform. The comparator produces a PWM signal to the main switches of the proposed converter. The duty ratio of the PWM signal depends on the value of the control voltage.

The Error amplifier shown in Fig.7 reacts fast to changes in the converter output voltage. Thus, the voltage-mode control provides good load regulation. Line regulation (regulation against variations in the input voltage) is, however, delayed because changes in the input voltage must first manifest themselves in the converter output before they can be corrected. To alleviate this problem, the voltage-mode control scheme is sometimes augmented by a so-called voltage-feed forward path. The feed forward path affects directly the PWM duty ratio according to variations in the input voltage.

B. *PI CONTROLLER*

A Proportional and Integral controller block diagram shown in Fig.8. PI controller continuously calculates an error value as the difference between a desired set point (SP) and a measured process variable (PV) and applies a correction based on proportional and integral is given by.

$$e(t)=SP-PV\dots\dots\dots\dots\dots\dots.(11)$$

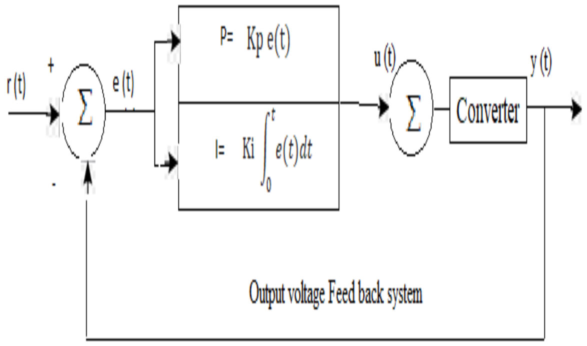

Fig.8: A block diagram of a PI controller in a feedback loop

The overall control function can be expressed mathematically as

$$u(t) = Kp\ e(t) + Ki \int_0^t e(t)dt \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where, $K_p$andK_i all non-negative, denote the coefficients for ∑ the proportional and integral, terms respectively (sometimes denoted P and I).

A PI controller gives the control signal based on the error value by comparing the obtained output voltage(Vo) and reference voltage. The major advantage of PI controller is its feasibility and it can be easily implemented. The PI controller based closed loop operations for the IBC with built in transformer and voltage multiplier modulein shown in fig.9.

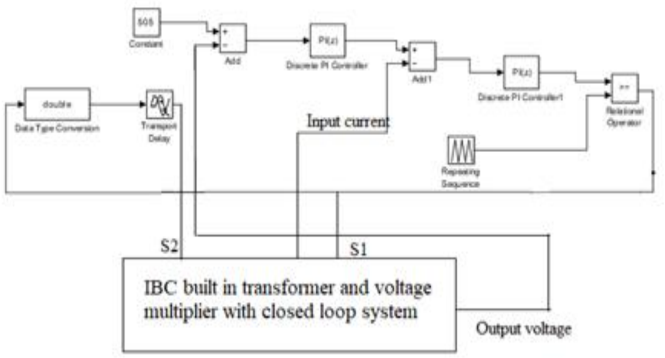

Fig. 9: IBC with built in transformer and voltage multiplier for closed loop control system.

V. SIMULATION RESULTS

The analysis of the closed loop control of high voltage gain IBC with the Voltage multiplier module is presented in this paper through simulation. The circuit components are connected in the Simulink model of thehigh step up IBC with the parameters mentioned intable I.

Table I: Parameters used for simulation

Parameters	Values
Vin (input voltage)	48V
Vo (output voltage)	505V
fs (switch frequency)	50kHZ
duty ratio	0.62
C_1,C_2,	10µF
C_O (Output capacitor)	120µF
L_1,L_2 (Filter inductor)	110µH

The Simulink model of the closed loop control of high voltage gain IBC with the Voltage multiplier module is shown in Fig.10.And the simulation results are compared with closed loop system, which are as follows.

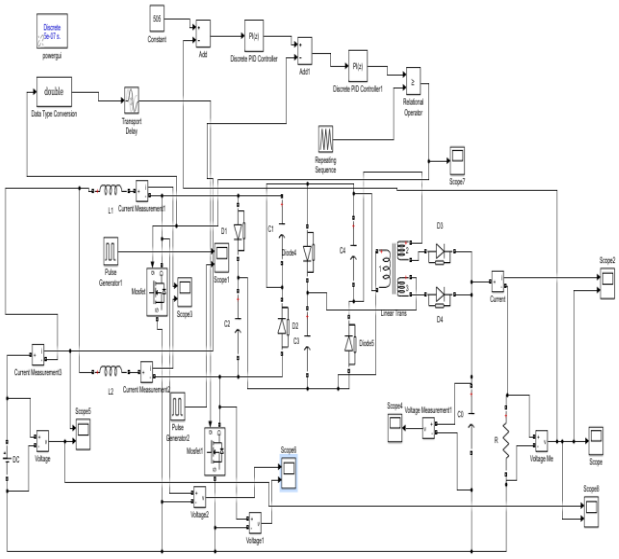

Fig. 10: Simulink Model of closed loop control of high voltage gain IBC with the Voltage multiplier module

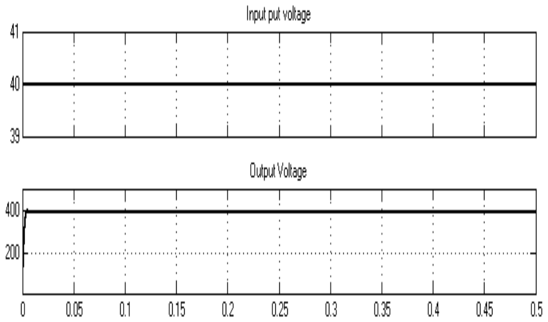

Fig. 11: Input voltage and output voltage waveform of the proposed IBC with open loop system

Figure 11 shows input and output voltage waveform of the proposed IBC with open loop model. The simulated input and output voltage waveform of the proposed IBC converter with open loop control system is V_{in} = 40V and V_{Out}=400V. Fig.12 shows the simulated input and output voltage waveform of the proposed IBC converter with closed loop control system is V_{in} = 40V and V_{Out}=505V.

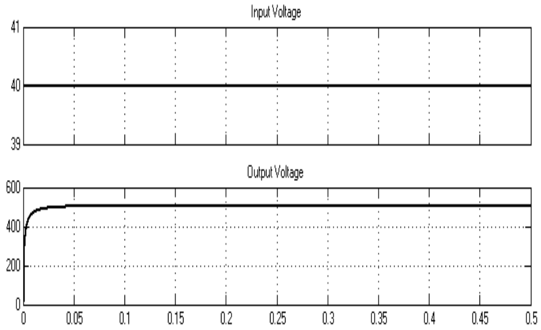

Fig. 12: Input voltage and output voltage waveform of the proposed IBC with closed loop

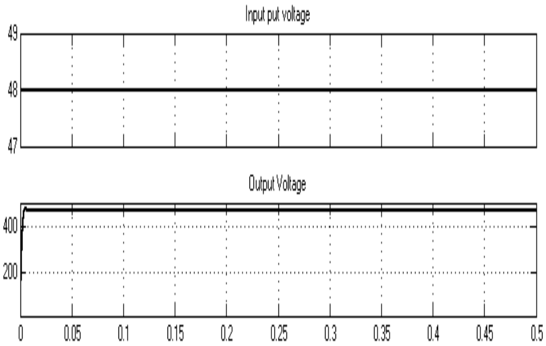

Fig. 13: Input voltage and output voltage waveform of the proposed IBC with open loop

Figure 13 shows input and output voltage waveform of the proposed IBC with open loop model.The simulated input and output voltage waveform of the proposed converter with open loop control system is V_{in} = 48V and V_{Out}=505V. And Fig.14The simulated input and output voltage waveform of the proposed converter with closed loop control system is V_{in} = 48V and V_{Out}=505V.

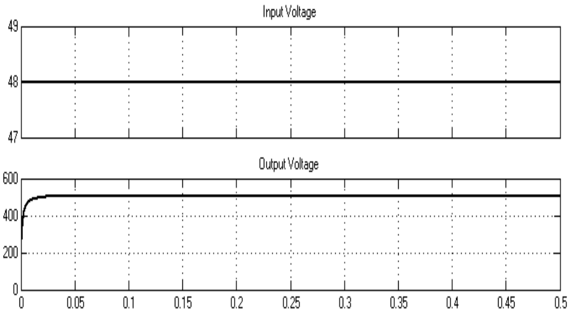

Fig.14: Input voltage and output voltage waveform proposed IBC with closed loop system

Figure 15 shows input and output voltage waveform of proposed IBC with open loop system, The simulated input and output voltage waveform of proposed IBC with open loop control system V_{in} = 60V and V_{Out}=600V. And Fig.16 shows the simulated input voltage and output voltage waveform of the closed loop control system with voltage multiplier V_{in} = 60V and V_{Out}=505V.

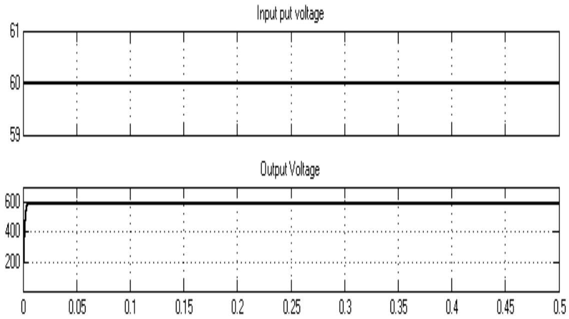

Fig. 15: Input voltage and output voltage of proposed IBC with open loop system

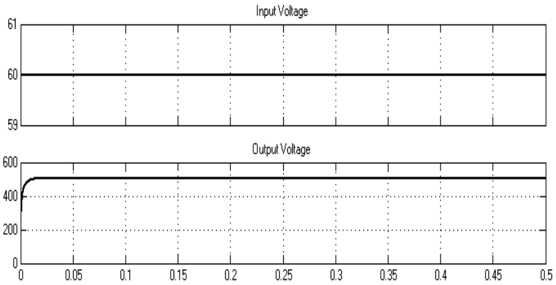

Fig.16: Input voltage and output voltage waveform for proposed IBC with closed loop

Table II: Comparison of open loop and closed loop system output voltages of the proposed IBC

	Open Loop system	Closed Loop system
Input Voltage in volts	Output Voltage in Volts	Output Voltage in Volts
40V	400V	505 V
48V	505 V	505 V
60 V	600 V	505 V

Table II shows the performance comparison of the IBC with built in transformer and voltage multiplier for open loop and closed loop control system. From the table it is observed that output voltages are maintained at constant values for the Variation of input voltages in the case of closed loop system compared to open loop system. The closed loop system output voltages remain constant and robust for the variation of input voltages.

VIICONCLUSION

An Interleaved Boost Converter with voltage multiplier module along with closed loop control system has been proposed for high voltage gain conversion for renewable energy system.The Closed loop control system of high voltage gain IBC with the Voltage multiplier module is implemented and simulated using MATLAB Simulink. For variation in input voltages, the closed loop control system maintains the constant output voltage and improves the converter performance.

REFERENCES

[1] B.Bryant and M. K. Kazimierczuk, “Voltage- loop power-stage transfer functions with MOSFET delay for boost PWM converter operating in CCM,” IEEE Trans. Ind. Electron., vol. 54, no.1, pp. 347–353, Feb. 2007.

[2] X. Wu, J. Zhang, X. Ye, and Z. Qian, “Analysis and derivations for a family ZVS converter based on a new active clamp ZVS cell,” IEEE Trans. Ind. Electron., vol. 55, no. 2, pp. 773–781, Feb. 2008.

[3] D.C.Lu, K. W. Cheng, and Y. S. Lee, “A single-switch continuous conduction- mode boost converter with reduced reverse-recovery and switching losses,” IEEE Trans. Ind. Electron., vol. 50, no. 4, pp. 767–776, Aug. 2003.

[4] K. C. Tseng and C. C. Huang, “High step-up high-efficiency interleaved converter with voltage multiplier module for renewable energy system, ‘‘IEEE Trans.Ind.Electron,vol.61,no.3,pp.1311-1319,March 2014.

[5] Y. Zhou, D. E. Macpherson, W. Blewitt, and D. Jovcic, “Comparison of DC–DC converter topologies for offshore wind-farm application,” in Proc. 6th IET Int. Conf. PEMD, 2012, pp. 1–6.

[6] S. K. Ki and D. D. Lu, “A high step-down transformerless single-stage single-switch AC/DC converter,” IEEE Trans. Power Electron., vol. 28, no. 1, pp. 36–45, Jan. 2013.

[7] Rabiya Rasheed, Ann Mary Jose, ‘‘Control of an High Step - Up Interleaved Converter Integrating Built- In Transformer Voltage Multiplier Cell With Fuzzy Logic Controller’’IJAREEIE,Vol. 4, Issue 9, September 2015.

[8] NR. Anand and Dr. S. Rama Reddy, ‘‘Modeling and Simulation Closed Loop Controlled Interleaved boost converter’’,International Conference on Circuits, Power and Computing Technologies [ICCPCT-2013].

[9] Maria T Kuriyakose, Aswathy Rajan, ‘Closed loop Contol of ZCS Interleaved High Step Up Converter For Sustainable Energy Applications’’,International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) – 2016.

[10] Wuhua Li, Weichen Li, Xiangning He, and David Xu, ‘‘General Derivation Law of Nonisolated High-Step-Up Interleaved Converters with Built-In Transformer’’ IEEE Transactions on Industrial Electronics, Vol. 59, No. 3, March 2012.

[11] Kuo-Ching Tseng and Chi-Chih Huang, ‘‘High Step-Up High-Efficiency Interleaved Converter with Voltage Multiplier Module for Renewable Energy System’’ IEEE Transactions on Industrial Electronics, Vol. 61, No. 3, March 2014

[12] Kuo-Ching Tseng, Chun-An Cheng, and Chun-Tse Chen ‘‘High Step-Up Interleaved Boost Converter for Distributed Generation Using Renewable and Alternative Power Sources’’ IEEE Journal Of Emerging And Selected Topics In Power Electronics, Vol. 5, No. 2, June 2017.