A Novel Soft-Switching Based Closed Loop KY Converter with Ripple-Free Current

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***Abstract*— *A soft-switching based closed loop KY converter with ripple-free output current is proposed. This converter is based on a voltage boosting converter, named KY converter. Initially the basic function of traditional KY boost converter with soft switching and also output current ripples is discussed. It is achieved by utilizing an auxiliary circuit to the KY boost converter, the zero-voltage-switching (ZVS) of power switches is achieved. Moreover, the auxiliary circuit cancels out the filter inductor current ripple. Then, ripple-free output current is achieved. For the improvement of the functionality of the KY boost converter the PI controller in voltage mode control path is used. Finally the output response of conventional boost converter and KY boost converter in open loop and closed loop of the methods are compared. A comparison study was conducted to characterize the output voltage ripple percentage, output current ripple percentage and switching losses of each switch in the converter. The switching loss is reduced and the system efficiency is improved. The operational principle and a steady-state analysis of the closed loop KY boost converter are provided in detail.*

Keywords— *KY converter, soft-switching, conventional boost converter, ripples free.*

I. INTRODUCTION

In recent days, the DC-DC conversion technology plays a major role in power engineering and drives. These converters are broadly applied in several industrial applications such as discharge lamp for automobile, fuel cell energy conversion systems, and computer hardware circuits. Also, these are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklifts trucks, mine haulers and are applied in DC voltage regulators. Owing to they provide high efficiency, and the conversion techniques are developed very rapid [1]. These portable power systems have requirements such as small size, light weight, compactness, small output ripple and so on.

BLOCK DIAGRAM OF TRADITIONAL TOPOLOGY

Input power for the DC-DC boost converters are taken from any appropriate DC sources such as DC generators, batteries, solar panels and rectifiers etc.

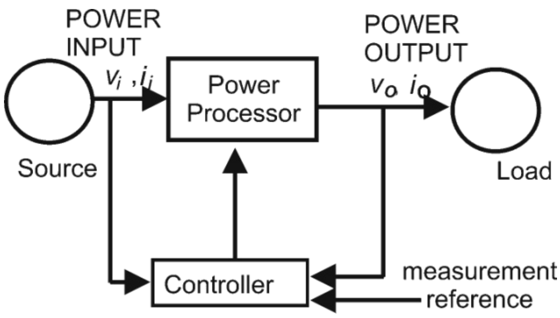

Figure 1(a): Basic Power Electronics Circuit Diagram

The technique that changes one DC voltage to a different DC voltage is called as DC to DC conversion. Commonly, a boost converter is a DC to DC converter with an output voltage more than the input source voltage. And also there is a plenty of demand for portable power systems using the low batteries. These portable power systems have requirements such as small size, lightweight, compactness, small output ripple, and so on. Moreover, sometimes, they are needed to boost low input voltage to an adequately high and constant level and their output voltage. For this reason boost converters are used.

A. Conventional Boost Converter

A Boost converter is a switch mode DC-DC converter in which the output voltage is greater than the input voltage. It is also called step up converter. The traditional type DC-DC boost converter cannot offer high level controlled DC voltage gain for an excessive duty cycle.

These are widely used to efficiently produce a regulated voltage from a source. DC-DC Converters are high-frequency power conversion circuits that use high-frequency switching and inductors, transformers, and capacitors to smooth out switching noise into regulated DC voltages.

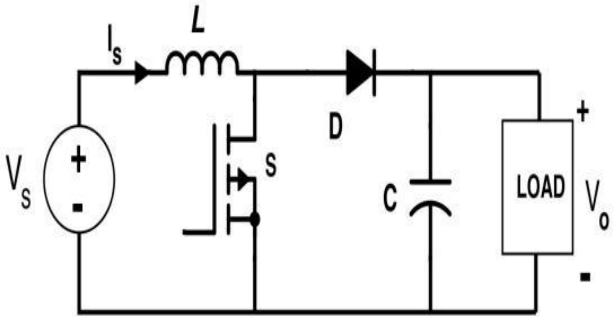

Figure 1(b): Basic Boost Converter Circuit Diagram

1) During ON-State

The switch s is closed, which makes the input voltage appear across the inductor, which causes a change in current flowing through the inductor during a time period by the formula:

$$\frac{\Delta I_l}{\Delta t} = \frac{V_i}{L} \qquad (1)$$

2) During OFF-State

The switch S is open, so the inductor current flows through the load. If we consider zero voltage drops in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of IL is:

$$V_i - V_o = L\frac{dI_L}{dt} \qquad (2)$$

From equations (1) & (2)

The duty cycle is to be:

$$D = 1 - \frac{V_i}{V_o} \qquad (3)$$

It may cause in reverse recovery crisis and amplify the rating of all devices. Accordingly, the conversion efficiency is decreased. [2] The main merits of DC-DC boost converter is simple structure and continues input current. At the same time, it has demerit such as when the switch is OFF, high output voltage is impressed on the switch, low voltage transfer gain and more ripples of current and voltage. Therefore, the classical boost topology is not fit for large power application owing to the occurrence of parasitical resistance.

Closed feedback loops maintain constant voltage output even when changing input voltages and output currents. At 90% efficiency, they are generally much more efficient and smaller than linear regulators. The main disadvantages of boost converters are noise and complexity. And also large output capacitor is required to reduce ripple voltage as output current is pulsating.

B. KY Boost Converter

For reducing these problems KY Boost converters are introduced. This converter is based on a voltage-boosting converter, named KY converter. [3] This KY converter has features of KY converter such as clamped switch voltage stresses to input voltage, non-pulsating output current and fast transient response.

The duty ratio of the KY converter is:

$$\frac{V_o}{V_i} = 1 + D \qquad (4)$$

To reduce voltage ripples, one way is using a large LC filter on output stage. However, this method enlarges system size and weight. Another way is adopting a high-frequency operation. However, this solution brings low system efficiency due to large switching loss for conventional boost and buck-boost converter under hard-switching operation. Interleaving technique can be often adopted to reduce voltage ripples and processed power capacity of converters [5]-[7].

In the interleaved converters, several identical converters are connected in parallel and each converter is controlled by switching signals in the interleaved fashion which has the same switching frequency, same duty ratio, and same phase shift. Although such interleaved techniques lead to lower output voltage ripple, many components are necessary to reduce output voltage ripple. Therefore, the multichannel interleaved structure requires many components and its control algorithm is also complex.

In [3], a voltage-boosting converter, named KY converter is suggested. It has advantages such as fast transient response, non-pulsating output current, small voltage ripple, and clamped switch voltage stresses to input voltage. However, in order to reduce the output current ripple which contributes to minimize output voltage ripple, the inductance needs to be raised significantly. Also, since the converter operates with hard-switching, the switching loss which decreases power conversion efficiency is large.

In order to improve efficiency by reducing the switching loss, a ZVS scheme for a pulse width modulation (PWM) converter under discontinuous conduction mode/continuous conduction mode boundary was suggested[8]-[10]. The ZVS control scheme can reduce switching loss, but it increases the inductor current ripple which causes large conduction loss. The auxiliary circuits providing ZVS function can be a solution [11]-[15]. However, most of them include one or more active switches and it requires additional control circuit. Thus, the overall cost is raised.

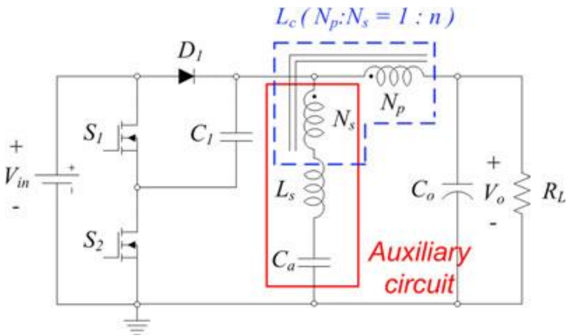

Figure 2(a): Circuit diagram of the KY Boost converter

Active clamping technique was presented as one of the attractive ZVS method due to reducing switching loss and improving efficiency [16]-[20]. Although active clamping technique has these merits, the voltage stress of the switches is increased. Switching devices with high voltage ratings are required and it may raise the cost. Aside from these methods, other soft-switching techniques were proposed [21]-[26].

However, they cannot provide both soft-switching and low current ripple. And all of these soft-switching techniques have at least one of the disadvantages such as high voltage stress, complex structure, much component count, high cost, high circulating current, etc.

In order to overcome aforementioned problems, a soft switching step-up converter with ripple-free output current shown in is proposed. The proposed converter is based on the KY converter[3] in which has features such as non-pulsating output current, fast transient response, and clamped switch voltage stresses to input voltage. In addition to the features of the KY converter, the proposed converter provides soft-switching of the power switches and ripple-free filter inductor current by utilizing a simple auxiliary circuit consisting of an additional winding of the filter inductor, a serial inductor and a capacitor [27]. Therefore, it improves the system efficiency by reducing switching loss and cancels out ripple component of the filter inductor effectively.

The operation of the proposed converter in one switching period *TS* can be divided into six modes:

1) ***Mode 1[t0, t1]:***

This mode begins with turned OFF of the lower switch S2. Then, current difference between the auxiliary inductor current I_{Ls} and the filter inductor current I_L starts to discharge C_{s1} and charge C_{s2} and C_{D1}. Therefore, the voltage V_{S1} across S1 decreases toward zero and the voltages V_{S2} across S2 and the voltage V_{D1} across *D*1 increase toward V_{in}. Since the capacitances C_{s1},C_{s2} and C_{D1} are very small, the transition time interval *Tt*1 is very short and it can be simplified as follows:

$$T_{t1} = t_1 - t_0 = (C_{S1} + C_{S2} + C_{D1}) * \frac{V_{in}}{(1-n)I_{Ls(\max)} - I_{Lm(\min)}} \quad (5)$$

2) ***Mode 2[t1, t2]:***

When the voltage V_{S1} across S1 arrives at zero, this mode begins and the body diode D_{S1} starts to conduct. Then, the gate pulse for the upper switch S1 is applied. Since the switch voltage V_{S1} is already zero before S1 is turned ON, the zero-voltage turn-on of S1 is achieved. The voltage V_{Lm} across the magnetizing inductance is $2V_{in} - V_o$. Then, the current I_{Lm} increases linearly as follows:

$$i_{Lm}(t) = I_{Lm(\min)} + \frac{2V_{in} - V_O}{L_m}(t - t_1) \quad (6)$$

3) ***Mode 3[t2, t3]:***

At t_2, the auxiliary inductor current I_{Ls} arrives at zero and changes its direction. Since the voltages V_{Lm} and V_{Ls} are not changed, all the currents I_{Lm}, I_{Ls}, i_L and I_{s1} continue to increase or decrease linearly with the same slope as in Mode. At the end of this mode, the auxiliary inductor current I_{Ls} arrives at its minimum value and the magnetizing current I_{Lm}, the filter inductor current i_L, and the upper switch current I_{s1} arrive at their maximum values $I_{Lm(\max)}$, $I_{Lm(\max)} - nI_{Ls(\min)}$ and $I_{Lm(\max)} + (1-n)I_{Ls(\min)}$ respectively.

4) ***Mode 4[t3, t4]:***

At t_3, the upper switch S1 is turned OFF. Then, this mode begins and current difference $I_{Ls} - I_L$ starts to charge C_{s1} and discharge C_{s2} and C_{D1}. Therefore, the voltage V_{S1} across S1 increases toward V_{in} and the voltage V_{S2} across S2 and the voltage V_{D1} across *D*1 decreases toward zero. With a similar manner in Mode 1, the transition time interval *Tt*2 can be simply expressed as follows:

$$T_{t2} = t_4 - t_3 = (C_{S1} + C_{S2} + C_{D1}) * \frac{V_{in}}{I_{Lm(\max)} + (1-n)I_{Ls(\min)}} \quad (7)$$

5) ***Mode 5[t4, t5]:***

This mode begins when the voltage V_{S2} across S2 arrive at zero. At the moment, the diode *D*1 and the body diode D_{S2} start to conduct. Then, the gate pulse for the lower switch S2 is applied. Since the switch voltage V_{S2} is already zero before S2 is turned ON, the zero-voltage turn-on of S2 is achieved. In this mode, the voltage V_{Lm} of the magnetizing inductance is $-(V_o - V_{in})$. Thus, the magnetizing current I_{Lm} is decreases linearly as follows:

$$i_{Lm}(t) = I_{Lm(\max)} - \frac{V_o - V_{in}}{L_m}(t - t_4) \quad (8)$$

6) ***Mode 6[t5, t6]:***

At *t*5, the auxiliary inductor current I_{Ls} arrives at zero and changes its direction. However, since S2 is still on and the voltages V_{Lm} and V_{Ls} are not changed, the currents I_{Lm}, I_{Ls} and I_L continue to increase or decrease linearly with the same slope as in Mode 5. At the end of this mode, the magnetizing current I_{Lm} and the filter inductor current I_L arrive at their minimum value $I_{Lm(\min)}$ and $I_{Lm(\min)} + nI_{Ls(\max)}$ and the auxiliary inductor current I_{Ls} and the lower switch current I_{s2} arrive at their maximum values $I_{Ls(\max)}$ and $I_{s2(\max)}$, respectively.

By solving equations (5), (6), (7) and (8)

$$M = \frac{V_o}{V_i} = 1 + D \qquad (9)$$

The duty ratio of soft-switching KY converter

It is the same as that of the conventional KY converter.

7) *Zero Ripple Condition*

$$L_s = n(1-n)L_m \qquad (10)$$

Where Ls = auxiliary inductor

Lm = magnetizing inductor

n = no of turns

8) *ZVS Condition*

The ZVS condition of the upper switch S1 is given by

$$(1-n)I_{Ls(\max)} - I_{Lm(\min)} > 0 \qquad (11)$$

It can be rewritten as

$$L_s < \frac{n(1-n)(2V_{in} - V_o)DT_s}{2I_o} \qquad (12)$$

Where I_o is the output current

Similarly, for ZVS of the lower switch S2, the following inequality should be satisfied.

$$I_{Lm(\max)} + (1-n)I_{Ls(\min)} > 0 \qquad (13)$$

II. PROPOSED TOPOLOGY

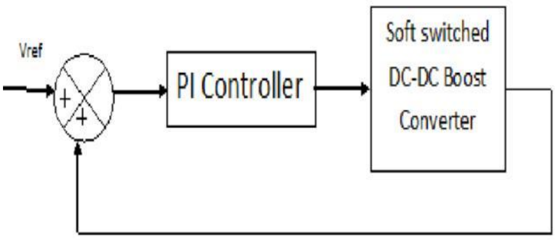

Figure 3(a): Closed loop circuit diagram of Soft-Switched KY Boost converter

The open loop operation is insensitive to load and line disturbances. So this operation is ineffective. Therefore closed loop operation is selected.

Fig. 3(a) shows the closed loop of the soft switched KY boost converter with PI controller. During the design of the PI controller for the KY boost converter, a closed loop operation is performed.

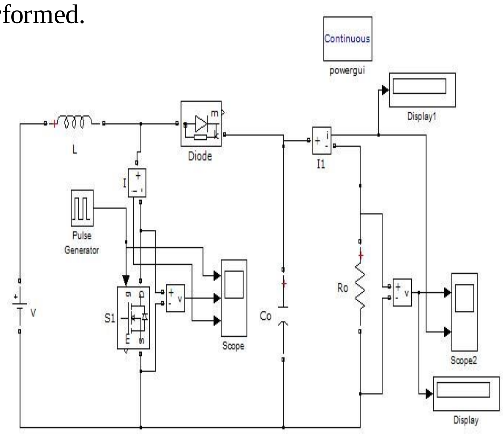

Figure 1(b): MATLAB/SIMULINK Diagram of Conventional Boost Converter

The closed loop control uses a feedback signal from the process, a desired value or set point (output voltage) and a control system that compares the two and derives an error signal. The error signal is then processed and used to control the converter to try to reduce the error. The error signal is usually processed using a Proportional-Integral (PI) controller whose parameters can be adjusted to optimize the performance and stability of the system. Once a system is set up and is stable, very efficient and accurate control can be achieved.

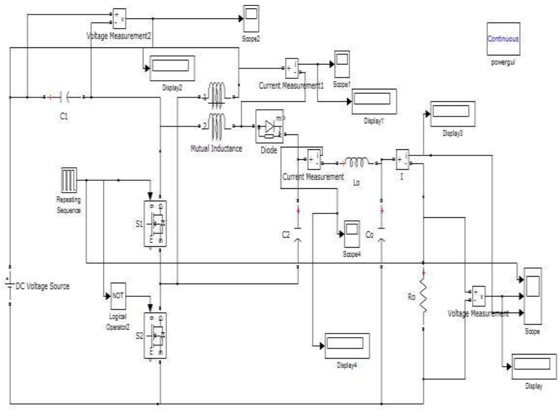

Figure 2(b): MATLAB/SIMULINK Diagram of KY Boost Converter

Then the output of the PI controller changes the pulse width of the square wave which changes the firing angle of the MOSFET switch, so the output of the converter is controlled for different load disturbances.

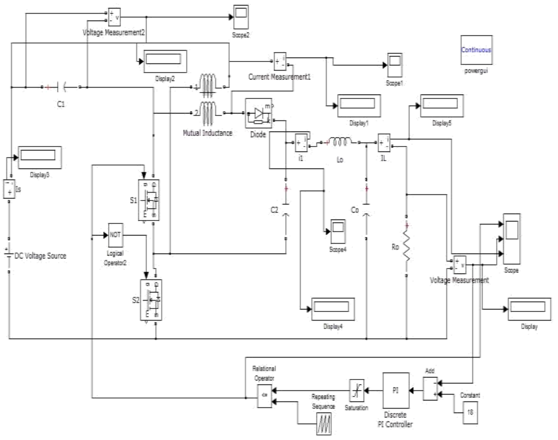

Figure 3(b): MATLAB/SIMULINK Diagram of Closed loop KY Boost converter

III. DESIGN EXAMPLE

To validate the characteristic of the proposed converter, a design example in the section is given with the fallowing specifications: input voltage V_{in}= 12V, output voltage V_o=18v. Maximum output power $P_{o\ (max)}$ = 32.4w, switching frequency F_s=200[KHZ].

TABLE I
LIST OF CIRCUIT PARAMETERS

Parameter	Values
Magnetizing Inductor, Lm	100µH
Energy transferring capacitor, C1	174µF
Charge pump capacitor, C2	69 µF
Output capacitor, Co	300 µF
Output inductor, Lo	180 µH
Output resistor, Ro	90Ω
Resonance inductor, L_r	10 µH
Resonance capacitor, C	10Nf

TABLE II
LIST OF DESIGN PARAMETERS

Parameter	Values
Input voltage	12V
Output voltage	18V
Output current	1.8A
Output power	32.4W
Switching frequency	200KHz

A. *Duty Ratio D and Selection of n:*

Duty ratio D can be calculated as 0.4. Thus, duty ratio D is constant regardless of load condition; turn ratio n should be selected as value less than unity in order to achieve ZVS of S2. Then turn ratio n is selected as 1/8.

B. *Selection of L_S:*

Inductance of inductor L_S should be small enough to achieve ZVS of lower switch S_2 when D=0.4 and n=1/8, the inequality gives L_S<30.625[µH] at full load. Then L_S is selected as 19.4[µH]

C. *Selection of L_m:*

For zero ripple of output current, it should be satisfied. Therefore, when L_S=19.4[µH] and n=1/8, gives L_m=177.37[µH]. The magnetizing inductance L_m is selected as 178[µH].

TABLE III
VOLTAGE VALUES OF BOOST, KY CONVERTER AT DIFFERENT DUTY RATIOS

Duty ratio	Output voltage in (V)					
	Boost converter		KY converter		Soft-switching KY converter	
	(PV)	(TV)	(PV)	(TV)	(PV)	(TV)
40%	19.04	20	15.86	16.8	17.44	18
60%	28.28	30	18.07	19.2	20.96	21

Where P V= Practical value T V=Theoretical value

TABLE III
COMPARISON OF PERCENTAGE RIPPLE OF BOOST, KY AND CLOSED LOOP SOFT SWITCHING KY CONVERTER CALCULATION

S no	Boost converter	KY converter	Soft-switching KY converter
Output current	0.787%	0.567%	0.027%
Output voltage	0.735%	0.063%	0.022%

IV. EXPERIMENTAL RESULTS

The experimental waveforms of the traditional topology and proposed topology of KY converter, boost converter and soft-switching KY converter are shown here.

A. *MATLAB Results of Boost Converter*

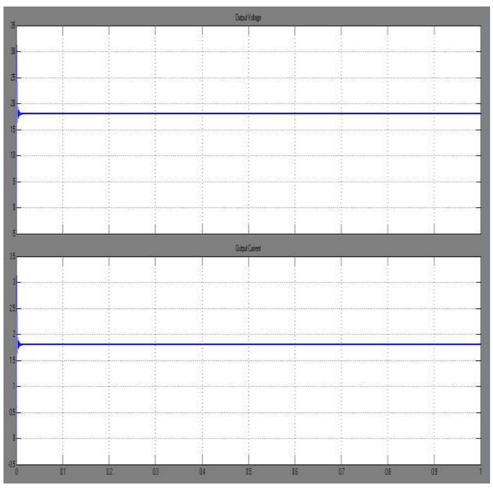

Figure 4: Output Voltage and Output Current of Boost Converter

Here the conventional boost converter is operated at input 12V. And output is 28.28V at 60% duty ratio. Then the switching pulses, switch Voltage and switch current are shown here.

All topologies are operated under same conditions means same input voltage, input current and same duty ratio. Here the ripple content is very low value in proposed topology compared to traditional topology.

Output voltage and output current is presented. Here the ripple content is high in the output voltage and output current.

B. *MATLAB Results of Soft-Switching KY Converter*

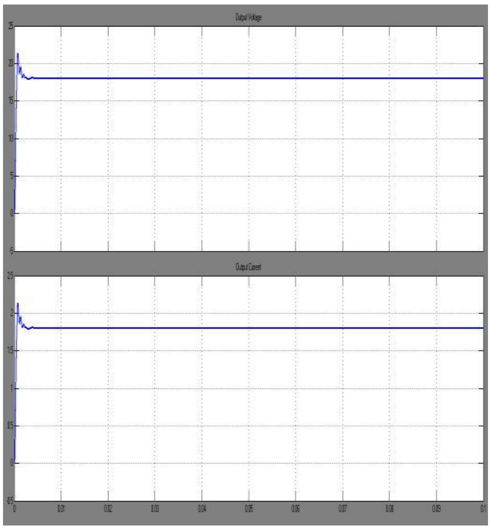

Figure 5: Output Voltage and Output Current of soft-switching KY Boost converter

C. *MATLAB Results of Soft-Switching Closed Loop KY Converter*

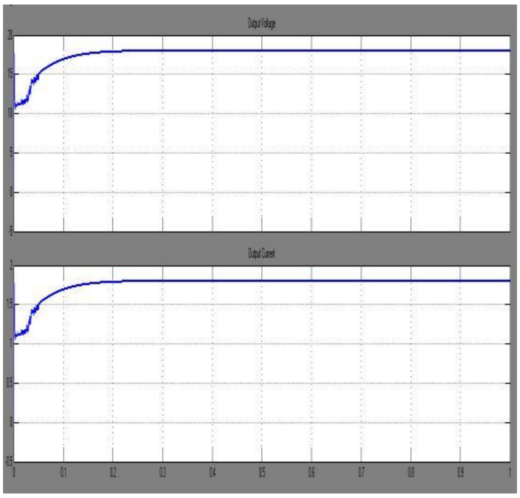

Figure 6: Switching Pulses, Output Voltage and Output Current of Closed loop KY Boost converter

Here the closed loop soft-switched KY boost converter mat lab results are discussed. This converter is also operated at same input voltage and same duty ratio. Input voltage is 12V. And duty ratio is 60%. And the output voltage is our requirement.

Finally compared to conventional Boost converter KY converter has less ripple percentage. And soft-switching KY converter has less ripple content compared to conventional KY converter. At last the closed loop system has less ripple percentage and desired voltage compared to the open loop system.

V. CONCLUSION

The soft-switching KY converter using PI controller has been demonstrated with MATLAB/SIMULINK software platform. The designed converter is tested at different operating conditions using PI controller has produced excellent performance. Many simulation results are presented to prove the effectiveness of the soft-switching KY converter over the conventional boost converter. Also, the designed converter has produced minimal ripple of the output voltage. Therefore, it is more suitable for constant power supply for LCD display, MP-3 player, medical equipments, and renewable energy source.

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