Analysis and Simulation of a Non-Isolated Cascaded High Gain Boost Converter

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Abstract: Conventional dc-dc boost converters can't practically achieve a voltage gain beyond 6 to 7 due to the requirement of high duty ratio above 0.9, which causes increased switching losses and subsequently lower operational efficiency. Two or more boost converters in cascade can help in achieving high voltage gain but with the cost of two-stage conversion loss and high initial cost of investment. On the other hand, generation of 230 V ac supply using conventional single phase inverter requires input dc bus level of at least 360 V. In this work, a single stage non-isolated cascaded boost converter using a coupled inductor is presented to step up a dc source from 48 V to the level of 360 V, as required for single phase inverter. This converter can find wide applications in telecommunication systems for supply of ac power to local loads like modems, LANs, lights, fans etc. at base transceiver stations. Only few passive components like a coupled inductor, two capacitors and three diodes, in addition to the required minimum components of conventional boost converter are required for this converter. The operating modes and key waveforms of the developed converter have been presented along with key mathematical equations governing dynamic behavior of the converter. Computer simulation using MATLAB/Simulink of the present converter at different load conditions has been carried out to verify its performance and the important results are presented in this paper.

Keywords: Boost –converter; coupled inductor; duty-ratio, cascade; voltage gain.

1 INTRODUCTION

Increasing demand of telephone and internet services at remote locations has led to the installation of telecommunication systems at stations distant from power grid. Telecommunication applications typically use 48 V dc. power supplies for the equipment, whereas an auxiliary single phase ac. supply at 230 V, 50 Hz. is also required for other applications like computers, LANs, modems, hubs, lights, fans etc. Generation of 230 V ac supply using conventional single phase inverter requires input dc bus level of at least 360 V. A conventional boost converter gets the first consideration for this application but it is very difficult to boost 48 V dc supply to the level - of 360 V dc as the required duty ratio lies above 90%. The voltage stress of the switch operating with duty

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ratio above 90% is very high and large current ripple causes high switching loss.

Conventionally, two or more boost converters in cascade can help in achieving high voltage level of 360 V from a dc bus at 48 V, but with the cost of two-stage conversion loss and high initial cost of investment.

In recent years, many DC-DC converters [1]-[8] with large step-up ratio have been suggested to find a suitable solution alleviating these problems. A comparative study between a conventional boost converter, quadratic boost converter, tapped-inductor boost converter and cascaded boost converter have been discussed in [1] along with few suggestions for topological improvements. A coupled-inductor boost converters to achieve high voltage gain has been described in [2] along with its mathematical model and design guidelines for selection of active and passive components. Another high step-up, clamp mode coupled-inductor DC-DC converter has been described in [3] along with theoretical analysis and practical design considerations. A single switch cascading high step-up DC-DC converter utilizing a boost converter at the front stage and a coupled inductor at the rear semi-stage has been described in [4]. A two-stage non-isolated high gain boost converter with a coupled inductor has been described in [5] along with design methodology to find the optimal coupling coefficient of the coupled inductor. Optimal design of a high gain dc-dc boost converter for high voltage photovoltaic application has been described in [6]. A new high efficiency, high step-up dc-dc converter for photovoltaic (PV) module integrated converter has been described in [7].

In this paper, a single switch non-isolated cascaded high gain boost converter operating in continuous conduction mode is proposed for stepping up a 48 V dc supply to the level of 360 V, suitable for

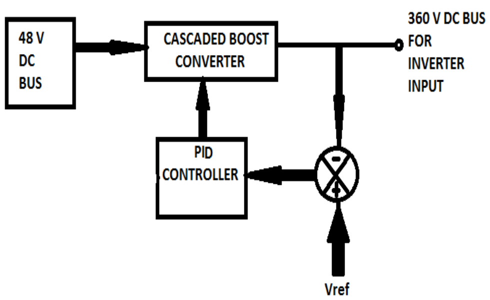

Fig. 1. Block diagram of cascaded boost converter.

generation of 230 V single phase ac. supply. This converter enjoys the advantages of reduced input current ripple and available duty cycle range required to achieve reasonable higher voltage gain. Moreover, the voltage stress of the power switch is not very high and the leakage inductor energy is recycled to clamp capacitor and output capacitor to improve the conversion efficiency.

2 CASCADED HIGH GAIN BOOST CONVERTER

The block diagram of closed loop control scheme for generation of 360 V dc supply from a 48 V dc bus is described in Fig. 1. The cascaded boost converter is designed to operate in continuous conduction mode. A closed loop control scheme has been adopted for automatic variation of duty cycle to maintain constant voltage at the output in spite of variation in input supply (V_s) and/or output load. The closed loop control scheme improves stability and reduces sensitivity of the system.

3 DESCRIPTION AND ANALYSIS OF PROPOSED CASADED BOOST CONVERTER

The non-isolated cascaded high gain boost converter as shown in Fig. 2 uses a coupled inductor (L_1 and L_2), two clamping capacitors (C_1,C_2) and three diodes (D_1, D_2, D_4) in addition to basic minimum components required by a boost converter. The output voltage of the proposed cascaded boost converter is regulated by varying the pulse-width of the main switch (S_w). To facilitate explanation of operation of the converter, Fig. 3 shows the topological equivalent circuits and Fig. 4 shows the key waveforms of the converter over a complete cycle of operation in continuous conduction mode. The principle of operation in steady-state condition is described with the following assumptions.

1. The input inductor (L_{in}) is large enough so that the input current (I_s) is assumed to be constant during one switching cycle.
2. Output capacitor (C_o) is so large that output voltage (V_o) is assumed to be constant during one switching cycle.

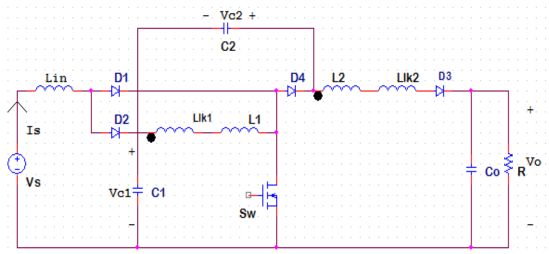

Fig. 2. Single switch cascaded boost converter.

3. The clamping capacitors (C_1 & C_2) are large enough to maintain constant voltage (V_{c1} and V_{c2}) across them respectively.

This converter has four operating modes in a switching cycle. During passive mode of operation, the input current (I_s) flows through diode (D_2), primary inductor (L_1), diode (D_4), secondary inductor (L_2), boost diode (D_3) and the load (R). The clamping capacitor (C_2) now discharges by a fraction of input current through inductor (L_2), diode (D_3 & D_2). This is the passive mode of boost converter. The operation of the converter starts as the boost switch is turned on at t_o .

MODE 1 (t_0 - t_1): As soon as the switch (S_w) is turned ON, the diode (D_1) starts conducting input current (I_s) through the switch (S_w). Hence, the diode (D_2) is reversed biased by the voltage (V_{C1}) and stops conducting. The primary inductor current (I_{L1}) is now maintained through the switch (S_w) and the capacitor (C_1). So the capacitor voltage (V_{c1}) is impressed across the primary leakage inductance (L_{lk1}) . The switch current is given by,

$$i_{sw} = I_S + \frac{V_{C1}}{L_{lk1}}(t - t_0) \tag{1}$$

$$V_{C1} = V_{L1} \tag{2}$$

Now the energy stored in secondary leakage inductance (L_{lk2}) is transferred to the output through boost diode (D_3) and capacitor (C_1) in series with (C_2). Thus, secondary leakage current (I_{lk2}) is reduced linearly from its initial value (I_{lk20}) . So, the secondary leakage current can be expressed as,

$$I_{L1k2} = I_{Lk20} - \frac{V_0 - (V_{C1} + V_{C2})}{L_{lk2}} (t - t_0) \tag{3}$$

This mode ends at t_1 when the secondary inductor current reaches to a value of zero.
Duration of this mode is therefore given by,

$$t_{01} = t_1 - t_0 = \frac{I_{lk20} ? L_{k2}}{V_0 - (V_{C1} + V_{C2})} \tag{4}$$

At the end of this mode, the primary leakage current is now reaches to a value of

$$I_{Lk11} = \frac{V_{C1}}{L_{lk1}} t_{01} \tag{5}$$

MODE 2 (t_1 - t_2): As soon as current through secondary inductor (L_2) reaches zero, its voltage across the secondary jumps to [k× $V_{primary}$] according to the dot polarity shown (where k = n_2 / n_1 and $V_{primary}$ = Voltage across primary). The primary leakage current now therefore becomes steady to its initial value (I_{Lk11}). However the input current (I_s) continues flowing through diode (D_1) and the switch. So, the switch (S_w) current (i_{sw}) during this mode is given by,

$$i_{sw} = I_S + I_{lk11} \tag{6}$$

This is the active mode of the boost converter and this mode ends at t_2 when the switch (S_W) is turned off.

MODE 3 (t_2 - t_3): As soon as the switch is turned off the diode (D_1) stops conduction. The input current (I_s) is now transferred from diode (D_1) to diode (D_2) and maintained through the capacitor (C_1). The primary inductor current is maintained through two paths - one through diode (D_4) and capacitor (C_2) and another path is maintained through diode (D_4), inductor (L_2), diode (D_3), load, input and diode (D_2). So, the capacitor voltage (V_{C2}) is now impressed across the primary inductor. Thus the part of the energy stored in primary inductor is transferred to the output and the rest for charging capacitor (C_2). Thus the current through inductor (L_1) reduces from its initial value and the current through inductor (L_2) rises linearly from zero. This mode ends when the current of primary and secondary inductor become equal and the capacitor (C_2) is charged to its maximum level.

MODE 4 (t_3 - t_4): At t_3 , primary inductor current (I_{L1}) becomes equal to secondary inductor current (I_{L2}). However the energy stored in primary inductor (L_1) is still transferred to the output through diode (D_4), secondary inductor (L_2), diode (D_3) and diode (D_2) so its current reduces linearly. Now the capacitor (C_2) starts discharging through secondary inductor (L_2), diode (D_3), load and diode (D_2). Therefore the current through secondary inductor (L_2) continues rising as before. This mode ends at t_4 when the boost switch is turned on and operation of next cycle starts.

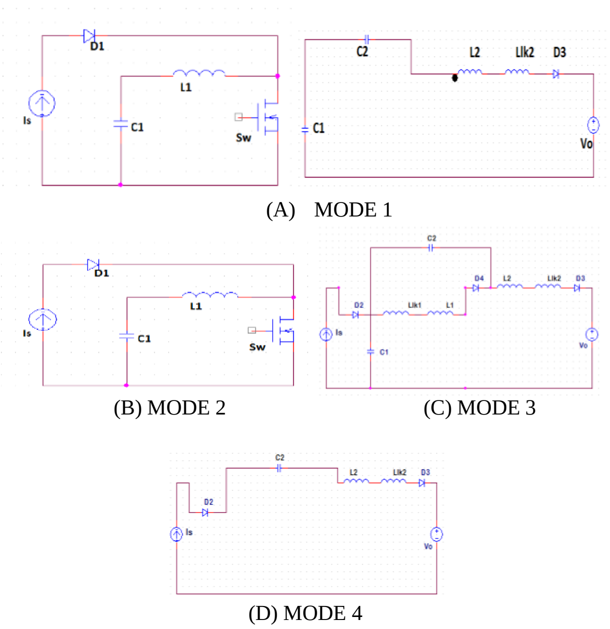

Fig. 3. Topological equivalent circuits cascaded boost converter.

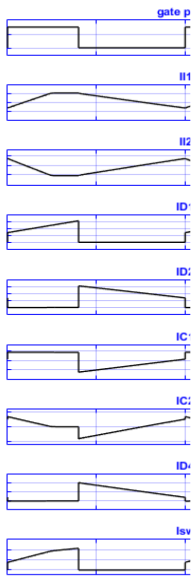

Fig. 4. Key waveforms of cascaded boost converter.

4 SIMULATION OF PROPOSED CASCADED BOOST CONVERTER

In order to investigate the performance of the proposed cascaded boost converter, a thorough computer simulation has been carried out with Matlab/simulink with rated specification and major active and passive components as per Table 1.

The simulation circuit of the cascaded boost converter with closed-loop PID control scheme for regulation of output voltage is shown in Fig.5.The gain parameters of the controller are also given in Table I. Fig.6 shows the input supply voltage(V_s), output (V_o) load voltage and the gate pulse waveform. Fig. 7 shows the input inductor current (I_{Lin}), current through diodes (I_{D1}, I_{D2} & I_{D3}) ,current through capacitors (I_{C1} & I_{C2}).

Table 1. Rated specifications of circuit elements.

Specifications	Rated input voltage supply = 48 V; Rated output voltage = 360 V; Rated output power = 1.2 kW Switching frequency = 1 kHz.
Major components	Rated input inductor, L_{in}= 250 μH Rated clamp capacitor, C_1, C_2=100 μF Rated output capacitor, Co= 470 μF Diode Rating: D_1, D_2 : 300 V, 75 A D_3: 600 V, 25 A D_4: 300 V, 15 A Switch Rating: 600V, 75 A
Controller parameters	Proportional gain , k_p=0.1 Integral gain k_i=0.3 Derivative gain, k_d=0.3

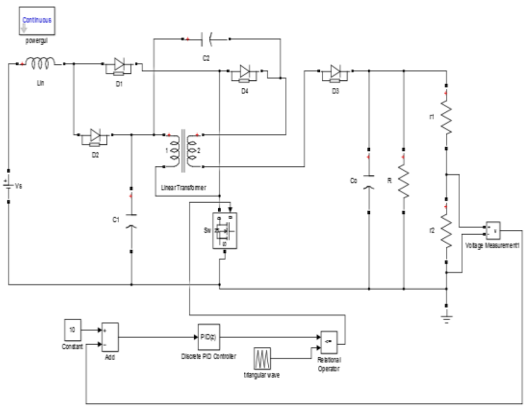

Fig. 5. Simulation circuit of cascaded boost converter.

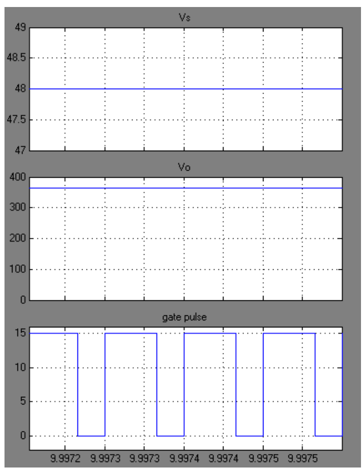

Fig. 6. Waveforms of input supply (V_S), output (V_O) and the gate pulse.

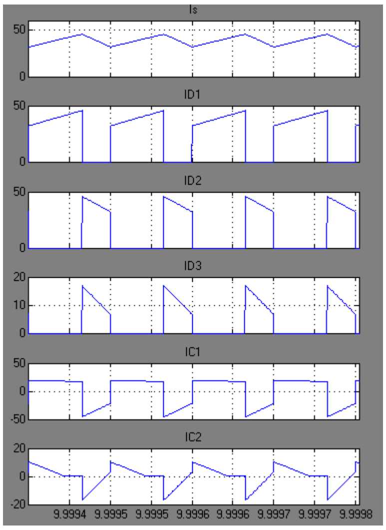

Fig. 7. Waveforms of the input current (I_S), diode currents (I_{D1}, I_{D2} & I_{D3}) and the capacitor currents (I_{C1} & I_{C2}).

5 CONCLUSION

A single switch non-isolated cascaded high gain boost converter operating in continuous conduction mode is proposed in this paper for stepping up a 48 V d.c. supply up to the level of 360 V d.c. suitable for generation of 230 V single phase a.c. supply. This converter can therefore find wide applications in telecommunication applications.

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