Steady State Analysis and Hardware Implementation of a Switched Capacitor Based High Gain DC-DC Boost Converter

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Abstract

A high step-up DC-DC converter is required to boost the low output voltage sources like solar PV system, fuel cell etc. to connect it to the high bus voltage. Considering the merits of both the high voltage gain and good output voltage regulation, a non-isolated switched capacitor (SC) converter is presented, analyzed and implemented in hardware. The paper includes operating principle, steady state analysis of the converter. The performance of the converter is verified by MATLAB/SIMULINK and a laboratory prototype of 220V, 500 Watts.
1. Introduction

In recent times, the notable problem faced in power sector is the increasing power demand. This increasing power demand overloads the grid which ends in unstable grid operation, degradation in power quality, ending in interrupted power supply etc. The present centralized power generation units aren’t sufficient to fulfill the endlessly rising power demand. This problem of power demand and lack of flexibility in power distribution is tackled by the use the distribution generation (DG) system based on the renewable energy sources (RES) in conjunction with power electronics. Distributed generation is becoming more common due to the benefits of producing power near the desired load center. These DG systems are powered by micro-sources such as fuel cells, batteries, photo-voltaic (PV) cells, wind power, etc. However these micro-sources will produce only a low voltage dc sources. So, to boost the voltage, usually high step-up DC-DC converters are connected in the front end, to step the voltage from low to high. The converters, those are connected to the distributed generation systems, are required to have high efficiency, large voltage conversion ratio and small volume.

The conventional DC-DC boost converters will provide a very high voltage gain with the high duty ratio. But, practically the parasitic elements associated with the components of the converter such as inductor, capacitor, switch and diode cannot be ignored. Hence it will reduce the theoretical voltage gain. As the solution to overcome these problems, many converters have been proposed to achieve high voltage gain without high duty ratio. Converters for high voltage gain include switched capacitor and switched inductor types, the boost type integrating with switched capacitor technique, the voltage lift type, the transformer-less dc-dc converters, and the capacitor-diode multiplier type. A single switch is incorporated to achieve high voltage gain in the converter presented here. This converter has two intermediate switched capacitors and diodes to attain high step up voltage gain. These two capacitors are charged in parallel and discharge in series via switch. Therefore the converter has low conduction loss. Another advantage of this proposed converter is that the low voltage stress on the switch and on the diodes.

2. Power Circuit Diagram

The power circuit diagram of the SC converter is shown in Figure 1. The circuit consists of one inductor (L1), one active switch (S1), two switched capacitors (C1 and C2), two switched diodes (D1 and D2), one output diode (D0) and one output capacitor (C0). Switched capacitors are charged in parallel and discharge in series to provide high voltage gain.
3. **Steady State Analysis**

The steady state analysis in continuous conduction mode (CCM) and discontinuous conduction mode (DCM) is presented here.

3.1. **CCM Operation**

The converter operates in two modes during CCM operation. When the switch S1 is ON is known as Mode 1. When the switch S1 is OFF is identified as Mode 2. Figure 2 shows the characteristic waveforms of the converter during its continuous conduction mode of operation.

![Figure 1: Power Circuit Diagram of the SC Converter](#)

![Figure 2: Characteristic Waveforms of the Converter in CCM](#)
Figure 3: Equivalent Circuit during Mode 1 of CCM

Figure 4: Equivalent Circuit during Mode 2 of CCM

Mode 1 (When switch is ON)

Figure 3 shows the equivalent circuit diagram during Mode 1 operation of CCM. During this interval, Switch S1 is ON. Inductor L1 charges and two intermediate switched capacitors discharge through switch S1. Therefore, the voltage across L1 is given as

\[ V_{L1} = V_{in} \quad (1) \]

Mode 2 (When the switch is OFF)

Figure 4 shows the operation of the converter during mode 2 of CCM. During Mode 2, switch S1 is OFF. Inductor L1 discharges and two intermediate switched capacitors charge in parallel. The voltage across L1 is given as

\[ V_{L1} = V_{in} - \frac{V_0}{2} \quad (2) \]

Applying volt-sec balance theory across inductor L1,

\[ V_{in} \times D + (V_{in} - \frac{V_0}{2}) \times (1 - D) = 0 \quad (3) \]

Voltage gain during CCM of the SC converter is given by,

\[ \frac{V_0}{V_{in}} = \frac{2}{(1-D)} \quad (4) \]
3.2. DCM Operation

The converter operates in three modes during DCM operation. Figure 5 shows the characteristics waveform of the converter in DCM modes of operation.

**Mode 1 (When switch is ON)**

This mode is similar to the mode 1 of CCM operation of the converter. Figure 3 shows the equivalent circuit of the converter during Mode 1 of DCM operation. The peak inductor current is given by,

\[ I_{L1} = \frac{V_{in}}{L_1} D T_S (5) \]

Figure 5: Characteristic Waveforms of the Converter in CCM

Figure 6: Equivalent Circuit during Mode 3 of DCM
Mode 2 (When the switch is OFF and inductor is conducting)

This mode is similar to the mode 2 of CCM operation of the converter. Figure 4 shows the equivalent circuit of the converter during Mode 2 of DCM operation. The peak inductor current is given by,

\[ I_{L1} = \left( \frac{V_{in} - \frac{V_0}{2}}{L_1} \right) DT_s \]  

(6)

Mode 3 (When the switch is OFF and inductor is not conducting)

In this mode of operation the switch is OFF and all the diodes are reversed biased. Figure 6 shows the equivalent circuit during Mode 3 of DCM operation of the converter. During this interval, only the output capacitor supplies energy to the load. The voltage gain of the converter during DCM operation is given by,

\[ \frac{V_0}{V_{in}} = 1 + \sqrt{\frac{1 + 2D^2}{K}} \]  

(7)

Where \( K = \frac{2L_1}{RT_s} \)

4. Design of Inductor and Capacitors

The value of the inductor is given by

\[ L_1 = \frac{(1-D)\times D \times R}{4f} \]  

(8)

The formula for the intermediate switched capacitors is given by,

\[ C_1 = C_2 = \frac{(1-D) \times I_{in}}{2f \Delta V_c} \]  

(9)

The output capacitor value is given by,

\[ C_0 = \frac{D}{2 \times f \times R} \]  

(10)

5. Simulation and Hardware Results of the SC Converter

The simulation of proposed boost converter is done in MATLAB/SIMULINK environment. The simulation results and analysis are shown. Figure 7 shows the simulation result of output voltage of 220V for an input of 70V. Figure 8 presents the simulation waveforms of input and output current for the input voltage of 70V. The input current is 10A and the output current is 2.3A. The hardware prototype of the SC converter of 500 W is developed in laboratory. The duty cycle is maintained as 0.4 and the switching frequency is 50 kHz. Figure 9 shows the output waveforms of the input and output voltage and current. An output voltage of 208V is obtained for an input voltage of 70V. The input current is 7.40A and the output current is 2.34A. The full load efficiency
of the converter is 93.7%. Figure 10 shows the voltage stress across the switch with respect to the rated output voltage 208V. The stress on the switch is 110V. Figure 11 shows the voltage stress across all the diodes with respect to the rated output voltage 208V. The stress on the diode is also 110V.

Figure 7: Simulation Waveforms of Input and Output Voltage

Figure 8: Simulation Waveforms of Input and Output Current

Figure 9: Hardware Result for An Input Voltage of 70V
6. Conclusion

The SC converter is simulated and tested in hardware to verify its performance. It has been observed that the proposed converter provides high voltage gain with low voltage stress across the active switch and all the diodes. It is also tested in different load condition to verify its voltage regulation. It is observed that the voltage regulation of the converter is very good which enables it to use for variable voltage sources like solar PV application.

References


