Indian Institute of Technology (BHU) Varanasi

Department of
Electrical Engineering

UG-PROJECT
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Developing a Switched Capacitor Based Bidirectional Converter for EV Charging

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1 Abstract

2 Introduction

Growing concern of carbon dioxide emissions, greenhouse efects and rapid depletion of fossil fuels raise the necessity to produce and adopt new eco-friendly sustainable alternatives to the internal combustion engine (ICE) driven vehicles. For this reason, in the last decade, EVs have become in some way widespread, principally because of their negligible fue gas emissions and lesser reliance on oil. It is estimated that by 2022, EVs will be over 35 million in the World. However, a critical problem associated with EVs is that their high penetration causes signifcant issues on the power distribution grid such as: power quality deterioration, enhanced damaged of line, downturn of distribution transformers, increased distortion and higher fault current.One efcient approach to relieve the efect is to integrate local power generation such as renewable energy sources (RESs) into the EV charging infrastructure.
On the basis of the power rating of the EV chargers can be divided Level 1, Level 2, Level 3:-

Power level	Charger location	Typical use	Typical power	Charging time	Connector
Level 1	On-board	Home	2 kW	4–11 h	SAE J1772
Level 2	On-board	Public	20 kW	1–4 h	SAE J1772
Level 3	Off-board	DC Fast	100 kW	< 30 min	CHAdeMO/ CCS COMBO 2

Figure 1: Caption

Not only the choice of the charging technology, but also the selection of the correct charging method is a feature that has to be considered during the charging procedure. The most popular charging strategies to recharge Li-ion batteries are constant-current/constant-voltage (CC/CV) and pulse current charging methods.
The cost of the EV batteries and Power electronics devices are falling. With the rapid growth of manufacturing industries and technology the size

of the devices are reducing and performance is increasing. Same performance can be achieved by the smaller and cheaper devices.

3 Switched Capacitor Based Boost converter

3.1 Step-up Circuit and its analysis

A Switched Capacitor based converter ideally can provide any line to line voltage ratio. If n is the number of capacitors used in SC structure, then

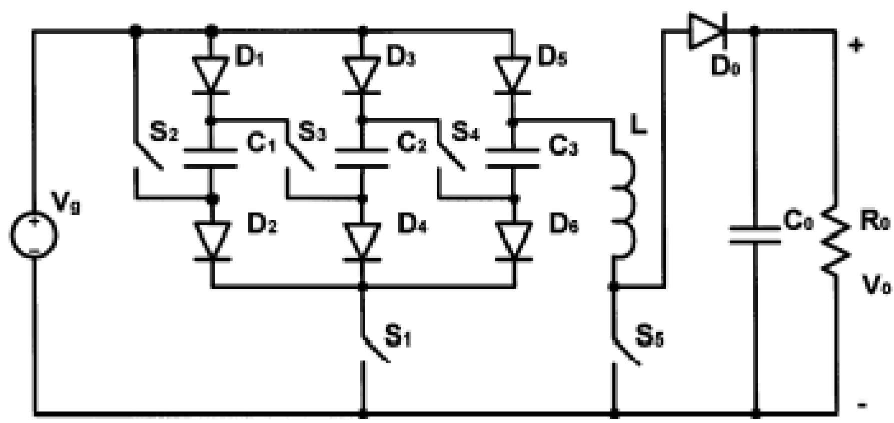


Figure 2: Boost Converter with SC circuits n=3

$$V_{0ideal} = (n+1)V_g \tag{2}$$

where, V_g input voltage,V_0 output voltage. The output Capacitor C_0 is not counted in n,because it role is to reduces ripple output voltage only. Any voltage ratio can be achieved by choosing n.The SC converter would be the ideal choice for an application where no isolation is needed, if it were not for the efficiency requirement.As

$$\eta = \frac{V_0}{(1+n)V_g} \tag{3}$$

In Figure 1, a Boost converter with SC circuit is shown. SC circuit is composed of three capacitors $C_1 - C_3$ and seven diodes $D_1 - D_7$. The

Switch S_5, inductor L, diode D_0, and capacitor C_0 form an usual Boost converter, i.e., the SC circuit is inserted between the line and the boost stage.

Three switching topologies are present in proposed converter.
1. The duration of three topologies are xDT_s, $(1-x)DT_s$ and DT_s.
2. The classical on-topology of a boost converter is split into two stages.
3. The first stage overlaps the on-topology of the SC circuit.
4. The second stage is combined with the off topology of the SC circuit.
5.The second part of the off-topology of the SC circuit overlaps the off-topology of the Boost converter

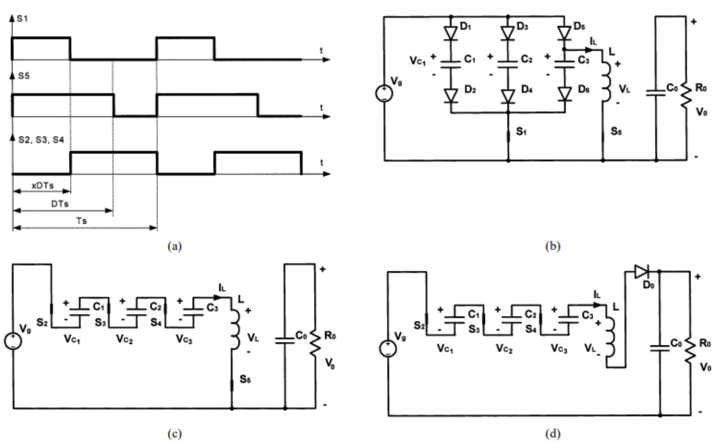


Figure 3: (a)Timming diagram;(b)First Switching topology;(c)Second Switching topology;(d)Third Switching topology

For the first switching topology

$$
\begin{aligned}
\frac{\partial v_{Ck}}{\partial t} &= -\frac{1}{C(r_c + r_{s1})} v_{Ck} + \frac{V_g - 2V_D}{C(r_c - r_{s1})} \\
\frac{\partial i_L}{\partial t} &= -\frac{r_L + r_{S5}}{L} i_L + \frac{V_g - V_D}{L} \\
\frac{\partial v_{C_0}}{\partial t} &= -\frac{1}{RC_0} v_{C_0}
\end{aligned} \tag{4}
$$

For the second switching topology

$$\frac{\partial v_{C_1}}{\partial t} = \frac{\partial v_{C_2}}{\partial t} = \frac{\partial v_{C_3}}{\partial t} = -\frac{1}{C} i_L$$

$$\frac{\partial i_L}{\partial t} = \frac{1}{L} v_{C_1} + \frac{1}{L} v_{C_2} + \frac{1}{L} v_{C_3} - \frac{3r_{S_1} + r_{S_5} + r_L + 3r_C}{L} i_L + \frac{V_g}{L}$$

$$\frac{\partial v_{C_0}}{\partial t} = -\frac{1}{RC_0} v_{C_0} \tag{5}$$

For the third switching topology

$$\frac{\partial v_{C_1}}{\partial t} = \frac{\partial v_{C_2}}{\partial t} = \frac{\partial v_{C_3}}{\partial t} = -\frac{1}{C} i_L$$

$$\frac{\partial i_L}{\partial t} = \frac{1}{L} v_{C_1} + \frac{1}{L} v_{C_2} + \frac{1}{L} v_{C_3} - \frac{3r_{S_1} + 3r_C + r_L}{L} i_L + \frac{V_g - V_D}{L} - \frac{v_{C_0}}{L}$$

$$\frac{\partial v_{C_0}}{\partial t} = \frac{1}{C_0} i_L - \frac{1}{RC_0} v_{C_0} \tag{6}$$

An approximate input-output voltage ratio M can be obtained by using voltage second balance principle. During first, second and third topology voltage acorss inductor L is equal to V_g, $4V_g$ and $4V_g - V_0$ in steady state cycle.

$$V_g x D T_s + 4V_g(1-x)DT_s + (4v_g - V_0)DT_s = 0$$

$$M = \frac{V_0}{V_g} = \frac{4 - 3xD}{1 - D}$$

3.2 Design Aspects of converter

Four parameters have to be chosen L, C, x, and $f_s (f_s = 1/T_s$, is the switching frequency). The first design formula for is the classical one

$$L \geq V_g \frac{D}{\Delta i_L f_s} \tag{7}$$

$$L \geq \frac{nV_g(1-x)D}{\Delta i_L f_s}$$

The first design formula for C is the classical one, requiring for a small ripple in the voltage ΔV_C

$$C = \frac{V_0}{2R_0(\Delta V_C f_s)} \tag{8}$$

$$C_1 = C_2 = C_3 \geq \frac{V_g x D}{r_C \Delta V_C f_s}$$

4 Maximum Power Point Tracking

Maximum Power Point Tracking (MPPT) is an efficient method for PV systems to enhance the solar energy to solar power conversion efficiency. The peak value of PV output current Ipv and voltage Vpv is located in the IV curve MPP [6]. Since this stage is non-linear and continues to change based on the climatic circumstances, it must be continually monitored and the PV module must be operated on this MPP. MPPT is recognized as this whole method of monitoring the point and running the PV system at the full energy level [10]. Figure presented the P-V curve of a solar module where the generated power is plotted vertically and output voltage is plotted horizontally. The monitoring of MPP and the operation of the PV

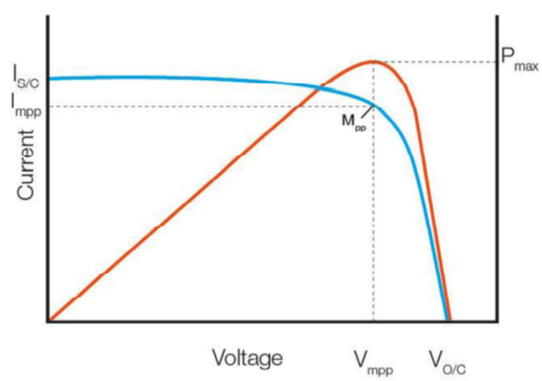


Figure 4: I-V and P-V characteristics of solar PV cell

module on MPP involves two primary categories. One might be related to the type of DC-DC converter and the type of load connected to the PV source, while the other might be the software or the techniques of MPPT achieving.

5 Non-isolated Three-Port DC–DC Converters From DIC and DOC

6 Switched Capacitor Based Bidirectional DC-DC Converter

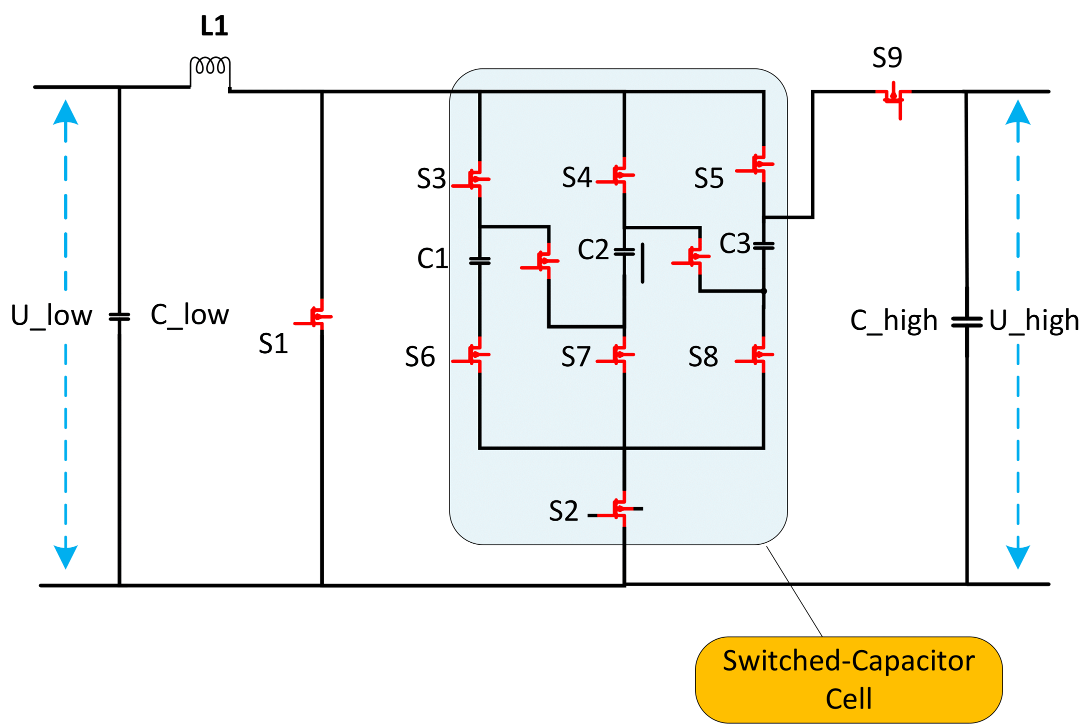


Figure 5: Switched-Capacitor based Bidirectional DC-DC Converter

6.1 Operating Principle and Analysis Of The Converter

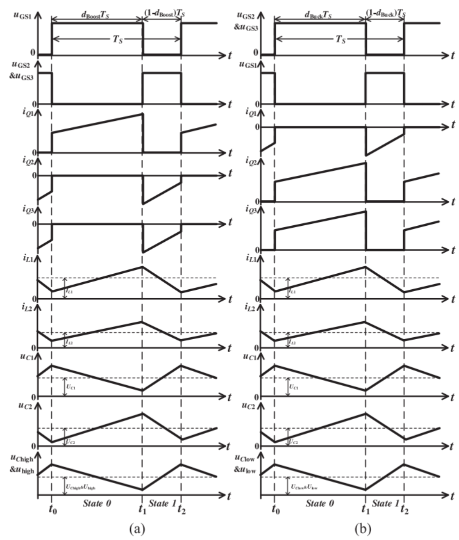
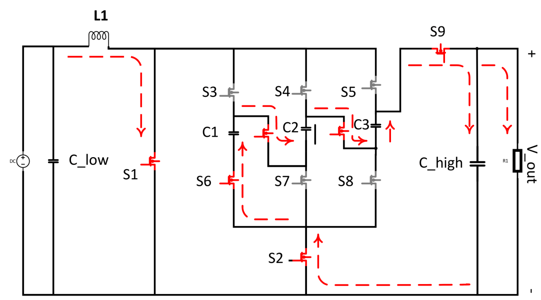


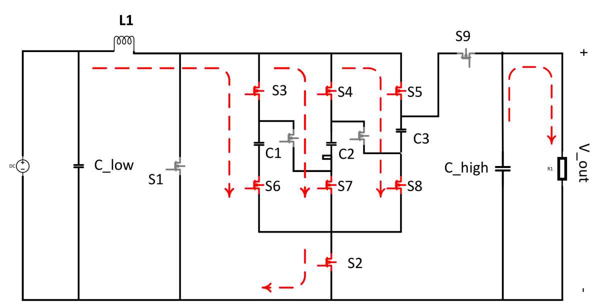
Figure 6: Typical Waveforms of the proposed converter. (a) Step-up mode.(b) Step-down mode.

6.2 Analysis of Steady-State Characteristics

6.2.1 Step-Up Mode of the Proposed Converter:



(a)



(b)

Figure 7: Typical Waveforms of the proposed converter. (a) Step-up mode.(b) Step-down mode.

Mode1

$$\begin{cases} U_{L1} = U_{low} \\ U_{C_{low}} = U_{low} \\ U_{high} = U_{C_{high}} \\ U_{C1} = U_{C2} = U_{C3} \\ U_{C_{high}} = U_{C1} + U_{C2} + U_{C3} \end{cases} \tag{9}$$

$$\begin{cases} i_{C1.dBoost} = i_{C2.dBoost} = i_{C3.dBoost} = -I_{high} \end{cases} \tag{10}$$

MOde2

$$\begin{cases} U_{L1} = U_{low} - U_{C1} \\ U_{C1} = U_{C2} = U_{C3} \\ U_{high} = U_{C_{high}} \end{cases} \tag{11}$$

$$\begin{cases} i_{C1.dBoost} = i_{C2.dBoost} = i_{C3.dBoost} = i_{L1} \end{cases} \tag{12}$$

Voltage gain using Voltage second balance princple

$$U_{low}d_{Boost} + (U_{low} - U_{C1})(1 - d_{Boost}) = 0$$

$$M_{Boost} = \frac{U_{high}}{U_{low}} = \frac{3}{1 - d_{Boost}} \tag{13}$$

Ampere Second Balance principle

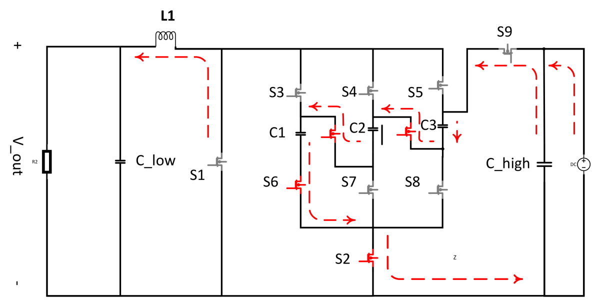
$$i_{C1.dBoost}d_{Boost} + i_{C1.(1-d_{Boost})}(1 - d_{Boost}) = 0$$

$$\begin{cases} I_{L1} = I_{high}\frac{d_{Boost}}{1-d_{Boost}} \end{cases} \tag{14}$$

Voltage Stress across Capacitors

$$\begin{cases} U_{C1} = U_{C2} = U_{C3} = \frac{U_{C_{high}}}{3} = \frac{U_{low}}{1-d_{Boost}} \\ U_{C_{low}} = U_{low} \\ U_{C_{high}} = U_{high} = \frac{3U_{low}}{1-d_{Boost}} \end{cases} \tag{15}$$

6.2.2 Step-down Mode of the Proposed Converter:



(a)

(b)

Figure 8: Typical Waveforms of the proposed converter. (a) Step-up mode.(b) Step-down mode.

Mode1

$$\begin{cases} U_{L1} = -U_{low} \\ U_{C1} = U_{C2} = U_{C3} \\ U_{C1} + U_{C2} + U_{C3} = U_{C_{high}} \\ U_{C_{high}} = U_{high} \end{cases} \tag{16}$$

$$\begin{cases} i_{C1_{Buck}} = i_{C2_{Buck}} = i_{C3_{Buck}} = I_{low} \end{cases} \tag{17}$$

Mode2

$$\begin{cases} U_{L1} = -U_{lowUC1} \\ U_{C1} = U_{C2} = U_{C3} = U_{L1} + U_{low} \\ U_{low} = U_{C_{Clow}} \\ U_{C_{high}} = U_{high} \end{cases} \tag{18}$$

$$\begin{cases} i_{C1_{Buck}} = i_{C2_{Buck}} = i_{C3_{Buck}} = -I_{L1} \end{cases} \tag{19}$$

Voltage gain using Voltage second balance principle

$$-U_{low}d_{Buck} + (U_{C1} - U_{low})(1 - d_{Buck}) = 0$$
$$M_{Buck} = \frac{U_{low}}{U_{high}} = \frac{1 - d_{Boost}}{3} \tag{20}$$

Ampere Second Balance principle

$$i_{C1.dBuck}d_{Buck} + i_{C1.(1-d_{Buck})}(1 - d_{Buck}) = 0$$

$$I_{L1} = I_{low}\frac{d_{Buck}}{1 - d_{Buck}} \tag{21}$$

6.2.3 Parameter design of Inductor

$$\begin{cases} L1 \geq \frac{U_{low}(1-d_{Boost})}{f_s I_{high} x_L} \\ L1 \geq \frac{U_{high}(1-d_{Buck})^2}{3 f_s I_{low} x_L} \end{cases} \tag{22}$$

6.2.4 Parameter design of Capacitor

$$\begin{cases} C1 = C2 = C3 \ \geq \frac{I_{high} d_{Boost} (1 - d_{Boost})}{f_s U_{low} x_c} \\ C1 = C2 = C3 \ \geq \frac{3 I_{low} d_{Buck}}{f_s U_{high} x_c} \end{cases} \tag{23}$$

7 Simulation and Results

7.1 Switched Capacitor based Boost converter

Values of components used for simulation:

$$f_s = 5kHz \;\; x = 0.39 \;\; D = 0.7 \;\; r_c = 0.02\Omega$$

$$L = 10^{-4}H \;\; C_1 = C_2 = C_3 = 100\mu F \;\; C_0 = 100\mu F \;\; R = 100\Omega$$

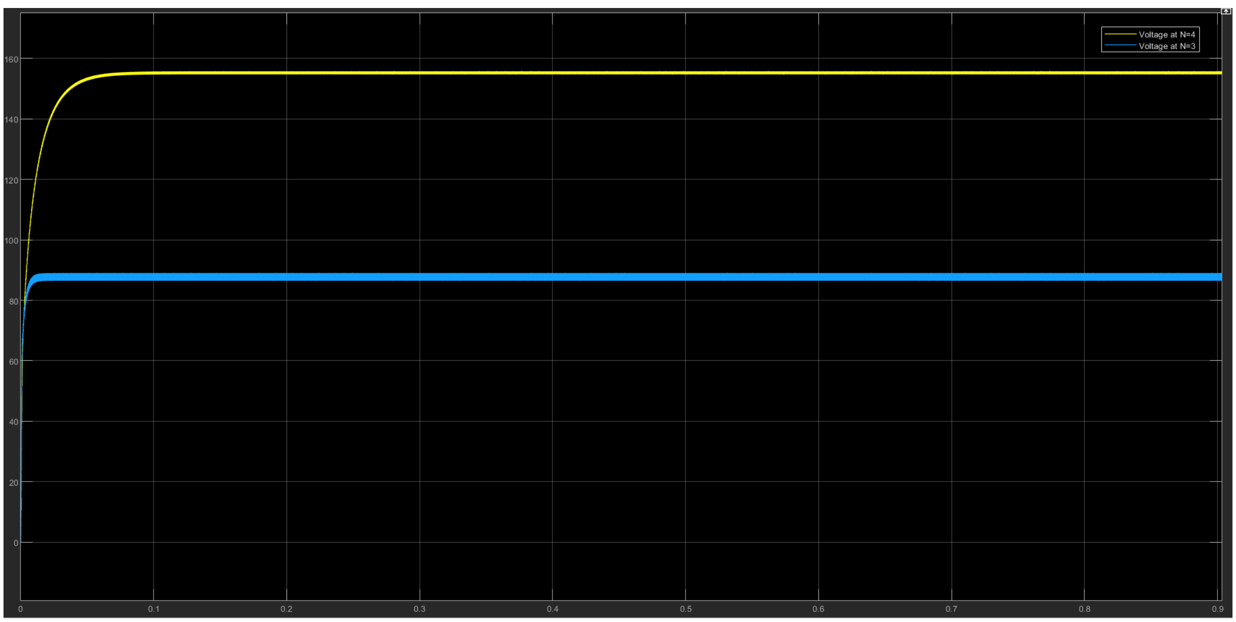


Figure 9: Output voltage at n=3 and n=4

7.2 Switched Capacitor based Boost converter and MPPT

8 Reference