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High Step-up Gain Interleaved DC-DC Converter with Switched Capacitor and Regenerative Boost Configuration for Traction Applications

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ABSTRACT
PV based traction systems employ DC-DC convert- ers for boosting the PV output voltage to adequate levels. Modern traction applications requires high voltage levels (500V to 750V) and hence, conventional boost converters are inadequate. In order to establish an efficient traction system, a high step-up gain interleaved DC-DC converter is presented. A high step-up gain interleaved DC-DC converter is designed by combining the switched capacitor and regenerative boost (SCRB) configuration. Since the switched capacitor and regenerative boost operations take place simultaneously, the voltage gain and efficiency is improved. In addition, interleaving reduces ripple content, which helps to elongate the lifetime of traction motors. Moreover, it offers low switching stress across the semiconductor devices. A comparison of key performance factors like voltage gain, switching stress and ripple content of the interleaved SRCB converter is made with other conventional converters using MATLAB simulation. It is seen that SCRB converter is superior in all key factors. FPGA is used to generate pulses for the switches.
***Index Terms*—**SCRB, Regenerative Boost, FPGA

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I. INTRODUCTION

The dc-dc converter is the most promising and attractive converter for renewable energy systems. In solar and wind energy conversion system the generation voltage level is so far from grid voltage. After voltage source inverter (VSI) stage, a transformer is mainly used to step-up the AC voltage to meet grid requirement for effective synchronization. Because of cost, size, and weight of the 50Hz transformer it becomes the primary burden in grid connected solar PV-system and hence it decreases the whole system efficiency. In order to avoid the use of a transformer, a high step-up gain DC-DC converter is presented by combining the switched capacitor and regenerative boost (SCRB) configuration in this work. In classic boost type and derived converters, the device stresses and losses associated with the converter are high and result in lower efficiency. In this converter, the switched capacitor and regenerative boost operations take place simultaneously using lossless passive components and a minimum number of semiconductor devices. However, the modified converter presented further[7] operate at lower duty ratio to support for higher conversion ratio. The harmonic boosted resonant Converter [8] presented to extend the DC voltage gain has complicated design due to resonant behavior in nature for boosted-up operation. Varieties of dual coupled-inductor and single inductor based reconfigurable converters were reported in recent days and they can operate with high efficiency under transient conditions. However, they introduce electromagnetic interference (EMI), more device count and additional snubbed circuitry is required to mitigate stored energy present in leak- age inductance. After all these converters, an ultra-high gain converter [11] is proposed with low voltage stress. However, the converter DC-voltage gain is not sufficient to meet DC-link voltage. The galvanically isolated type dc-dc converters arrived at the market to increase appropriate conversion ratio. But, it has several issues like voltage stress on the primary switch, increased size and volume and also EMI issues. Among these, the switched capacitor (SC) converters are the most common solution to achieve improved gain. When the switched capac- itors are integrated with classic boost type, the DC-voltage gain drastically improves. Obviously, the reactive components of the converter increase to attain higher DC-voltage gain. A new SC-based active network converter (SC-ANC) was proposed later [16]. However, the device stresses are high and comparatively less DC-voltage gain. In the proposed converter, the switched capacitor and regenerative boost operations take place simultaneously using lossless passive components and a minimum number of semiconductor devices. Thereby, it highly increases the DC-voltage gain and enhances efficiency. In addition, it also dominates with fewer ripple content, which helps to elongate the lifetime of devices and suppress the electromagnetic interference.

A high step-up gain DC-DC converter with switched capacitor and regenerative boost configurations introduced recently [1]. This operation takes place simultaneously using lossless pas- sive components and a minimum number of semiconductor devices. Thereby, it drastically increases the DC-voltage gain and enhances efficiency. It also dominates with fewer ripple content, which helps to elongate the lifetime of devices and suppress the electromagnetic interference. In non-isolated single-inductor DC/DC converter with fully reconfigurable structure for renewable energy applications [2] discussed a topology is to integrate a regenerative load such as DC bus and motor with dynamic braking, instead of the widely reported consuming load, with a photovoltaic (PV)-battery system. Switched-capacitor/switched-inductor structures for getting transformer less hybrid DC-DC PWM converters [3] introduced a few simple switching structures, formed by either two capacitors and two-three diodes (C-switching), or two inductors and two-three diodes (L-switching) are proposed. The main advantage of the new converters is their lower energy in the magnetic elements, what leads to weight, size and cost saving for the inductors. A novel non-isolated ultra- high voltage gain DC-DC converter [4] with low voltage stress is presented. While keeping high voltage gain, this topology illustrates low switching voltage stress resulted in high efficiency. In [5] it gives the idea of an energy efficient charging technique for switched capacitor voltage converters with low duty ratio. Charging a capacitor array of a switched- capacitor (SC) DC-DC converter, supplying load circuits with a very short active period, can be pivotal to achieve high energy efficiency of its operation. This is because the capacitors may lose most of the stored energy during a long sleep period, and thus every sleep-to active transition requires full recharging of the capacitors. In this work, an energy efficient capacitor charging technique called split-capacitor charging, which charges a capacitor array in a step-wise fashion is presented.

An isolated coupled inductor integrated DC-DC converter with non-dissipative snubber for solar energy applications are introduced[6]. The proposed converter realizes high step- up voltage gain without incurring a high coupled inductor turns ratio by adapting a dual-voltage doubler circuit. In [7] describes a galvanically isolated DC-DC converter based on current-reuse hybrid-coupled oscillators. This work presents a fully integrated DC-DC converter consisting of only two CMOS chips, which are a power oscillator with integrated transformer and a full-bridge rectifier. A thick inter-metal oxide layer guarantees a galvanic isolation rating as high as 5 kV. A current-reuse hybrid-coupled oscillator is proposed, which is based on a three-winding tapped isolation transformer and improves both output power and silicon area occupation.

In order to overcome the problems pointed in above papers a high step-up gain DC-DC converter with switched capacitor and regenerative boost configuration is introduced combining switched capacitor and regenerative boost configuration. The main goal of this converter is to achieve high DC-voltage gain by avoiding the use of the transformer in solar PV applications due to cost, size and weight.

II. OPERATING PRINCIPLE OF THE PROPOSED CONVERTER

A. Configuration of The Proposed Converter

Because of cost, size, and weight, the transformer is the pri- mary burden in grid connected solar PV-system and it decreases the whole system efficiency. Normally the switched capacitor networks are used to improve the voltage gain in an efficient manner. Hence goal of this work is to improve the voltage gain by regenerating the boosted voltage using switched inductor and capacitor during on state of the switches. During the off state of the switches, the reactive elements will discharges consecutively. Hence voltage gain increases to an extreme level.

High step-up gain DC-DC gain converter contains three active switches $S1$, $S2$, $S3$ inductors $L1$, $L2$, $L3$ and diodes $D1$, $D2$, $D3$ and $D4$. It also consist of capacitors $C1$, $C2$ and $C3$. The additional components $L3$ and switch $S3$ forms the interleaving structure. Figure 1 shows the interleaved high step-up gain DC-DC converter.

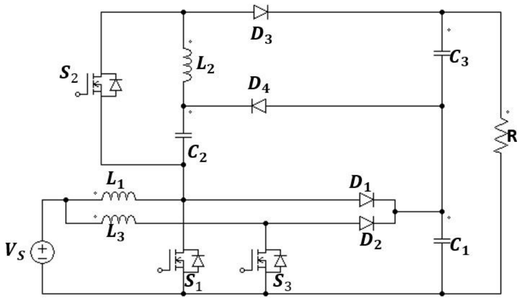

Fig. 1. Interleaved High Gain Converter

B. Operating Modes of The Proposed Converter

Two major operating modes are identified in the converter at every switching period.

Mode 1

The same gating signals are given to all the three switches present in the converter. In mode 1 operation both the three inductors are charging. At this instant only capacitor C_2 is charging and capacitors C_1 and C_3 are discharging. The current paths are clearly depicted in the circuit as shown in Fig. 2. During this interval, the theoretical waveforms are illustrated in Fig. 4.

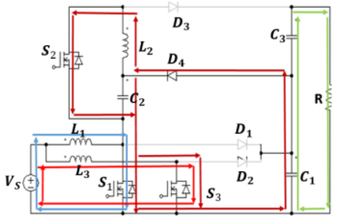

Fig. 2. Operating Circuit Of Mode 1

Mode 2

In mode 2 operation the three switches are in OFF condition and both the three inductors are discharging. At this instant only capacitor C_2 is discharging and capacitors C_1 and C_3 are charging. The current paths are clearly depicted in the circuit as shown in Fig. 3. During this interval, the theoretical waveforms are illustrated in Fig. 4.

The current path is depicted as in the figure 4. In a normal

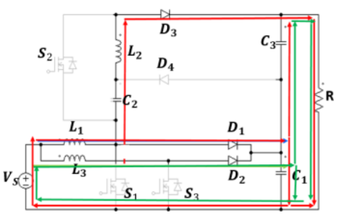

Fig. 3. Operating Circuit Of Mode 2

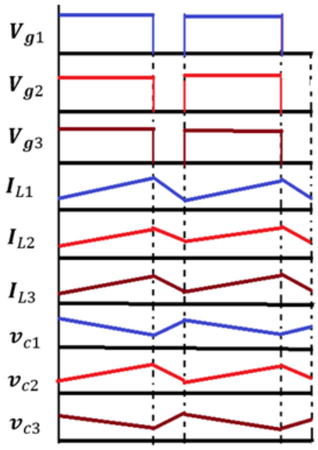

Fig. 4. Theoretical Waveforms

switched capacitive regenerative boost converter there is both continuous mode discontinuous mode. But for the practical applications, mainly concentrating on the continuous current conduction mode. For an interleaved SCRB converter there are mainly two modes of conduction. A proper design should be done for all the components in order to get the maximum voltage gain with reduced voltage stress and improved effi- ciency.

III. DESIGN OF THE COMPONENTS

The high step-up gain DC-DC converter is designed for input voltage 24V with a duty ratio of 0.8. Beyond this duty cycle, the inductor core is saturated and generates noise in the circuit. The converter operates at 10kHz for an output power of 100W.

A. Duty Ratio and Output Voltage

For any practical applications, the dc-dc converter must be operated at lower duty ratios to get maximum efficiency and the duty ratio can be extended up to 0.8. Beyond this duty cycle, the inductor core is saturated and generates noise in the circuit, which automatically degrades the performances.

$$V_o = V_{in} * D \quad (1)$$

$$V_o = 24 * 0.8 = 720V \quad (2)$$

B. Load Resistor R_o

Taking P_o as 100 W and input voltage as 24 V, load resistance is calculated as

$$R_o = \frac{V_o^2}{P_o} = 5184\Omega \quad (3)$$

C. Inductors L_1, L_2 and L_3

Let the Δi_L be the ripple in input side inductor. In order to find this find ripple current we need the output current.

$$i_{out} = \frac{P_{out}}{V_{out}} = 0.138A \quad (4)$$

$$\Delta i_L = 0.2 * \frac{V_o}{V_{in}} * i_{out} \quad (5)$$

$$L = \frac{D(1-D)V_o}{(3+D)\Delta i_L * f_s} = 3.6mH \quad (6)$$

The one of the three inductors are chosen as 4mH and the interleaved inductors are chosen as half value of 4mH. Hence L_1 and L_2 are 2mH. Choose all the capacitors as 10 μ F.

IV. SIMULATION RESULTS AND ANALYSIS

A. Simulation Results

Simulation parameters for the high gain DC-DC SCRB converter and interleaved SCRB converters are same which is given in Table 1.

TABLE I: SIMULATION PARAMETER

Parameters	Specification
Input voltage V_{in}	24V
Switching frequency f_s	10kHz
Output voltage	720V
Inductor L_1, L_2	2µH
Inductor L_3	4µH
Output power	100W
capacitors C_1, C_2, C_3	10µF
Load Resistance	5184Ω

An input voltage V_{in} of 24 V gives an output voltage V_o of 720 V for an output power P_o of 100 W. The switches are MOSFET/Diode with constant switching frequency of 10 kHz. The duty cycle of switches is taken as D=0.80.

Figure 5 shows the gate pulses and voltage across the switches $S1$, $S2$ and $S3$. The same duty ratio is given to all the three switches. The switch $S1$ and $S3$ has the voltage stress 113.5V. The second switch $S2$ has the voltage stress 620V. Figure 6 shows the current through the three inductors present in the DC-DC high step-up interleaved converter. The first two inductors present in the input side has currents 1.9A each. The third inductor $L3$ has current of 2.8A through it.

Figure 7 shows the output voltage and output current of the interleaved converter. The new proposed high gain step-up interleaved converter has output voltage of 761.5V and ripple content is 1V. Output current is 0.1302A and ripple of the output current is 0.0002A.

B. Analysis

The analysis of bidirectional DC-DC converter is carried out by considering parameters like voltage gain, efficiency, and duty cycle.

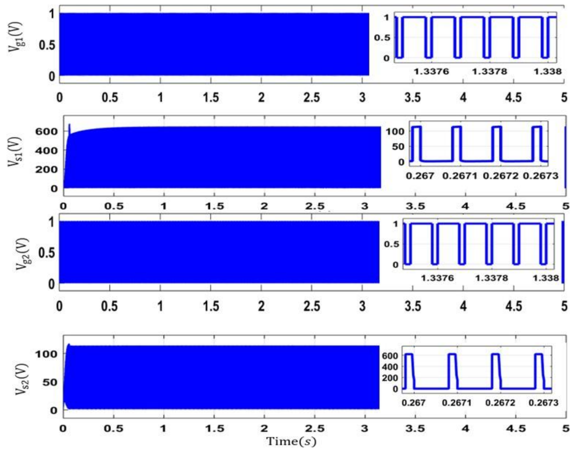

Fig. 5. (a)Gate pulse (V_{gS2}), (b) Voltage across switch (V_{S2}) ,and (c)Current through switch (I_{S2})

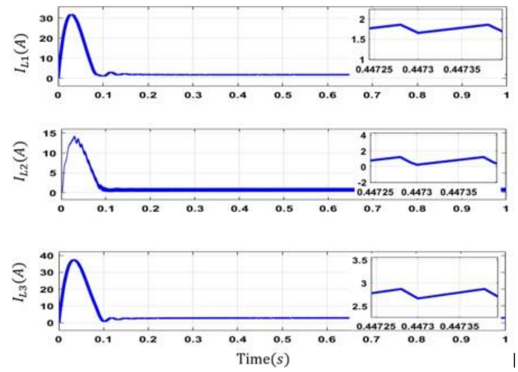

Fig. 6. Inductor Currents (a)(I_{L1})(b)(I_{L2})c(I_{L3})

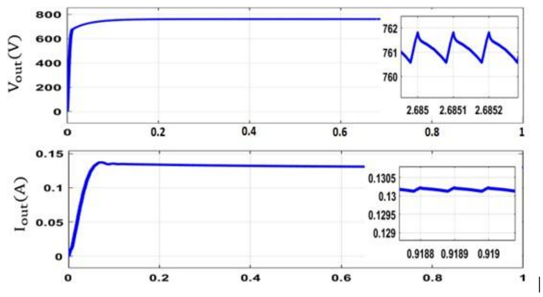

Fig. 7. (a)Output Voltage(V_{out}), (c)Output Current (I_{out})

Efficiency Vs Output power

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. The efficiency is the fraction of the input power delivered to the load. A typical curve for the variation of efficiency as a function of output power is shown in Figure 8. The converter efficiency is around 80% for 100W output power for R load. The converter efficiency is around 76.9% for 100W output power for RL load. For an interleaved SCRB converter the efficiency is 91.8% and for RL load the efficiency is about 88.1% for a load of 100W.

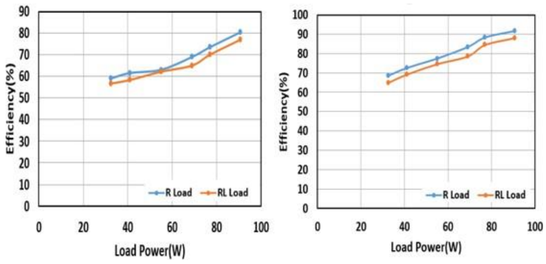

Fig. 8. (a)Efficiency of converters in R and RL Load

Gain Vs Duty Ratio curve

The plot of voltage gain as a function of duty ratio is shown in Figure 9.

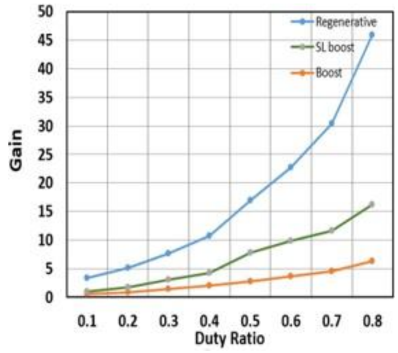

Fig. 9. Gain Vs Duty Ratio

For any practical applications, the dc-dc converter must be operated at lower duty ratios to get maximum efficiency and the duty ratio can be extended up to 0.8. Beyond this duty cycle, the inductor core is saturated and generates noise in the circuit, which automatically degrades the performances. At 0.8 duty ratio we get 29.7 gain for a normal SCRB converter. For a modified interleaved SCRB converter the value of gain is 31.7.

C. Comparison

The comparison between conventional converter and the modified converter is given in Table 2. The modified SCRB converter is compared with basic switched capacitor regener- ative boost converter .
It is observed from the above discussions that in the mod- ified interleaved DC-DC converter efficiency, output voltage ripple and current ripple voltage and stresses on the switches are reduced is reduced to a desirable value. But the number of

TABLE II: COMPARISON OF CONVENTIONAL AND MODIFIED CONVERTER

Criterion	SCRB Converter	Modified Converter
No.of switches	2	3
No.of diodes	3	4
No.of capacitors	3	4
No.of inductors	2	3
Efficiency	80	91.8
Gain	29.6	31.7
Voltage stress	S_1=120V S_2=620V	S_1=113.5V S_2=620V S_3=113.5V
Output voltage ripple	5V	1V
Output current ripple	0.005	0.0002

Components like switches, diodes and capacitor are increased. Voltage gain is increased from 29.75 to 31.7.

V. CONCLUSION

The SCRB converter and interleaved SCRB converter is simulated according to the designed parameters. The voltage gain for the normal converter is 29.6 and for an interleaved SCRB converter is increased to 31.7. From the simulation diagrams it is observed that in the interleaved converter the switching stress of two switches out of three decreases. The voltage stress across one switch still remains the same .

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