High Step up Switched Capacitor Inductor DC-DC Converter for UPS System with Renewable Energy Source

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***Abstract*—A new converter using a switched-inductor cell integrated with a switched-capacitor cell within a boost-like structure is proposed. The converter can achieve a very high dc conversion ratio. It can serve as the front-end dc-dc converter for a fuel cell in a UPS system. The inductors and capacitors are switched in a parallel-series configuration. The charging circuit of the inductors from the source is separated from the load. A dc analysis of the new circuit leading to the formula of the dc gain and a breakdown calculation of the losses are given. The proposed Switched Capacitor Inductor (SCI) converter circuit can meet the high efficiency requirement and simple structure. A small resonant inductor is used in these converters to limit the current peak caused by switched capacitor. Therefore, the SCI converters have good performance and high efficiency as well the voltage stress of the converter is reduced. In order to verify the proposed Switched Capacitor Inductor (SCI) dc-dc converter, modeling and simulation was carried out by using MATLAB.**

***Index Terms*—switched capacitor, switched inductor, high voltage gain**

I. Introduction

The need for a DC/DC converter of this caliber is a great one. The future is looking towards alternative power sources all of which will need to be regulated in one Form or another. To make this possible, a highly efficient low cost product will have to be designed. Among all the different converter designs only a few are capable of providing high power with high efficiency. The basic switched-mode dc–dc converters including buck, boost, buck-boost, cuk, zeta, and sepic have been used in various electronic applications due to their numerous advantages such as simple structure, good performance, high efficiency, easy design, and simple control circuit [1]. The resonant converters such as single-ended and bridge type are also very popular in the last decade [2], [3]. And the basic switched-capacitor (SC) converters also have wide application as their advantages of nonmagnetic components employed and small size and high power density [4], [5]. A small resonant inductor has been added in SC converters to eliminate the current peak and achieve soft switching in [6] and, therefore, the SC Converters have good performance and high step up as well. In recent years, many researchers are trying to take these types of converters aforementioned into a new type of combination converters to obtain high step-up voltage gains [7]-[12]. Specifically, two step-up SC cells have been introduced to zeta, cuk, and sepic converters, respectively, to obtain high step-up voltage conversion ratios in [7]. In the literature [8], some step-up SC cells are presented and combined with boost and buck converters to achieve high step-up voltage gains. An ultra-step-up converter is presented in [9], which is produced by connecting a Step-up switched-inductor cell and a step-up SC cell; and another high step-up converter based on coupled inductor and SC cell is introduced in [10]. In addition, two step-up converters integrating different step-up SC cells within a boost converter are introduced in [11] and [12], respectively. Even though these converters have different structures and can provide different voltage conversion ratios, they have a characteristic in common which is that all of them are multistage combination of switched-inductor cells and SC cells. Like other cascaded high step-up converters [13]-[15], in which energy is transferred from one unit to next unit and gradually to output stage, their efficiency is therefore generally not promising and is equal to the product of Efficiency.

In this paper, a high efficiency Switched Capacitor Inductor DC-DC converter is proposed and different converters efficiency and switching stress is compared. All members of the converter are composed of the same number of electronic components: include two energy transfer components, i.e., one Switched Capacitor C_1 and one switched inductor L_1, a small resonant inductor L_r that is employed to limit the current peak caused by SC, three active or passive switches and one output filter capacitor. The greatest feature of these converters is that energy flowing from input power sources is directly transferred to the two energy transfer components (C_1 and L_1) and then directly released to output terminal, i.e., these converters are actually single-stage dc–dc converters rather than like aforementioned converters obtained high voltage gain by using different cascading methods. When the two energy transfer components operate in parallel manner during a charging process and then in series manner during a discharging period, the

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higher output level can be produced. Similarly, this principle is not only suitable for deriving single-input converters, but can also be extended to dual-input dc-dc converters that are popularly used in dual-level dc distributional and renewable energy system. To distinguish the proposed family of converters from conventional SC/SI converters introduced in literatures, the proposed converters are hence named high efficiency switched capacitor inductor (SCI) converters. This paper is organized as follows: Section II introduces the block diagram of proposed UPS system. Section III introduces the proposed SCI dc-dc converter, which consists the detailed analysis of the operating principle and output waveform of SCI converter. The output voltage and voltage stress of SCI converter is analyzed with conventional methods in Section IV. And the simulation results are given in Section V. Finally, this paper is concluded in Section VI.

II. PROPOSED UPS SYSTEM

The classical UPS contains a dc-dc converter needed to step-up the 48V voltage of the back-up battery to the main bus dc voltage. In recent years, the battery is replaced by an alternative source of the energy, a fuel cell, as shown in Fig. 1. In addition of being environment-friendly, the fuel cell has more advantages: longer back-up time and up to 20 years of operation without maintenance. However, the typical output voltage of a fuel cell is 100V, within a range from 70V to 120V, and an ac three-phase power system with 230V rms bus requires an output voltage of the dc-dc converter of 230V, so a high step-up dc-dc converter is needed here. Previous research provided switched-capacitor converters able to step-up many times the voltage. However, this solution features a very pulsating input current. Insertion of a switched-capacitor cell in a boost converter, or use of switched-inductor cells has also been tried. Very high dc gain has been obtained by using a boost-flyback structure with paralleled outputs. However, in the application presented above, coupled-inductor or transformers have to be avoided for not affecting the efficiency.

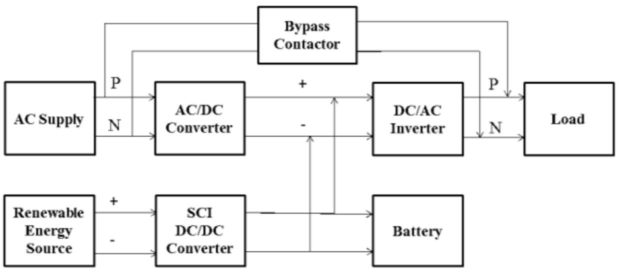

Figure 1. Proposed UPS system

III. SCI DC-DC CONVERTERS

The proposed SCI dc-dc converter circuit is shown in Fig. 2. The circuit uses only one active switch Q and a very small resonant inductor L_r which is employed to limit the current peak caused by capacitor C_1 when the switch Q is turned ON. The two energy storage components C_1 and L_1 are alternately connected in parallel and series according to different switching states.

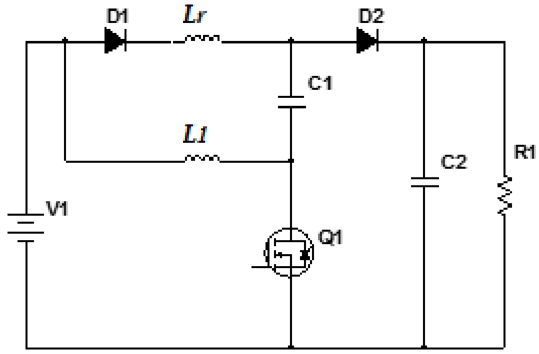

Figure 2. Proposed SCI converter

The voltage transfer relationship can be derived and expressed as follows,

$$V_0 = \frac{2-d}{1-d} V_{in} \tag{1}$$

There are two inductors employed in the new SCI converter, the energy transfer inductor L_1 and the resonant inductor L_r. The function of L_1 is to transfer energy while L_r is just used to limit the current peak caused by the capacitor C_1 when the switch Q is turned ON. Specifically, when switch Q is turned ON, the capacitor C_1 begins to be charged or to discharge, the charging or discharging current will soar to a very high peak at the moment of Q being ON if there are not any measures to limit it. For this reason, a small inductor L_r is added and connected in series with C_1 to form a resonant tank with the resonant frequency, $f_0 = 1/2\pi\sqrt{L_r C_1}$ during the switching ON period. With the resonant inductor, the charging or discharging current of C_1 gradually increases from zero when switch Q is turned ON. In order to ensure that the current changes back to zero before switch Q is turned OFF, the switch conduction time `d be longer than half of a period of the resonant frequency, i.e., $d\ T_S > \pi\sqrt{L_r C_1}$ (where T_S and d are the switching cycle period and duty ratio, respectively).

The SCI Step-up converter oscillation amplitudes of capacitor voltage and current are related to the parameters of the resonant tank and the output current and the switching cycle period. When the switch Q is turned ON, the charges flow into the capacitor C_1 from power source V_1 causing a gradual increase in capacitor voltage V_{C1}. And then, the switch Q is turned OFF and the charge stored in C_1 during the charging process flows out of capacitor C_1 to output filter capacitor C_2 and the load that causes the capacitor voltage V_{C1} gradually decreases from its maximum to its minimum. The amount of charge flowing into capacitor C_1 during the charging process should be equal to the amount of charge flowing out of C_1 during the discharging process, and the amount also should be equal to the amount of charge flowing though the load during one switching cycle, i.e.,

$$(V_{C1\_\max} - V_{C1\_\min}) C_1 = I_0 T_S \tag{2}$$

where I_0 is the average output current. The charging current I_{C2} changes in a sinusoidal manner with the resonant frequency $f_0=1/2\pi\sqrt{L_rC_1}$; hence, the amount of charges flow into C_1 during the charging process can also be expressed as

$$(V_{C1\_max}-V_{C1\_min})C_1=2I_{C1}\,L_r\,C_1 \tag{3}$$

The oscillation amplitude of resonant current I_{C1} can therefore be derived from (2) and (3)

$$I_{C1}=\frac{I_oT_S}{2\sqrt{L_rC_1}} \tag{4}$$

And the voltage oscillation amplitude can be derived from (2) and expressed as

$$\Delta V_{C1}=V_{C1\_max}-V_{C1\_min}=\frac{I_oT_S}{C_1} \tag{5}$$

For the inductor L_1, the amount of charge flowing though it during the discharging process is also equal to the amount of charge flowing out the capacitor C_1. Its average current I_{L1} can therefore be expressed as

$$I_{L1}=\frac{I_o}{1-d} \tag{6}$$

And the ripple current ΔI_{L1} is related to the input voltage V_2, the switching cycle T_S, and the duty ratio, i.e.,

$$\Delta I_{L1}=\frac{V_2}{L_1}dT_S \tag{7}$$

When the switch Q is turned OFF, the voltage across it is the difference between the output voltage V_0 and the capacitor voltage V_{C1}, and a voltage (V_1-V_0) is developed across the diode $D1$. The current flowing though the diode $D2$ is the same as the inductor current I_{L1} during the OFF state. Its average and maximum transient values therefore can be expressed as $I_{L1}/(1–d)$ and ($I_{L1}+\Delta I_{L1}/2$) respectively. When Q is turned ON, the voltage across $D2$ is the difference between the input voltage V_1 and the output voltage V_0. The current flowing though the diode$D1$ is the same as the capacitor current I_{C1} and the current flowing though the switch Q is the sum of the capacitor current and the inductor current, i.e., ($I_{C1}+I_{L1}$). Their average values can be derived form (4), and (6) and expressed as I_0 for $D1$ and (I_0+I_{L1}/d) for Q, respectively. The maximum current flowing though $D1$ is the same as I_{C1} and the maximum value of the current flowing though Q is the value of $[I_{C1}+I_{L1}-\Delta I_{L1}/2+V_2/(2\omega OL_1)]$. The switches stress therefore can be expressed as

$$V_{ds\_Q}=V_0-V_{C1}\approx V_0-V_1$$

$$V_{R\_D1}=V_0-V_1$$

$$V_{R\_D2}=V_0-V_2 \tag{8}$$

Based on the previous analysis, the oscillation amplitudes of resonant current and voltage can be calculated by the values of C_1 and L_r. In turn, the values of C_1 and L_r can be determined by the design requirements of the resonant current and voltage, and the value of L_1 can be determined by the design requirements of its current ripple.

The design process therefore can be divided into the following steps:

1) Determine the minimum and maximum values of the duty ratio and the switching frequency (usually, the switching frequency is higher than 50kHz), and then calculate the resonant frequency according to the condition that the switch conduction time should be longer than half of a period of resonant frequency, i.e.,

$$f_o=\frac{1}{2\Pi\sqrt{L_rC_1}} \tag{9}$$

2) The value of the capacitor C_1 can be calculated by (5), i.e.,

$$C_1=\frac{I_{o\max}T_s}{\Delta V_{C1}} \tag{10}$$

where ΔV_{C1} is the design requirement of the voltage oscillation amplitude. and $I_{o\max}$ is the maximum output current.

3) The resonant inductor L_r hence can be determined by the value of C_1 and the resonant frequency, i.e.,

$$L_r=\frac{1}{4\Pi^2 f_o{}^2C_1} \tag{11}$$

4) The value of inductor L_1 can be determined by (7), i.e.,

$$L_1=\frac{V_2}{\Delta I_{L1}}d_{\max}T_s \tag{12}$$

where ΔI_{L1} is the current flowing though L_1 and $d_{\max}$ is the maximum values of the duty ratio.

IV. Analysis with Conventional Method

The conventional methods like boost converter, switched capacitor, switched inductor converter circuits are analyzed. In boost converter the output voltage is step-up 3 times of input voltage with duty cycle 0.68. While the switch Q1 is ON voltage across Q1 equal to input voltage, and the OFF state the inductor current flows through the diode giving output voltage equal to switch voltage. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The duty ratio “d” is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. In the SC circuit the output voltage is step-up to 3 times of input voltage. The switched-capacitor dc-dc converter, the energy is transferred by the capacitors. By the high-frequency switching actions, the capacitors will be connected in series or in parallel directly by the switches. There are six switches used for getting 3 conversion ratio so that the switch stress is high and switch losses also high. Because of high switch losses the efficiency of the converter is reduced. For an output/input voltage boost ratio of N times (NX), the input current has to go through N switching devices. In SI converter circuit step-up the input voltage by 3 times of input voltage with 0.55 duty cycle. The efficiency of the converter is low. To mitigate the pulsating current, voltage spike, and switching loss, resonant switched-capacitor converters have been proposed with additional inductor to resonate with the capacitor. Yet, their practical potential to reach high voltage gain has not been extensively investigated. Some combinations of switched-capacitor and inductors have been reported for large voltage conversion ratio, the easy integration and light weight feature of switched-capacitor dc-dc converters disappears after introducing relatively large inductors.

The boost converter having the input power of 205W and the output power is 184. There is some losses due to turn OFF of switches so that it having 89% efficiency only. The Switched Inductor converter has the efficiency of 91.6%. This converter has low switching losses. The conventional SC converter has efficiency of 94%. The SC converter give continues output voltage due to charging and discharging of Capacitor C1. The proposed SCI converter connects Inductor L1 parallel with Capacitor C1 so that the fluctuation of output voltage is reduced and improves the efficiency. The SCI converter efficiency is improved about 95-98%. The value of Inductor, Capacitor, and Resistor are designed by using the above derived equations (9-12).

The following table shows the efficiency of conventional method is compared with the proposed SCI converter. Because of using more switches in SC converter the Output Voltage is 88V only.

TABLE I. COMPARISON WITH CONVENTIONAL CONVERTER

Sl.no	Converter type	Output Voltage	Output Power	Efficiency	Duty Cycle
1	Boost Converter	90	184	89.32	0.65
2	Switched Inductor Converter	90	220	91.6	0.55
3	Switched Capacitor Converter	88	176	94.6	-
4	SCI Converter	90	186	98.92	0.53

The efficiency of the converter is calculated by using input power and output power as follows

The input power of the converter is

$$P_{in} = V_{in} I_{in} \tag{13}$$

The output power of the converter is

$$P_0 = V_0 I_0 \tag{14}$$

The efficiency of the proposed SCI converter is

$$\%\eta = \frac{P_0}{P_{in}} \tag{15}$$

By calculating the input power from equation (13) and output power from equation (14) the efficiency of the converter is calculated. From the equation (15) the efficiency of the SCI converter is 98%. The efficiency of proposed converter is compared with conventional method is given by the above Table I.

V. SIMULATION RESULT

The Proposed SCI converter is simulated with Inverter circuit and the output waveforms are shown. In this simulation the 30V is applied to the converter and the 0.55 duty cycle is given to the switch pulse and the 90V output voltage obtained. The conversion ratio of the converter is 3 and the output current is 2A. The efficiency of the converter is calculated by using input power and output power (15). The output of the converter is given to the inverter circuit and it is converted into 230V AC output.

A simulation circuit with parasitic components of the single input step-up has been built as shown in Fig. 3. When the input powers *V*1 is 30V, the load is a 45Ω pure resistor, and the switch *Q* is operated at 102kHz switching frequency with duty ratio 0.53, the output voltage is 90V and some simulation waveforms are shown in Fig. 4 and Fig. 5 Accordingly, a prototype circuit of the single input step-up converter has also been built to confirm the theoretical analysis and simulation results. With the simulation parameters given in Table II.

TABLE II. SIMULATION PARAMETER

Input Voltage	30V DC
Maximum output Power	250W
Switching Frequency	102kHz
Capacitor C1	4.7µF
Capacitor C2	100µF
Inductor L1	95µH
Resonant Inductor Lr	0.3µH
Resistor R	45Ω

The SCI DC-DC converter simulation circuit is connected with H-Bridge inverter. The output of the inverter circuit are connect with LC filter and get the sinusoidal output waveform. The 30V input is given to the SCI converter and it is step-up to 90V. The output of SCI converter is given to the H-Bridge inverter and converted into 230V AC output voltage.

During Turn ON period the voltage across Capacitor and inductor is 30V. During Turn OFF period Voltage

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across Capacitor is 30V and inductor is -30V. The switch Voltage during Turn ON is 30V and during urn OFF is 0V. Therefore the Voltage stress of the converter is reduced, switch loss also reduced. Because of this reduced Voltage stress and switch loss the Efficiency of the converter is increased compared with conventional methods.

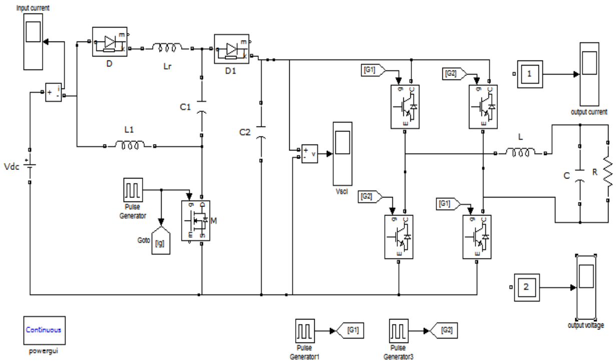

Figure 3. Simulation circuit of SCI converter

The output Voltage of SCI converter and Inverter are shown in the below Diagram (Fig. 4, Fig. 5, Fig. 6, and Fig. 7). It shows that the output voltage of converter is 90V and inverter is 230V.

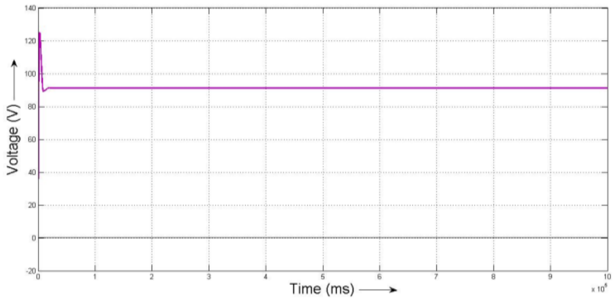

Figure 4. Output voltage of SCI converter

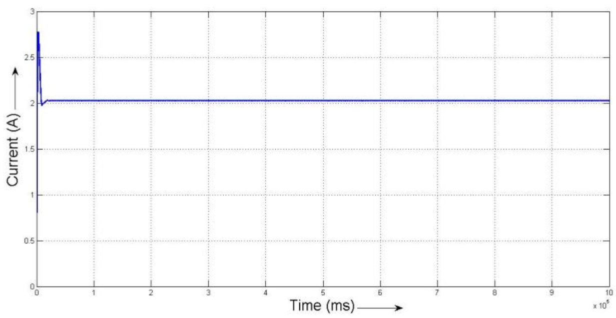

Figure 5. Output current of SCI converter

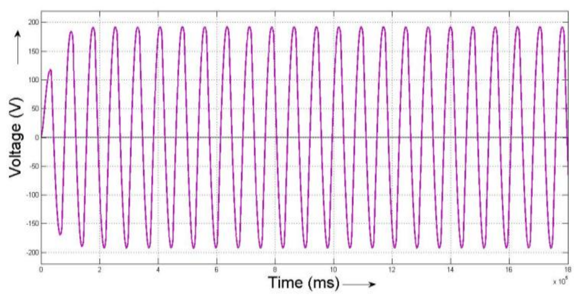

Figure 6. Output voltage of inverter

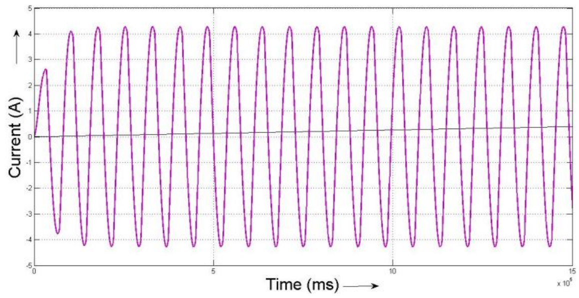

Figure 7. Output current of inverter

VI. CONCLUSION

The High step up Switched Capacitor Inductor dc-dc converter is proposed in this paper. From the above explanations SCI dc-dc converter give high step up and efficiency compared with conventional SC converter. The proposed converters employ two energy transfer components (one SC and one inductor) and do not use the cascade method like conventional SC/switched-inductor converters. The energy stored in the two components both directly come from input power sources and then directly been released to output terminal. This design can meet the high efficiency requirement with a simple structure. A resonance method is used in this paper to limit the current peak caused by the SC. Detailed analysis and design considerations are also introduced. Compared with traditional switched-mode converters, the proposed converters can provide higher or lower voltage gains and the switch stress is lower. The SC converter voltage stress is high because of using more number of switches. In SCI converter used one switch therefore voltage stress of the converter is reduced. The renewable energy sources can give more efficient power by using SCI dc-dc converter.

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