



Implementation of Cascaded Resonant DC-DC Converter Topology

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ABSTRACT: This paper presents different types of Cascaded Hybrid Topologies. The cascaded hybrid configuration is achieved by the combination of two resonant converter topologies- Switchless Resonant Converter and Double Switch Resonant Converter. The Soft Switching methodology is achieved with a duty cycle of 48% for the switches to achieve minimum switching losses. The Proposed Hybrid converter configurations achieves higher voltage gain of 9.3 and 9.8 with lower component count than the other DC-DC topologies. The simulation of Hybrid Resonant Converter and other two configurations are done using MATLAB/Simulink and the Voltage Gain for the different configurations are compared with the Simulation results.

KEYWORDS: Double switch configuration, Cascaded Hybrid configuration, Soft Switching methodology, Switchless configuration.

I.INTRODUCTION

The global demand for electricity generation has continuously increased over the last few decades. Alternative sources of electricity generation have drawn more and more attention in recent years. PV energy and Wind energy are the most important and promising renewable energy types and it will become the major contributors for electricity generation. DC-DC converter finds application in many power conditioning systems like Telecommunications, Renewable energy. Different types of DC- DC boost converter topologies have been implemented for the DC-DC conversion between the Power production and the Load station. Among that DC-DC Switched Capacitor Converters have gained great popularity in recent years. By the elimination of magnetic components and the usage of small ceramic capacitors makes them compact, light and able to retain in high temperature environment. These characteristic combines Switched Capacitor Converter to provide High efficiency and Power density, light weight. A variety of novel Switched Capacitor Converters have been developed to nullify the drawbacks with the conventional one [1]. The inherent drawback is due to a periodical forced charging. Conventional Switched-Capacitor DC-DC Converters have some common drawbacks: 1) weak output regulation ability and structurally determinate voltage conversion ratio; 2) pulsating input current and high current spike; 3) high voltage spike across the switching device; 4) high electromagnetic interference (EMI); and 5) unidirectional power conversion ability [2]-[4]. By the Resonant operation instead of the forced charging, Resonant Switched Capacitor Converter topology has advantages over a Conventional Switched Capacitor Converter with high efficiency even in a high output current region. Some of the Conventional Switched Capacitor Converters did not has capacity of voltage gain extension even more components are used. Switched capacitor converters have been employed in research since 1970's to obtain light weight, high efficiency, small in size and high power density.

Starting from the main idea of applying the basic Switched Capacitor Module [5] for power conversion, many methodologies of operating the switches and the capacitors, have been proposed. Each capacitor is basically going through a charging process from the supply while the other capacitor in discharging process to the load periodically. Modular circuit has the fault identification capability, which the affected module is by-passed and another good module can be activated in-order to provide continuous operation. That fault module can be physically removed from the system and can be repaired or replaced by another module. So the maintenance operation is easy with the modularity concept. The five-level Multilevel Modular Capacitor-Clamped DC-DC Converter (MMCCC) is designed to achieve any conversion ratio (CR) [6]. The Modular nature of the MMCCC topology is used to obtain redundancy and fault

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bypassing capability in the system, which increase the reliability of the system. The active and passive component count used in each module in the MMCCC is relatively high when compared with the achieved voltage gain. The Voltage Tripler topology is implemented with the multilevel modular concept featuring fault tolerance has considerable reliability. Soft-Switching technique was introduced to reduce switching losses and provide high efficiency for MMCC topologies [7]. Nevertheless, for high voltage gain requirements systems, the voltage stress of capacitors is increased that results in a low power density. The high efficiency step-up Resonant Switched-Capacitor Converter [8] is implemented for offshore wind energy system, which is characterized by the soft- switching condition for all switches and diodes which reduces switching losses, increases switching frequency and minimizes the overall system volume. On the other hand, the large number of capacitors leads to larger the physical size of the converters, high passive component losses, have limited the use of the topologies in high-voltage gain required system. A non-isolated boost DC-DC converter employing Edge-Resonant Switched Capacitor (ER-SWC) [9] cell is designed, in order to overcome the drawbacks of the PWM boost DC-DC converter in DCM. High efficiency and wide range Soft-Switching operation is obtained by the ER-SWC PWM Boost DC-DC converter, which can be usefully extended for the interleaved circuit topology, effectively canceling the input current ripple and reducing the size of the components as well as increasing the power rating. The Quasi-Resonant Bridge Modular Switched Capacitor Converter (BMSCC) is proposed by the employment of the stray inductance distributed in the circuit as a collective resonant inductor [10]. The output voltage ripple is greatly reduced with the symmetric construction and when compared with conventional SCCs, BMSCC employs fewer switches with the same conversion rate. However, the number of active switches is still large for high-power and high voltage applications, eventually leads to high system cost. A Flying-Capacitor DC-DC converter finds application in Hybrid Electric Vehicles (HEV). The traditional DC-DC converter which interfacing the battery with the inverter DC bus can be replaced by the Four-Level Flying-Capacitor DC-DC Converter which overcomes the drawbacks by dramatically reducing the inductance requirement [11].

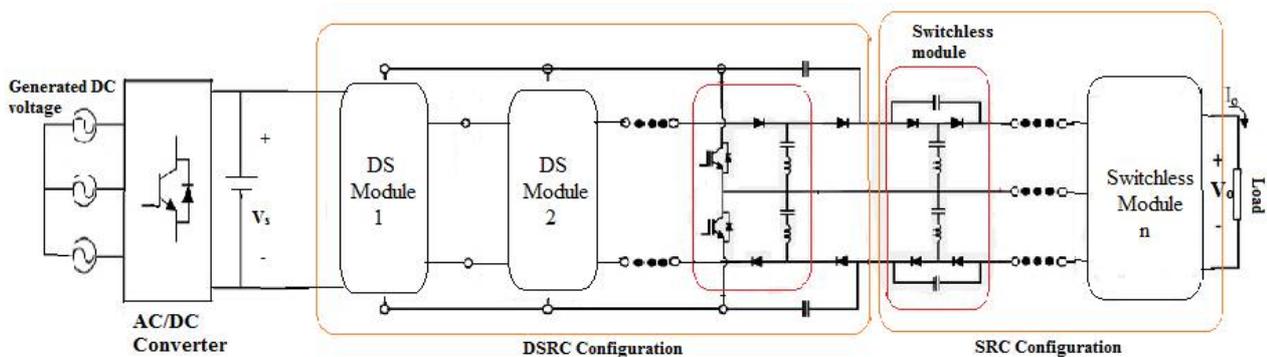


Fig. 1. Proposed Cascaded Hybrid Converter Topology

This paper presents the Switchless Resonant Converter (SLRC) and Double Switch Resonant Converter (DSRC) and finally Cascaded Hybrid Converter topology. Resonance action is the important stage with all the configurations discussed here. The resonance action is achieved by adopting the soft switching technique to achieve Zero Current Switching (ZCS) and Zero Voltage Switching (ZVS). Section II describes the SLRC and DSRC operation with analysis and Section III discusses the Hybrid configuration with the specifications and design for the components followed by the simulation results in Section IV and conclusion in Section V

II.SLRC AND DSRC CONFIGURATION

Fig.1 shows the general configuration with the three phase generated AC voltage and the AC/DC converter in-front of the proposed cascaded hybrid converter. A large capacitor with the voltage V_s is used as the energy storage element at the output to ac to dc converter. The cascaded hybrid converter has configuration with the combination of DS Resonant converter and the Switchless Resonant converter.

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The Basic Modular cell [12] has two active switches S_{t1} and S_{b1} , two resonant capacitors C_{rt1} and C_{rb1} , two resonant inductors L_{rt1} and L_{rb1} and diode D_{t1} and D_{b1} . In this paper, subscripts “t” and “b” represents the corresponding variables to the circuit elements at the top and bottom segments respectively. The following assumptions are made for the analysis simplification. 1) All the switches, diodes, capacitors, and inductors are ideal. 2) The output capacitors C_{to1} and C_{bo1} are large enough to be considered as voltage sources. 3) Two resonant inductors L_{rt1} and L_{rb1} have the same inductances. 4) The resonant capacitors C_{rt1} and C_{rb1} have identical values. 5) V_s is an ideal dc voltage source, and the load is modeled by a pure resistor R_{load} . 6) The switching frequency have to be less than the resonant frequency So that to set enough dead time for two main switches, and achieve a zero-current switching (ZCS). Therefore, the short time interval $[t_1-t_2]$ and $[t_3-t_4]$ are defined as the dead zone between active switches to avoid short circuit in each module.

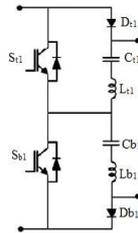


Fig. 2. Basic Modular cell

To understand the operating principle, SRC and DSRC topologies are selected for the analysis. Both the topologies are designed with a common basic modular cell, as shown in Fig. 2 and the topology can be designed by increasing or decreasing the modular cell connection which depends on the need of conversion ratio. Therefore both the SRC and DSRC topologies have the same circuit operation. The active switches S_{b1} and S_{b2} are controlled complementarily with a same duty cycle of 48% to achieve soft switching in-order to avoid the conduction losses for the power devices and passive components.

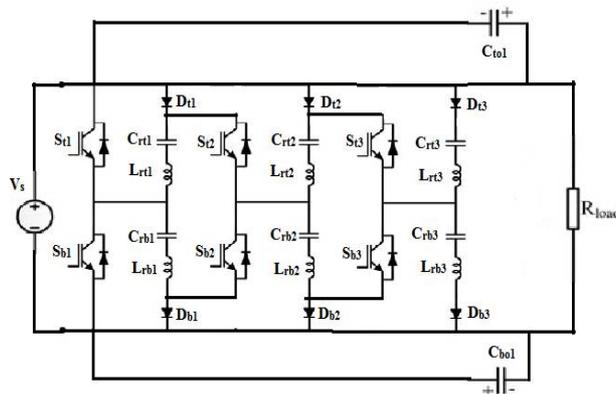


Fig. 3. Structure of Modular converters - DSRC configuration (Double Switch Resonant Converter)

The Fig. 3 is the configuration circuit of Double-Switch Resonant Converter, which has six switches, six resonant inductors and capacitors, six diodes and two output capacitors. The operational states with analysis are follows;

Mode I: At $t = t_0$, S_{bi} ($i = 1, 3, \dots, n-1$) and S_{ti} ($i = 2, 4, \dots, n$) are turned ON, whereas even switches in the bottom cell and odd switches in the top cell are turned OFF. So that in this mode the odd numbered C_{rti} 's (C_{rt1}, C_{rt3}) and even numbered C_{rbi} 's (C_{rb2}) are charged by V_s . In this state, the output capacitor C_{to} is charged by $C_{rt2}, C_{rb1}, C_{rb3}$, whereas C_{bo} is discharged to the load. The equations for operating mode I is

$$V_s = L_{rt1} \cdot \frac{di_{L_{rt1}}}{dt} + V_{C_{rt1}} \quad (1)$$



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$$iL_{r1} = C_{r1} * dvC_{r1}/dt \quad (2)$$

By ignoring the impact of the short times $t_1 \leq t \leq t_2$ and $t_3 \leq t \leq t_4$, it can be assumed that $t_0 = 0$, $t_1 = t_2 \approx T_s/2$, and $t_3 = t_4 \approx T_s$. The initial conditions of (1) and (2) are $VC_{r1}(0) = V_s - (\pi * P_o / (V_o * C_{r1} * \omega r))$ and $IL_{r1}(0) = 0$.

$$iL_{r1}(t) = \pi * P_o * \sin(\omega r t) / V_o \quad (3)$$

$$vC_{r1}(t) = V_s - (\pi * P_o * \cos(\omega r t)) / (V_o * C_{r1} * \omega r) \quad (4)$$

where P_o , V_o , and ωr are the output power, output voltage, and resonant frequency ($1/\sqrt{C_{r1}L_{r1}}$), respectively. The state equations of the operating mode I for the resonant capacitor and inductor in the bottom cell can be expressed as

$$VC_{b01} = L_{rb1} * (diL_{rb1}/dt) + VC_{rb1} \quad (5)$$

$$iL_{rb1} = C_{rb1} * dvC_{rb1}/dt \quad (6)$$

$$(P_o/V_o) + C_{b01} * (dvC_{b01}/dt) + iL_{rb1} = 0 \quad (7)$$

Substituting (5) and (6) into (7) yields

$$iL_{r1}(t) = -\pi * P_o * \sin(\omega r t) / V_o \quad (8)$$

$$vC_{rb1}(t) = V_s + \pi * P_o * \cos(\omega r t) / (V_o * C_{r1} * \omega r) \quad (9)$$

Equations (8) and (9) show that capacitor C_{rb1} is discharged in this mode.

Mode II: At $t=t_1$ to t_2 , all the switches are in OFF condition. The current does not enters in to any of the resonant circuit. The output capacitors C_{r1o} and C_{rbo} are connected in series with the load in order to discharge to the load.

Mode III: During this time interval, S_{b1} , S_{b3} and S_{t2} are OFF, whereas S_{b2} , S_{t1} and S_{t3} are ON. Therefore, in the top cells, C_{r1} , C_{r3} and C_{r2} are discharged to load. On the other hand, the resonant capacitors C_{rb1} , C_{rb3} and C_{rt2} are charged by V_s . So that the Mode III operation is just the inversion of the Mode I.

Mode IV: At $t=t_3$ to t_4 , is similar to mode II, all the switches are in OFF condition. The output capacitors C_{r1o} and C_{rbo} are connected in series with the load in order to discharge to the load.

The Fig. 4 is the configuration circuit of Switch less Resonant Converter, which has only two switches even for the n number of cascade connection. The operational states with analysis are follows;

Mode I: During the period of t_0 to t_1 , the bottom switch S_b is ON, whereas S_t is OFF. All the odd numbered diodes in each top cell are forward biased by V_s and all the capacitors in each top cell. Therefore, C_{rti} 's (C_{r1} , C_{r2}) are charged by V_s and C_{toi} 's (C_{t01} , C_{t02}). In this state, the output capacitors C_{to3} is discharged to the load. In contrast, in the bottom cells, C_{rbi} 's (C_{rb1} , C_{rb2} , C_{rb3}) are discharged to the output capacitors C_{b01} , C_{b02} , C_{b03} . The state equations in the Mode I for n number of levels is,

$$iC_{rti}(t) = \pi * P_o * \sin(\omega r t) / V_o, i=1,2,\dots,n \quad (10)$$

$$iC_{rbi}(t) = -\pi * P_o * \sin(\omega r t) / V_o, i=1,2,\dots,n \quad (11)$$

From (4.1), (4.2) and initial conditions of $VC_{rti}(0) = iV_s - (\pi * P_o / (V_o * C_{rti} * \omega r))$ and $VC_{rbi}(0) = iV_s + (\pi * P_o / (V_o * C_{rti} * \omega r))$,

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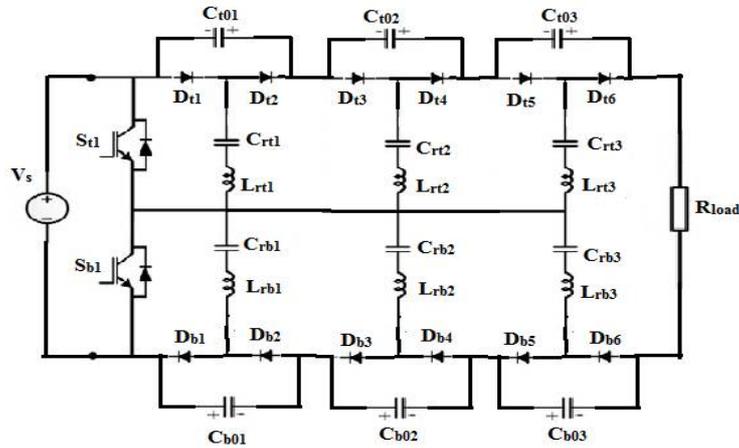


Fig. 4. Structure of Modular converter - SRC configuration (Switchless Resonant Converter)

the voltages of the top and bottom resonant capacitors can be obtained as follows:

$$v_{Cr_{ti}}(t) = iV_s - \pi P_o \cos(\omega t) / (V_o C_{rti} \omega), \quad i=1,2,\dots,n \quad (12)$$

$$v_{C_{rb_i}}(t) = iV_s + \pi P_o \cos(\omega t) / (V_o C_{rti} \omega), \quad i=1,2,\dots,n \quad (13)$$

Mode II: During t_1 to t_2 , both the switches are in OFF condition, thereby connecting all the output capacitors in top and bottom cell in series with the load and source in order to discharge the charge stored in the output capacitors. Mode IV is similar to Mode II.

Mode III: This mode begins with the top switch S_t is in the ON-state and S_b is in the OFF-state at t_0 . The even numbered diodes in the top cell and odd numbered diodes in the bottom cell are forward biased. In the bottom cells, C_{rb_i} 's (C_{rb1} , C_{rb2} , C_{rb3}) are charged by V_s and C_{boi} 's (C_{bo1} , C_{bo2}), whereas C_{rti} 's (C_{rt1} , C_{rt2} , C_{rt3}) are discharged to output capacitors at the bottom cell. As a result, the voltages of C_{rb_i} 's are equal to i times the input voltage level.

III. PROPOSED CASCADED HYBRID CONVERTER TOPOLOGY

The cascaded configuration is achieved to reduce the power device and passive component count for the systems which uses the earlier configuration. A smaller component count means lower cost, fewer failure points, and higher reliability. An apparent improvement would be the combination of SRC and DSRC-based configurations, so that a cascaded hybrid configuration with a reduced component count can be achieved, as shown in Fig. 4.

The hybrid configuration is achieved by cascading the resonant circuit of switchless resonant converter with double switch resonant converter. So that the switches in the double switch configuration act as the input switches for switchless configuration which is cascaded. This configuration has reduced number of active switches with high voltage gain when compared to the previous topologies. By reducing the switches, complexity of the system arrangement can be reduced and losses also predominantly minimized. This cascaded hybrid configuration can be extended to any number of levels according to the need of voltage conversion rate.

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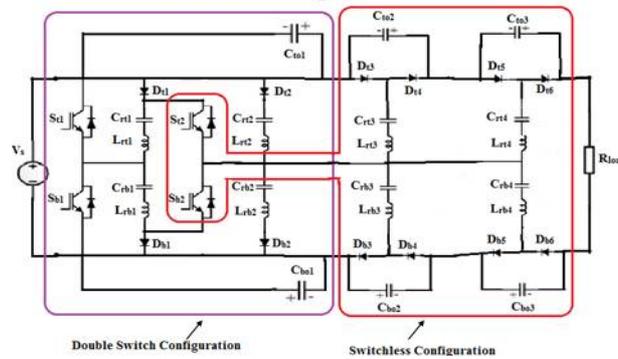


Fig. 4. Cascaded Hybrid Configuration

The fig. 5 and 6 shows the circuit diagram of cascaded hybrid configuration of resonant converter I and converter II respectively. The operating principle for both the cascaded converter are same as that of the double switch and switchless converter which is discussed earlier. The output capacitors C_{to1} and C_{bo1} has the charging and discharging operations in the mode I and mode III by the double switch configuration circuit. The output capacitors C_{to2} , C_{to3} , C_{bo2} and C_{bo3} charges and discharges with the switchless converter configuration. In Mode II and IV all the output capacitors has the discharging operation which are connected series with the load and source..

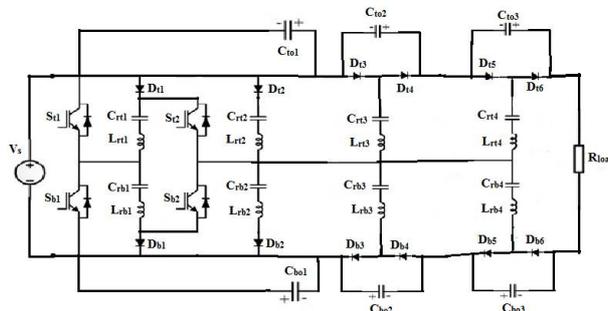


Fig. 5. Circuit Diagram of Cascaded Hybrid Converter I.

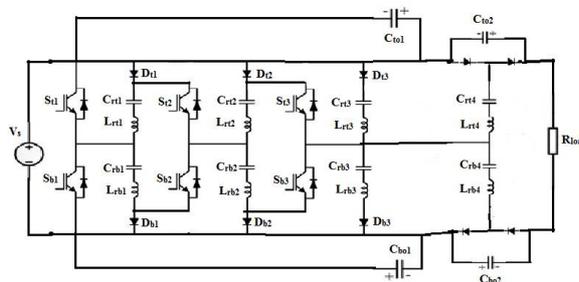


Fig. 6. Circuit Diagram of Cascaded Hybrid Converter II.

The Table I has the specifications for the components in the cascaded resonant converter topologies. The design of components starts with the capacitor value which should be chosen according to the output ripple voltage. The output capacitor value should be chosen five or more times larger than the resonant capacitors in order to withstand at high voltage level.



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TABLE I

Parameter	Value
Output capacitors	250 μ F
Resonant capacitors	50 μ F
Resonant inductor	20 μ H
Switching frequency	4.5kHz
Input voltage	100V
Output voltage	930V

V. RESULT AND DISCUSSION

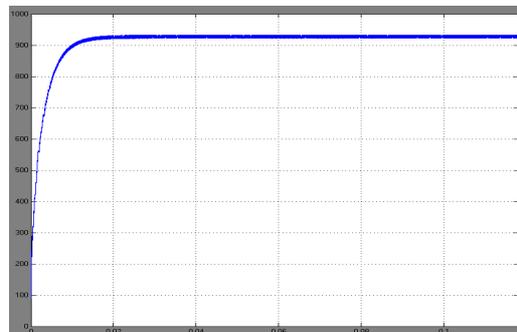


Fig. 7. Output Voltage waveform of the cascaded hybrid converter I.

Fig. 7 shows the Output voltage waveform of Cascaded converter I, has the output voltage of 930V for the input of 100V.

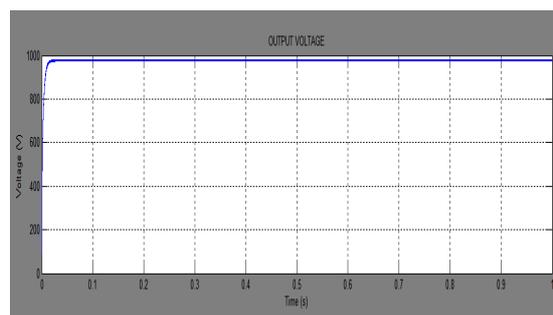


Fig. 8. Output Voltage waveform of the cascaded hybrid converter II

Fig. 8 shows the Output voltage waveform of Cascaded converter II, has the output voltage of 980V for the input of 100V.

From the simulation results, the output voltage of the cascaded resonant converter I is about 930V and converter II is about 980V for the input voltage of 100V. The switches are operated with the switching frequency of 4.5 kHz. The simulation for the cascaded hybrid configuration and other topologies which are discussed in the paper is done using the MATLAB/Simulink tool. From the Fig. 9, the output capacitors has the discharging and charging operation continuously with respect to their mode. The cascaded hybrid resonant converter has the higher voltage gain than the other topologies which are discussed in the paper. All the switches in the cascaded hybrid converter achieves zero

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current switching, thus by switching losses can be reduced

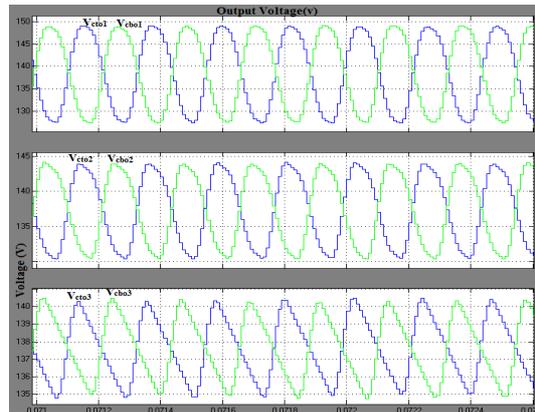


Fig. 9. Key voltage waveforms for output capacitors of cascaded hybrid converter

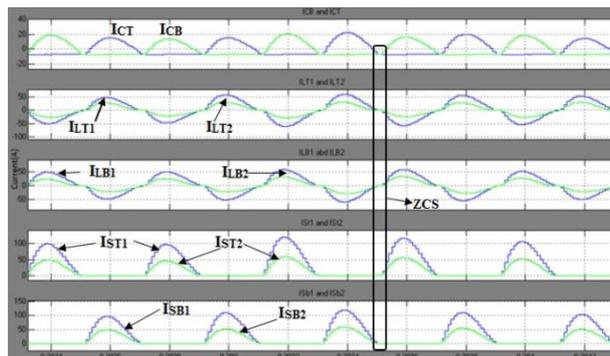


Fig. 10. Output current waveforms for the switches, inductors and capacitors.

TABLE I

Converter topologies	Switch count	Capacitor count	Input voltage	Output voltage	Voltage gain
Switchless resonant converter	2	6	100	556	5.56
Double switch resonant converter	6	2	100	450	4.5
Cascaded hybrid resonant converter I	4	6	100	930	9.3
Cascaded hybrid resonant converter II	6	4	100	980	9.8

VI.CONCLUSION

In this paper, four types of Switched capacitor converter configurations are discussed; the Switchless and Double switch resonant configurations and finally cascaded hybrid resonant converter I and converter II, achieves high voltage gain than other topologies with less component count. The cascaded hybrid converter II has higher voltage gain than the Converter I, because of the extra switch leg instead of switchless leg. By comparing these two hybrid converters with



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their connection arrangement, hybrid converter II has complex connection by the extra switch leg than the hybrid converter I. So that the cascaded hybrid converter I can be preferred for any Renewable energy applications that involves medium gain or high gain DC-DC conversion. From the Table II, it can be concluded that the cascaded hybrid converter has higher voltage gain than the other topologies and their efficiencies with the corresponding component conduction losses and stresses for these topologies can be calculated and compared for future reference.

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