Abstract - The proposed inverting type zero-current switching switched-capacitor (ZCS SC) DC/DC converters are a new type of bi-directional power flow control conversion schemes. They possess high efficiency, low EMI emission and current stress features for the proposed quasi-resonant switching-capacitor inverting converters. A family of inverting type zero-current switching switched-capacitor bi-directional converters is presented, which can improve the current stress problem during the bi-directional power flow control processing. They are able to provide voltage conversion ratios from -1/-1 (inverting unit-mode/inverting unit-mode) to -n/-n (inverting n-mode/inverting n-mode) by using four power MOSFET main switches and a set of switched-capacitors, series connected with a small resonant inductor. The principle of the converter operation of the proposed bi-directional power conversion scheme is described in detailed circuit model analysis. Simulation and experimental results are carried out to verify the validity and the soft switching performance of the proposed inverting ZCS SC bi-directional DC/DC converters. The maximum efficiency can achieve about 93.1% and 94.8% for the forward and reverse power flow control schemes, respectively.

I. INTRODUCTION

The switched-capacitor DC/DC converter is an inductor-less converter, which requires only capacitors and MOSFET switches in the power stage. This kind of converter has benefit of light in weight, smaller size and the feasibility of fabrication on a semiconductor integrated circuit chip. However, the larger switching losses and current stress are the essential issues in the conventional high frequency switching DC/DC converter [1-4]. The quasi-resonant converter is able to operate at constant switching frequency with zero-current or zero-voltage switching (ZCS or ZVS) to reduce the switching loss of the converter to overcome the aforementioned problems. A new topology of zero-current switching switched-capacitor quasi-resonant (ZCS SC QR) converters can operate at a high switching frequency with less switching losses i.e., increased efficiency of the converter with a smaller number of switches [2,3]. Although the proposed ZCS SC QR converter in [4,5] has lots of advantages, the power flow control works only uni-directional.

Bi-directional DC/DC power conversion is of great interest in systems fed by DC power including battery powered vehicles, fuel-cell systems and aerospace systems. The bi-directional nature in these applications is in the current flow while the polarity of the DC voltage at either end remains unchanged [6-10]. A bi-directional DC/DC converter is an excellent candidate for high voltage and high power industrial applications [8]. The bi-directional feature is especially useful for regenerative braking in electric vehicles (EV), hybrid electric vehicles (HEV) and battery equalization schemes [7], where the stronger energy of this system is transferred into the weaker energy subsystem by using the bi-directional power flow control scheme [9]. The class of soft switching bi-directional DC/DC converters is the expected candidate for applications such as uninterruptible power supply (UPS), battery charging and discharging systems, auxiliary power supply in HEV and dual voltage automotive systems [5,12]. A conventional bi-directional switched-capacitor dc/dc converter with hard switching had been proposed in [10].

This paper presents a new family of switched-capacitor quasi-resonant bi-directional DC/DC converters, which can be designed to operate at inverting mode and constant frequency ZCS for obtained low switching losses. An analysis of the non-inverting type triple-mode/trisection-mode ZCS SC bi-directional DC-DC converter had been proposed in [12]. The high switching current stresses can also be reduced under the bi-directional power flow control schemes. The proposed converters have topologies for a number of voltage conversion ratios from -1/-1 to -n/-n under various control strategies for the switched-capacitor networks. Analysis and experimental results are used to verify and validate the performance of the proposed inverting type ZCS SC bi-directional converters.

II. TOPOLOGIES DESCRIPTION

Figs. 1 (a) and (b) show the proposed non-inverting and inverting type of the ZCS SC QR bi-directional converter which was developed based on the ZCS SC Quasi-resonant converter. The converter comprises four main switches paralleled with Schottky diodes. Only a very small inductor series connected with a switched-capacitor is needed to construct the resonant tanks in the converters. A resonant inductor Lr is connected in series with the switching capacitor Cr to achieve a resonant cycle where either one of the switches Q1 (contains Q1P and Q1N) or Q2 (contains Q2P and Q2N) is switched on during the operating duty. The switches can be designed to switch on and off at the zero-current state while the Lr-Cr resonant current is rising and falling to zero to achieve ZCS for reducing the switching losses. Fig. 1 (a) shows a double-mode/half-mode non-inverting type ZCS SC QR converter. Switches Q1P or Q2N can control the forward power flow from one source V1 to the other source V2 as a double mode converter (i.e. V2 = 2 V1). On the other hand, switches Q2P or Q1N can also control the reverse power flow.
from \( V_2 \) to \( V_1 \) as a half mode converter (i.e. \( V_2 = V_1 /2 \)). When the resonant current increases to a peak value and decreases to zero current, it cannot reverse into negative current because there is a diode in the circuit loop of the converter, which ceases the current reversing [11].

Fig. 1 (b) shows a conventional inverting type ZCS SC QR converter. Switches \( Q_{1P} \) or \( Q_{1N} \) can control the forward power flow from one source \( V_1 \) to the other source \( V_2 \) as a conventional inverting type ZCS SC converter (i.e. \( V_2 = -V_1 \)) as shown in Fig. 2 (a)- 2 (d). On the other hand, switches \( Q_{2P} \) or \( Q_{2N} \) can also control the reverse power flow from \( V_2 \) to \( V_1 \) as an inverting mode converter (i.e. \( V_1 = -V_2 \)), as shown in Fig. 3(a) - 3(d). When the resonant current increases to a peak value and decreases to zero current, it cannot reverse into negative current because there is a diode in the circuit loop of the converter, which ceases the current reversing. The inverting ZCS SC QR bi-directional converter operating modes are now analyzed as follows:

Stage 1 (Fig. 2 (a); \( t_0 < t < t_1 \)): \( Q_{1P} \) turned on at \( t = t_0 \), the power flow is from \( V_1 \) positive through \( Q_{1P} \), resonant inductor \( L_r \), resonant capacitor \( C_r \), and \( D_{1P} \) to \( V_1 \) positive; the state equations in this charging interval are shown as follows:

\[
\begin{bmatrix}
L_r & 0 \\
0 & C_r
\end{bmatrix}
\begin{bmatrix}
\frac{dI_{L_r}(t)}{dt} \\
\frac{dV_{cr}(t)}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
-I_{L_r}(t) \\
0
\end{bmatrix}
\begin{bmatrix}
1 \\
0
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]  

(1)

with the initial conditions \( I_{L_r}(t_0) = 0 \) and \( V_{cr}(t_0) = V_{c01} \). The solution of (1) can be obtained as:

\[
I_{L_r}(t) = \frac{V_1 - V_{c01}}{Z_c} \sin \omega_c (t - t_0) = \frac{-\pi f_c I_{c1}}{f_s} \sin \omega_c (t - t_0)
\]  

(2)

\[
V_{cr}(t) = V_1 + (V_{c01} - V_1) \cos \omega_c (t - t_0)
\]  

(3)

where the resonant angular frequency in stage 1 is \( \omega_c = 2\pi f_c = \sqrt{L_r C_r} \), \( f_c \) is the switching frequency of the converter, and \( I_2 \) is the output current. The sinusoidal inductor current \( I_{L_r}(t) \) will increase to reach a peak value, and decrease to zero at \( t = t_1 \).

Stage 2 (Fig. 2 (b); \( t_1 < t < t_2 \)): The main switch \( Q_{1P} \) is still turned on and the diode \( D_{1P} \) cannot reverse into negative current which ceases the current reversing. During this interval, the inductor current will still stop at zero state until \( t \leq t_2 \). The states in this stage are \( I_{L_r}(t_1) = 0 \) and \( V_{cr}(t_1) = V_{c02} \).

Stage 3 (Fig. 2 (c); \( t_2 < t < t_3 \)): During this interval, \( Q_{1N} \) is turned on at \( t = t_2 \). The power flow is from the resonant capacitor \( C_r \), resonant inductor \( L_r \), \( Q_{2N} \), \( V_2 \) to negative, and \( D_{1N} \) to the \( C_r \) negative. Therefore, the stored energy in the capacitor \( C_r \) is transferred into the source \( V_2 \) through the \( L_r - C_r \) resonant tank circuit. The state equation in this interval can be expressed by:

\[
\begin{bmatrix}
L_r & 0 \\
0 & C_r
\end{bmatrix}
\begin{bmatrix}
\frac{dI_{L_r}(t)}{dt} \\
\frac{dV_{cr}(t)}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
-I_{L_r}(t) \\
0
\end{bmatrix}
\begin{bmatrix}
1 \\
0
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]  

(4)

with the initial conditions \( I_{L_r}(t_2) = 0 \) and \( V_{cr}(t_2) = V_{c02} \). The solutions of (4) can be obtained as:

\[
I_{L_r}(t) = \frac{-V_1 + V_{c02}}{Z_c} \sin \omega_c (t - t_2) = \frac{-\pi f_c I_{c1}}{f_s} \sin \omega_c (t - t_2)
\]  

(5)

\[
V_{cr}(t) = V_{c02} + (V_{c01} - V_{c02}) \cos \omega_c (t - t_2) - 1
\]  

(6)

The current of resonant inductor \( L_r \) will decrease along the sinusoidal function to the negative peak value and continuously fall to zero at \( t = t_3 \). After \( L_r \) resonates back to zero, diodes \( D_{1N} \) and \( D_{1P} \) are biased in reverse and this operation stage is terminated.

Stage 4 (Fig. 2 (d); \( t_3 < t < t_4 \)): During this interval, the inductor current will stay in zero current state, the states are \( I_{L_r}(t) = 0 \) and \( V_{cr}(t) = V_{c01} \). After a specified time, \( Q_{1N} \) is turned off at zero current state when \( t = t_4 \). According to stages 1 ~ 4, the resonant angular frequencies are both the same, so we can obtain the duty rate of \( Q_{1P} \) and \( Q_{1N} \) for the conditions of zero current switching as \( \lambda_{1P}T_S \geq \pi /\omega_c \) and \( \lambda_{1N}T_S \geq \pi /\omega_c \), where \( \lambda_{1P} \) and \( \lambda_{1N} \) are the duty ratios of \( Q_{1P} \) and \( Q_{1N} \), respectively, and \( T_S \) is the switching duty of the proposed bi-directional converter.
Figs. 3 (a) -3 (d) show the alternating equivalent circuits of the proposed inverting ZCS SC bi-directional converter under reverse power flow control scheme. In stage 1 (Fig. 3 (a); t₀ < t < t₁): When Q₂P is turned on at t = t₀, then D₂P is forced to turn on, the power flow of this stage is from V₂ positive via resonant inductor Lᵣ, resonant capacitor Cᵣ and to V₂ negative. Therefore, the energy is stored to the Cᵣ through the Lᵣ - Cᵣ resonant tank circuit. The state equations of stage 1 are the same as (4) with the negative state variables I₁(t) and V₁(t). In stage 3 (Fig. 3 (c); t₂ < t < t₃): The main switch Q₂N is turned on at t = t₂, then forced to turn on the diode D₂N. The stored electric energy in the resonant capacitor Cᵣ is discharged to the source V₁ through the resonant inductor, and the diode D₂N, and the switch Q₂N. The state equation in this interval is the same as (1) with the negative states. The analytical procedure is similar to that for the bi-directional converter in the forward power flow control and is omitted in this paper. The detail analysis of the non-inverting type bi-directional converter shown in Fig. 1 (a) is similar to the mentioned analysis method and had been suggested in [12].

Fig. 4 shows the inverting type double-mode/half-mode (-2-mode/−½-mode) zero-current switching switched-capacitor quasi-resonant DC/DC converter, composed of four MOSFET main switches paralleled with Schottky diodes and a very small inductor series connected with a switched-capacitor bank. The switched-capacitor bank is composed of MOSFET switches Q₁, Q₂, Q₁₂ paralleled with Schottky diodes D₁, D₂, D₁₂, and the capacitors C₁, C₂. The inverting double-mode/half-mode power conversion can be obtained by properly designing the turned-on and -off sequence of the MOSFET switches. The proposed converter topology can be extended to be designed as an inverting type -n-mode/−½-mode zero-current switching switched-capacitor quasi-resonant DC/DC converter, implementing the switched-capacitor configuration as shown in Fig. 5.
Fig. 3 (d) 

Fig. 3 Equivalent circuits for different operation intervals of inverting type unit mode/unit mode ZCS SC QR bi-directional converter with reverse power flow control (a) \( t_0 < t < t_1 \) (b) \( t_1 < t < t_2 \) (c) \( t_2 < t < t_3 \) (d) \( t_3 < t < t_4 \)

Fig. 4 -2-mode/1-mode ZCS SC QR DC/DC converter

Fig. 5 -n-mode/1-n-mode ZCS SC DC/DC converter

IV. EXPERIMENTAL RESULTS

In order to verify and validate the performance of the proposed inverting type ZCS SC bi-directional DC/DC converter, a PSpice simulation and experiments are carried out for the proposed inverting unit-mode / unit-mode ZCS SC QR converter. The designed parameters are listed as follows: MOSFET switches are IRF3710 (Q1P, Q1N, Q2P, Q2N), Schottky diodes are SBL 1040 (D1P, D1N, D2P, D2N), \( L_r = 1 \mu H \), \( C_r = 0.33 \mu F \), \( f_s = 170 \text{ kHz} \), the duty ratios are \( \lambda_{IP} = 0.4 \) and \( \lambda_{IN} = 0.43 \). The input voltages are \( V_1 = 36 \text{ (V)} \) and \( V_2 = -36 \text{ (V)} \) for the forward power flow control and \( V_2 = 36 \text{ (V)} \) for reverse power flow control. The output powers are all designed at \( P_o = 95 \text{ (W)} \). Figs. 6 (a) and 6 (b) show the simulation results of \( V_{gs-QP}(t) \), \( V_{gs-QN}(t) \), \( I_{QIP}(t) \), \( I_{QIN}(t) \), \( I_{Q2P}(t) \), and \( V_{o}(t) \) of the proposed inverting unit-mode ZCS SC QR converter for forward and reverse power flow control, respectively. The simulation output voltages are \(-34.33\text{(V)}\) and \(34.32\text{(V)}\) for the forward and reverse power flow control schemes, respectively. Figs. 7 (a) and 7 (b) show the experiments of the corresponding waveforms of the same converters. The experimental output voltages are \(-33.85\text{(V)}\) and \(33.76\text{(V)}\) for the forward and reverse power flow control schemes, respectively. The V-I trajectory of the MOSFET switches shown in Fig. 8 (a) and 8 (b) are used to inspect the performance of the zero-current soft switching for the corresponding power flow control schemes. Figs. 9 (a) and 9 (b) show the converter efficiency of forward and reverse power flow control under various load conditions, respectively. The average efficiency of the forward and reverse power flow control scheme are 89.9\% and 90.2\%, respectively. From the observations of Figs. 6 - 9, several performance aspects of the proposed ZCS SC QR bi-directional converter can be summarized, as follows:

- The power MOSFET switches of the proposed inverting type bi-directional converter are turned on and off at the zero-current state. The total switching losses of the MOSFETs in the converter can be significantly reduced compared with the conventional switched-capacitor bi-directional converter.

- The conductive EMI emission into the power source and the peak current stresses of the MOSFETs are significantly reduced compared with the conventional hard switching switched-capacitor bi-directional converter.

- The maximum efficiency can achieve about 93.1\% and 94.8\% for the forward and reverse power flow control schemes, respectively.

- The parasitic parameters ESR (equivalent series resistance) and ESL (equivalent series inductance) in the passive devices are well calculated when designing the high performance high-frequency ZCS SC QR converters.

- The output voltages of the proposed inverting converters are slightly less than the designed values due to the ESR voltage drop of the active and passive devices in the converter loop.

- The proposed bi-directional converter can be extended to design as a non-inverting type (n-mode/1-n-mode) or inverting type (-n-mode/1-n-mode) ZCS SC QR bi-directional converter for high frequency and high voltage conversion ratio power supply applications [12].
Fig. 6 Simulation waveforms of the inverting unit-mode ZCS SC bi-directional converter for (a) forward (b) reverse power flow control

Fig. 7 Experimental results of the inverting unit-mode ZCS SC bi-directional converter for (a) forward (b) inverting unit-mode reverse power flow control

Fig. 8(a)
V. CONCLUSION

From the simulations and experimental results, zero-current switching, quasi-resonant based, inverting type unit-mode/unit-mode bi-directional power conversion schemes have been developed. The advantages of this type of power converter are decreased switching losses, thus increasing the converter efficiency, reducing the MOSFET current stress of the converter, and easy extension to \(-n\)-mode / \(\frac{-1}{n}\)-mode bi-directional power flow control converter. The proposed ZCS SC QR converter is very much suitable for high frequency and high efficiency bi-directional power flow control power supply applications.

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