Multiple and Fractional Voltage Conversion Ratios for Switched-capacitor Resonant Converters

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***Abstract*-A Family of circuits based on classical switched-capacitor and zero-current switching resonant techniques is presented. This family of circuits has a number of topologies which provides different voltage conversion ratios including step-up, step down and inverting. Fractional and multiple ratios as well as multiple output voltages can also be produced.**

1. INTRODUCTION

Conventional switched mode converters use magnetic as their principal energy storage components. The sizes of the inductor and transformer are relatively large compared to the size of the whole converter. This approach has a number of problems such as loss in the magnetic components, difficulty in magnetics design, lack of complete IC solution. Some research works have proposed resonant converters [1-2] which can operate at very high frequencies. The sizes of inductors or transformers can be reduced considerably. However, the inductors still cannot be eliminated.

Another concept of power converters is to use capacitor only for the energy storage. This is the so-called Switched-capacitor converter [3]. This approach uses capacitors and switches only. The capacitors are charged and discharged by routing the switching appropriately. A number of topologies for different voltage conversion ratios can be achieved by various combinations of the switches and capacitors. The drawback of this approach is that the switching currents at the source, capacitor and transistor are very high [4] and the EMI is a main concern. Therefore in the past, it was only suitable for small power conditions [5-7]. In this paper, a new family of the switched-capacitor resonant converters is presented. It consists of a number of different voltage conversion ratio circuits.

2. THE FAMILY OF CIRCUITS

The family of switched-capacitor resonant converters is shown in Fig. 1-3. It can be seen that each of the circuits consists of two active switches and two diodes. The small inductor L_r is connected in series with the switching capacitor C_1 to assist the resonant switching. If L_r is zero or short circuited, the family of circuits will be similar to its classical counterparts [5-7]. The proposed circuits operate in zero-current switching. They are different from load-resonant converters [2] in that they use large capacitors which have large DC components and no parallel resonant capacitor is needed across the transistors.

The family consists of three basic circuits: step-down mode (Fig. 1), inverting mode (Fig. 2), and step-up mode (Fig. 3); and variations of the basic circuits: step-down one-third mode (Fig. 4), inverting half-mode (Fig. 5) and step-up triple mode (Fig. 6); and dual output inverting (Fig.

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7), dual output step-up (Fig. 8) and multiple output inverting and step-up (Fig. 9). The function of the resonant inductors L_r (Fig. 1-3), L_{ra} and L_{rb} (Fig. 4-9), are to create resonance cycles with C_1 (Fig. 1-3), C_{1a} and C_{1b} (Fig. 4-9) when each of the switches Q_1 or Q_2 is switched on. In each circuit, the switches are connected in such a way that when each device is turned on, the device current is the same as the instantaneous inductor current. Hence, it creates zero-current turn-on mechanism. When the resonant currents increase to peak value in sinusoidal resonant manner and then decrease to zero, they cannot reverse into negative current because the diodes stop the current reversing. The circuits use fewer diodes and switches compared to other multi-switches switched-capacitor circuits [6, 7]. Table 1 summarizes the resonant frequencies and the conversion ratios of the circuits.

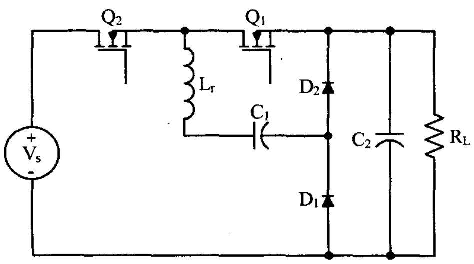

Fig. 1. Step-down half mode converter

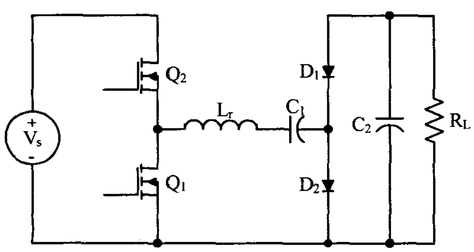

Fig. 2. Inverting mode converter

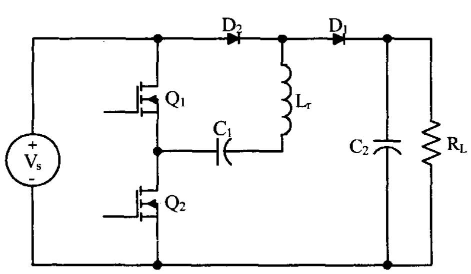

Fig. 3. Step-up double mode converter

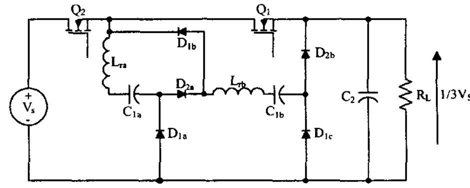

Fig. 4. Step-down one-third mode converter

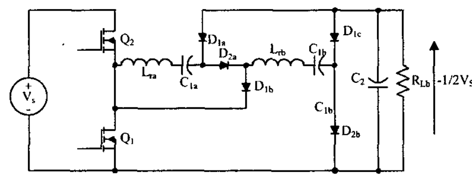

Fig. 5. Inverting half mode converter

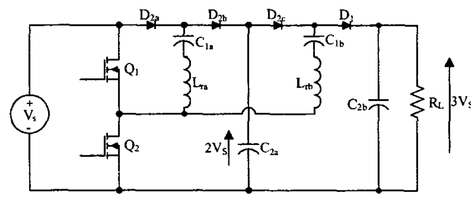

Fig. 6. Step-up triple mode converter

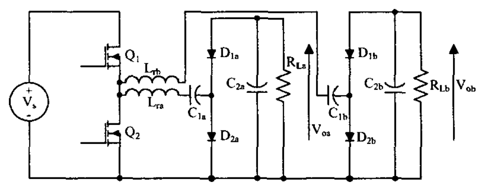

Fig. 7. Dual output inverting circuit

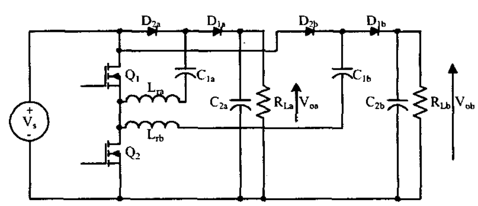

Fig. 8. Dual output step-up circuit

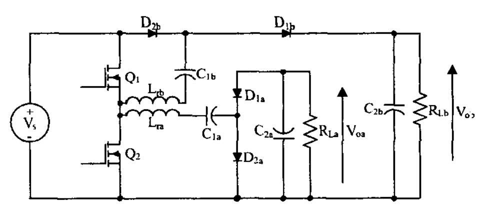

Fig. 9. Multiple output inverting and step-up circuit

TABLE I Values of ω_0, and voltage conversion ratio

VALUES OF ω_0 AND VOLTAGE CONVERSION RATIO

	ω_0 during Q_1 on	ω_0 during Q_2 on	V_o/V_s
Step-down half mode	$1/\sqrt{(L_rC_1)}$	$1/\sqrt{(L_rC_1)}$	0.5
Inverting mode	$1/\sqrt{(L_rC_1)}$	$1/\sqrt{(L_rC_1)}$	-1
Step-up double mode	$1/\sqrt{(L_rC_1)}$	$1/\sqrt{(L_rC_1)}$	2
Step-down one-third mode	$1/\sqrt{(L_{rab}C_{1ab})}$	$1/\sqrt{(L_{ra}C_{1a})}$	1/3
Inverting half mode	$1/\sqrt{(L_{rab}C_{1ab})}$	$1/\sqrt{(L_{ra}C_{1a})}$	-1/2
Step-up triple mode	$1/\sqrt{(L_{rb}C_{1b})}$	$1/\sqrt{(L_{rb}C_{1b})}$	3
Dual output inverting mode	$1/\sqrt{(L_{ra}C_{1a})}$	$1/\sqrt{(L_{ra}C_{1a})}$	-1
Dual output step-up mode	$1/\sqrt{(L_{ra}C_{1a})}$	$1/\sqrt{(L_{ra}C_{1a})}$	2
Multiple output inverting and step-up mode	$1/\sqrt{(L_{ra}C_{1a})}$	$1/\sqrt{(L_{ra}C_{1a})}$	-1 and 1

Where $L_{rab}=L_{ra}L_{rb}/(L_{ra}+L_{rb})$; $C_{1ab}=C_{1a}C_{1b}/(C_{1a}+C_{1b})$

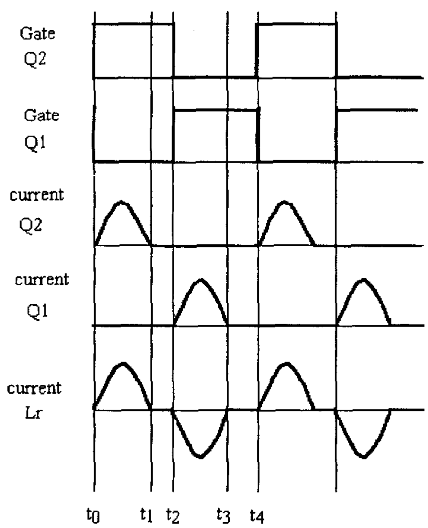

Fig. 10. Idealized waveforms of the proposed switched capacitor resonant converters

III. THE CIRCUITS

A. Binary Ratio Cconversion Ratio Circuits

Fig. 1-3 show the basic circuits of the family with simple conversion ratios of 0.5, -1 and 2, respectively. The idealized waveforms of the converters are shown in Fig. 10. Every time when Q_2 is turned on, C_1 is charged with a voltage in a resonant manner with L_r. This voltage is then re-connected to C_2 when Q_1 is turned on next. Q_1 and Q_2 are under zero-current switching-on because of the resonant circuit of L_r and C_1. They are also under zero-current switching-off since the diodes D_1 and D_2 stop the resonant current from reversing and they are therefore turned off naturally under zero-current. The diodes are under zero current switching as well.

B. Fractional Conversion Ratio Circuit

Fig. 4 shows a switched-capacitor resonant circuit with conversion ratio of 1/3. The circuit differs from half-mode circuit by adding components L_{rb}, C_{1b}, D_{2b} and D_{1c}. When Q_2 is turned on, C_{1a}, C_{1b} and C_2 is connected in series to share the voltage V_S by approximately one-third of the source. During this time, D_{2a} and D_{2b} are in forward bias. When Q_1 is turned on and Q_2 is turned off, C_{1a} and C_{1b} are each connected in parallel with C_2. During this time, D_{1a}, D_{1b} and D_{1c} are conducting. Resonant inductors L_{ra} and L_{rb} are added to achieve zero-current switching. Each time when either one of the transistors is turned on, the current must pass through L_{ra} and L_{rb}. Therefore, all the transistors are switched on under zero-current. The diodes also serve a second purpose. During the resonance, they only allow unit direction of the current flow. The resonance will stop when the resonant current wants to reverse into negative region. This feature allows the transistor to switched off under zero-current.

C. Inverted Fractional Conversion Ratio

Fig. 5 shows a switched-capacitor resonant converter with fractional inverted output voltage conversion ratio. When Q_2 is turned on, D_{2a} and D_{2b} are in forward bias, while all the other diodes are in reverse bias. L_{ra}, L_{rb}, C_{1a} and C_{1b} are connected in series to source voltage V_S.

Capacitors are charged from source voltage V_S. C_{1a} and C_{2b} are re-connected in parallel but in anti-parallel to C_2 through L_{ra} and L_{rb} respectively. The output voltage is $-V_S/2$.

D. Multiple Conversion Ratio Circuit

Fig. 6 shows circuit with a conversion ratio of three. The basic circuit is formed by Q_1, Q_2, D_{2a}, D_{2b}, C_{1a}, L_{ra} and C_{2a} which is called double mode circuit as shown in Fig. 3. By adding components D_{2c}, D_1, C_{1b}, L_{rb} and C_2, the output voltage is increased by one V_S. Again, resonant inductors L_{ra} and L_{rb} are put in series with each of the switching capacitors C_{1a} and C_{1b} respectively in order to achieve zero-current switching when Q_1 or Q_2 is turned on or off. The amplitudes of DC voltage amplitude have been annotated next to the capacitors for clarity.

E. Dual Output Circuits

Basic topology of switched-capacitor resonant converter can be merged to generate multiple output voltage. Fig. 7 shows a circuit with dual outputs of $-V_S$. It is a combination of two inverting mode circuits. Both V_{oa} and V_{ob} produce $-V_S$ but they are isolated from each other by diode D_{1a} and D_{1b}. Fig. 8 shows a circuit with dual outputs of $2V_S$. It is a combination of two step-up double mode circuits. Again, the two outputs are isolated by diodes D_{1a} and D_{1b}. The loading dependent effect of each of the outputs has subtle effect on the other.

F. Multiple Output Circuits

Fig. 9 shows a multiple output circuit with output voltages of $-V_S$ and $2V_S$. It is a combination of the inverting mode and the step-up circuit. Other combinations of the higher order circuits are also possible to generate different multiple output circuits. In fact, the higher order circuit as shown in Fig. 6 is also multiple outputs where voltage across C_{2a} and C_2 give constant output voltages of $2V_S$ and $3V_S$, respectively.

Considering the multiple output inverting and step-up circuit shown in Fig. 9, when Q_1 is turned on and Q_2 is turned off at t_0, the current through Q_1 is the sum of the currents of the resonant inductors L_{ra} and L_{rb}, which is:

$$i_{Q1} = I_{oa}\pi\frac{T_s}{T_{oa}}\sin\omega_{oa}(t-t_0) + I_{ob}\pi\frac{T_s}{T_{ob}}\sin\omega_{ob}(t-t_0) \tag{1}$$

where $I_{oa} = V_{oa}/R_{La}$, $I_{ob} = V_{ob}/R_{Lb}$, $\omega_{0a} = 1/\sqrt{(L_{ra}C_{1a})}$, $\omega_{0a} = 1/\sqrt{(L_{rb}C_{1b})}$, $T_{oa} = 2\pi/\omega_{oa}$, $T_{ob} = 2\pi/\omega_{ob}$ and T_s is the switching frequency.

When Q_2 is turned on at t_2, the current through Q_2 is the same as i_{Q1}:

$$i_{Q2} = I_{oa}\pi\frac{T_s}{T_{oa}}\sin\omega_{oa}(t-t_2) + I_{ob}\pi\frac{T_s}{T_{ob}}\sin\omega_{ob}(t-t_2) \tag{2}$$

To ensure zero-current switching is achieved on both switching devices, the resonant frequencies, ω_{oa} and ω_{ob}, should be designed to be the same and also:

$$\frac{T_{oa}}{T_s} = \frac{T_{ob}}{T_s} < 1 \tag{3}$$

IV. EXPERIMENTAL RESULTS

The multiple output inverting and step up circuit has been designed and constructed. The parameters of the designed circuit are:

C_{1a}, C_{1b} = 0.5 μF; L_{ra}, L_{rb} = 1 μH; C_{2a}, C_{2b} = 47 μF; Q_1, Q_2 = IRF510; D_1, D_2 = MBR10100

The electrical specification of the converter is :

V_s = 50V, V_{oa} = -50V, V_{ob} = 100V, total output power = 100W (each output power = 50W), T_s = 200kHz..

The experimental waveforms for 100W operation are shown in Fig. 11 – 14. The time bases in all figures are 1μs. The measured output voltages of V_{oa} (the inverting mode output) and V_{ob} (the step-up double mode output) are –48.5V and 99.2V respectively.

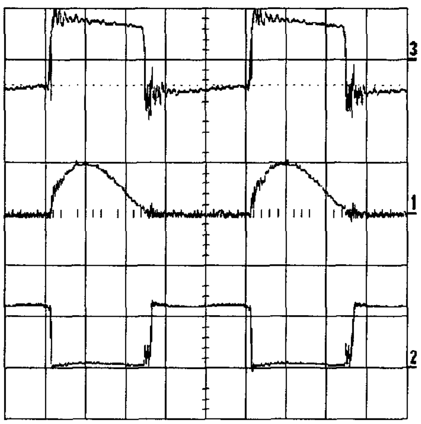

Fig. 11. Experimental waveforms of Q_1; upper: Vgs of Q_1, 20V/div; middle: i_{Q1}, 5A/div; lower: V_{ds} of Q_1, 40V/div

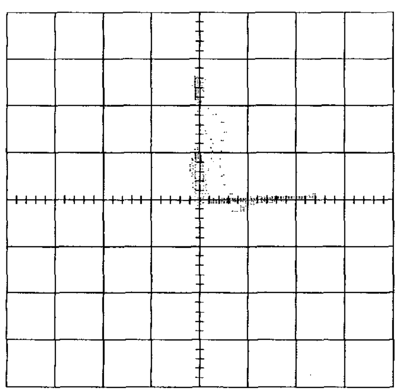

Fig. 12 v-i trajectory of Q_1; X: i_{Q1}, 2A/div; Y: V_{ds} of Q_1, 20V/div

Fig. 13 shows the measured waveforms of Q_2. Both of the v-i trajectory of Q_2 shown in Fig. 14 and Fig. 13 confirm that Q_2 is also in zero-current switching condition. The efficiency of the circuit has been measured.. The relationship between the efficiency and the output power of the converter is shown in Fig. 15. The output power varies from 20W to 100W. By the experiment, it shows that about 95% to 96.2% of efficiency can be achieved.

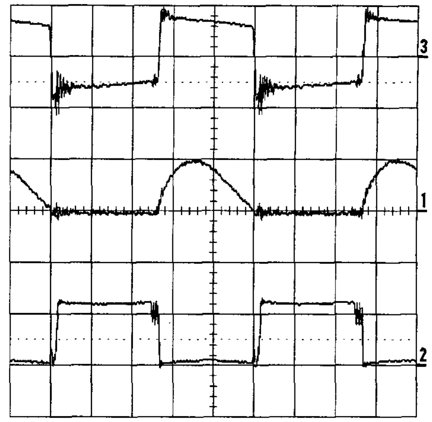

Fig. 13. Experimental waveforms of Q_2; upper: Vgs of Q_2, 20V/div; middle: i_{Q1}, 5A/div; lower: V_{ds} of Q_1, 40V/div

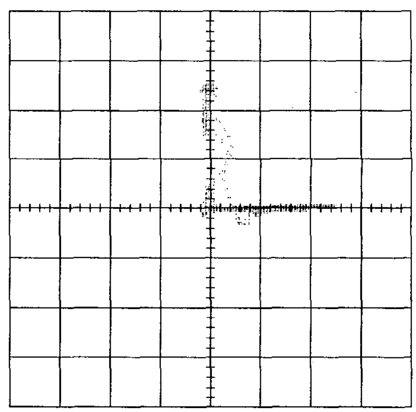

Fig. 14. v-i trajectory of Q2; X: i_{Q2}, 2A/div; Y: V_{ds} of Q_2, 20V/div

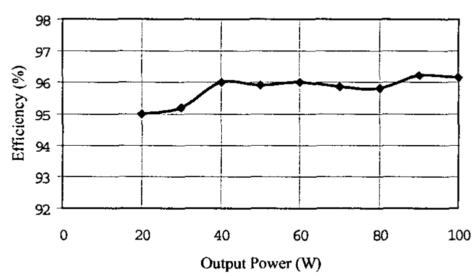

Fig. 15. Measured efficiency of the multiple output inverting and step-up circuit

V. CONCLUSION

A family of zero-current switching switched-capacitor converter is proposed in this paper. All the devices are zero-current switching and hence can operate at high switching frequencies. Pulsational switching current and EMI are low compared with the other switched capacitor circuits [5-7].

The family of switched-capacitor circuits consists of step-down, inverting and step-up modes. Each of them uses only two switching devices, two diodes, one small resonant inductor, one switching capacitor and one output filter capacitor. One switching device is for charging up the switching capacitor and the other one is for discharging it. The resonant inductor is usually very small and hence does not pose problems for magnetics design, construction nor packaging. Prototype multiple output inverting and step-up switched-capacitor converter has been constructed. Experimental results indicate that all the converters are suitable for high frequency operation. All the devices are zero-current switching. The efficiency is high and the output voltage is reasonably constant when the load varies by eight times with open loop control only.

Variations of this concept produce higher order circuits by adding switching-capacitors and diodes. This includes output voltage conversion ratios of 1/3, -0.5 and 3. Other fractional and multiple values can also be generated by using this concept. Multiple output voltages circuits can also be generated. These have conversion ratios of -1 and 2.

This new generation of switched-capacitor converters have only small magnetic components. No high flux core nor large core for energy storage even in high power applications. It has also the same advantage of other conventional switched-capacitor converters that all the proposed circuits are possible to be fabricated on semiconductor chips. Because of the zero-current switching characteristic, both switching loss and EMI are low. It can operate with further higher switching frequency. The size and the weight of the capacitors of the converters can be decreased and hence, the power density can be higher.

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