Development of Multiple Output Operation Based on Single Stage Switched-capacitor Resonant Converters

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Abstract **- Power converters are commonly based on the Switched Mode techniques which use pulse-width modulation to control the converters. Switching loss and switching noise restrict high frequency operation such as more than 200kHz. Resonant converter is a solution of the above problem. The resonant converter enables switching devices to operate under zero-current or zero-voltage switching. The main disadvantage is that the parasitic effect is very difficult to handle and the transistors may not work at zero-voltage/current switching through the whole range of operation. A family of switched-capacitor circuits using two transistors is presented to overcome the above problems. This family only requires very small inductor for resonance and therefore is suitable for hybridization. It has variable topologies, which provide different voltage conversion ratios. Each of the topology can be merged to produce multiple outputs easily that is very difficult to perform when classical switched-mode or resonant converters are used. This paper investigates the feasibility of this circuit merger technique. Experimental and theoretical analyses are presented. Results confirmed that the converter operated under zero-current switching. The circuit is simple and multiple outputs can be obtained by simply connecting the switching capacitor states together. Experimental results have confirmed that the converter can produce high conversion efficiency. This paper will present the double inverting, double step-up, and inverting and step-up circuits.**

I. INTRODUCTION

Switched-mode technique is commonly used in power conversion. Most power converters use pulse-width modulation (PWM) to control their output voltages. For traditional switched-mode converters, because of the non-idealised characteristics of semiconductor devices, transistors suffer switching loss and switching noise when they are turned on or off. It restricts high frequency operation of converters so that this type of converters is usually low in power density and large in size.

Resonant converters have been developed for solving this problem [1]. Soft-switching technique has advantages of low switching loss and switching noise so that they can operate in high frequency. Sizes of components for energy storage such as inductors and capacitors are small and hence, they enjoy small size and low weight. However, for some operation condition of the converters, resonant converters cannot achieve zero-voltage or zero-current switching such as under low power operation. This is example the phase-shifted DC/DC converter [2].

The size and weight of power converter circuits are mainly dependent on their magnetic components like inductors and transformers. Because inductor and transformers are usually wire-wounded on a magnetic cores or air-cores, reduction of converter size and weight has a certain limitation. Considering core loss, eddy current and proximity effect on the windings imposes difficulty of design of these converters.

To avoid the difficulties of magnetic components, some switched-capacitor converters have been proposed [3-5]. Capacitors are then the only energy storage components. Fabrication of the converters in integrated circuit chips is possible. Drawbacks of this type of converters are that they need large number of switching devices for routing charging and discharging of switched-capacitors and hard-switching method are usually used in traditional switched-capacitor converters. Switching loss and switching noise make efficiency of the circuits to be low.

A family of single stage switched-capacitor resonant converters has been proposed in [5]. This type of converter has only 2 transistors and a very small inductor. All transistors are operated under zero-current switching in full range of power of operation. It provides high efficiency, low switching noise, small size and high power density.

This paper is an extension of the research work of switched-capacitor resonant converters for reference [5]. A multiple output switched-capacitor zero-current switching resonant converter circuit is introduced. Design of this converter is based on merging the proposed single stage switched-capacitor resonant basic converters.

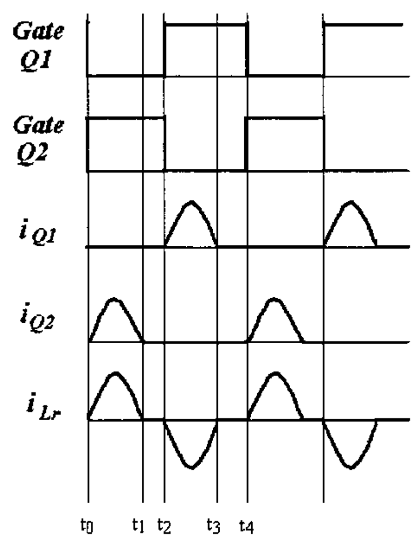

Fig. 1 Idealised waveforms of basic converters

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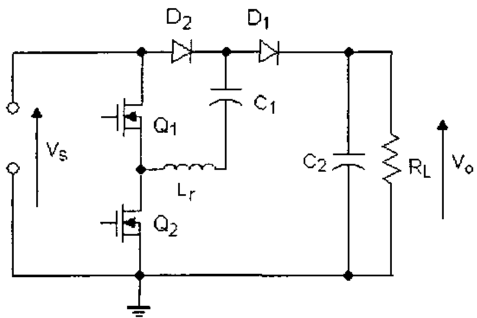


Fig. 2 Step-up double mode converter.

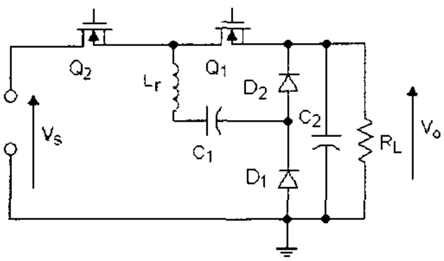


Fig. 3 Step-down half mode converter.

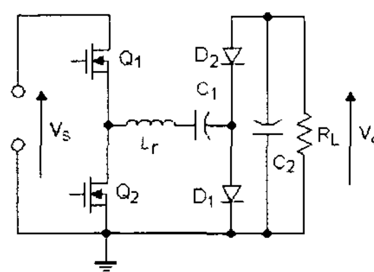


Fig. 4 Inverting converter.

II. THE SWITCHED-CAPACITOR RESONANT CONVERTER FAMILY

Idealized waveforms of three basic converters are shown in Fig. 1 and their circuits are shown as Fig. 2 to Fig. 4.

A. Step-up circuit

The step-up circuit as shown in Fig 2 provides a voltage conversion ration of 2. In the circuit, two transistors are connected in a half-bridge module configuration. When one is on and the other are off and vice versa. They are usually has a mark-space ratio of 50%. Their principal function is to conduct the voltage from the source to the switched-capacitor C_1. C_2 is a large capacitor for smoothing the output voltage. The principle of operation is as follows: The capacitor C_1 is charged up when Q_2 is switched on at t_0 whereas Q_1 is off. The energy from source V_S is connected to the L_r and C_1 through Q_2. L_r and C_1 resonate together. Because of the presence of L_r, the current resonates from zero. The resonant current then increases to a peak and then decreases to zero at t_1 in a resonant manner. The current cannot reverse as the diode D_2 stops it from reversing. The equation of Q_2 is the same as the current in L_r, whereas the current in Q_1 is zero as shown below:

$$i_{Q1} = 0 \tag{1}$$

$$i_{Q2} = I_0 \pi \frac{f_o}{f_s} \sin \omega_0 (t - t_0) \tag{2}$$

where I_0 is output current, f_s is switching frequency, and f_o is the resonant frequency $f_0 = \omega_0 / 2\pi$ with $\omega_0 = 1/\sqrt{L_{ra} C_{1a}}$,

Before the end of half a cycle at t_2, Q_2 is switched off and it cannot be turned under zero-current switching. Q_1 is then switched on at t_2 after half a cycle. C_1 is then discharged through Q_1 to the output. With the presence of L_r, the current behaves in a resonant manner and hence it increases from zero and returns to zero at t_3 again after it has reached a peak in a sinusoidal resonant manner. C_1 behaves as connected in series with the source, therefore a twice of the input voltage is charged to the output C_2. When the current in L_r reaches zero and stops as the diode D_1 does not allow any reverse conduction. The equations of the inductor current is the same As the current in Q_1. The current in Q_1 is zero in this time period. Hence the equation can be shown to be:

$$i_{Q1} = I_0 \pi \frac{f_0}{f_s} \sin \omega_0 (t - t_2) \tag{3}$$

$$i_{Q2} = 0 \tag{4}$$

As described above, the two transistors and diodes are all under zero-current switching during turning-on and off. The spike current appears in the classical switched-capacitor can therefore be eliminated.

B. Step-down converter

For a step-down circuit as shown in Fig 3, the position for the transistor and diodes are interchanged. The charging mechanism happened when Q_2 is switched on at t0 and Q_1 is switched off. C_1 and C_2 are then connected in series. Similar to the previous converter, the resonance mechanism gives a zero-current switching on Q_2 during turning-on and off. D_2 is to stop any conduction when the resonant current reaches zero at t_1. Q2 can be turned off after the resonant current has reached zero.

$$i_{Q1} = 0 \tag{5}$$

$$i_{Q2} = I_0 \pi \frac{f_o}{2 f_s} \sin \omega_0 (t - t_0) \tag{6}$$

At t_2, Q_1 is turned on at zero-current. C_1 and C_2 are connected in parallel and supply power to the load. Again, all the transistors and diodes are under zero-current switching.. It can also be proved that the dc components of both C_1 and C_2 are 0.5Vs. Equations of the transistor currents in this period are:

$$i_{Q1} = I_0 \pi \frac{f_o}{2f_s} \sin \omega_o (t - t_2) \tag{7}$$

$$i_{Q2} = 0 \tag{8}$$

C. Inverting converter

Fig 4 shows the inverting version of the family. The circuit gives unity output and its operation is very similar to the previous ones. The charging of C_1 is through a resonant mechanism with L_r when Q_1 is turned at together with D_1 is in forward bias.

$$i_{Q1} = 0 \tag{9}$$

$$i_{Q2} = I_0 \pi \frac{f_o}{f_S} \sin \omega_o (t - t_2) \tag{10}$$

After the resonant current reaches zero, Q_1 can be turned off. Q_2 can then turned on after half a cycle. C_1 is connected in parallel with C_2 and its positive pole is reversely connected to ground. As a result, the output voltage is inverted. The turn-off of Q_2 is also in a resonant manner.

$$i_{Q1} = I_0 \pi \frac{f_o}{f_S} \sin \omega_o (t - t_0) \tag{11}$$

$$i_{Q2} = 0 \tag{12}$$

D. Summary of the Voltage ratings of the three converters

The voltage impressed on transistors, diodes and capacitors are mainly a dc component and an ac resonant component. Usually the design is to ensure the ac components small so that the loss due to the resonant is negligible. Hence the voltage ratings of the components of these three converters can be approximated in Table I.

TABLE I VOLTAGE AND CURRENT RATING OF THE CONVERTER COMPONENTS

	Q_1, Q_2	D_1, D_2	V_{c2}	V_{c1}	$i_{Lr}, i_{Q1}, i_{Q2}, i_{D1}, i_{D2}$
Step-up Double mode	V_S	V_S	V_S	$2V_S$	$I_o \pi f_o / f_s$
Step-down Half mode	$V_S/2$	$V_S/2$	$V_S/2$	$V_S/2$	$I_o \pi f_o / f_s$
Inverting mode	V_S	V_S	V_S	$-V_S$	$\frac{1}{2} I_o \pi f_o / f_s$

III. MULTIPLE OUTPUT CIRCUIT

From the basic double mode step-up circuit shown in Fig. 2 and inverting mode circuit shown in Fig. 4, it may be found that transistors, Q_1 and Q_2, are arranged as a half bridge. Because of their similar operation method and configuration of active switching devices, by merging these two circuits, multiple output circuit can be generated. The multiple output inverting and step-up circuit is shown in Fig. 5.

To analyze the multiple output circuit, it may be divided into two parts, inverting unity mode and step-up unity mode circuits. As shown in Fig. 5, inverting unity mode circuit is formed by L_{ra}, C_{1a}, D_{1a}, D_{1b}, C_{2a} and R_{La} where R_{La} is the load of this part. Output voltage of this part is equal to $-V_S$. On the other hand, step-up unity mode circuit is formed by L_{rb}, C_{1b}, D_{1b}, D_{2b}, C_{2b} and R_{Lb} where R_{Lb} is its load. Simulation waveforms of this circuit are shown in Fig. 6.

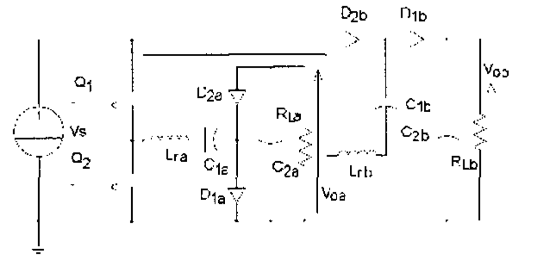


Fig. 5. Multiple output inverting and step-up circuit.

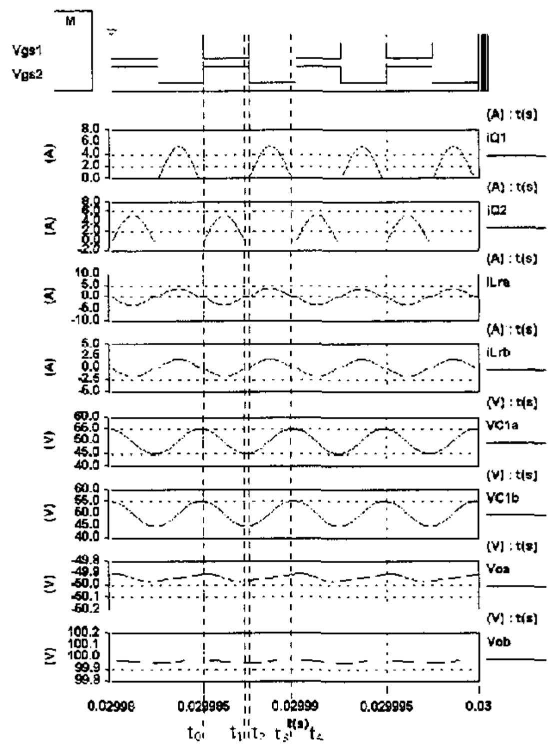


Fig. 6. Simulation waveforms of multiple outputs inverting and step-up circuit.

It can be seen that the new circuit retains the switching device stage, i.e. switching on and off in approximate 50% duty ratio alternatively, and the operation is the same as the basic circuits mentioned as above. Each part of the circuits has its own resonant inductor L_r (i.e. L_{ra} in inverting unity mode part and L_{rb} in step-up unity mode part) and resonant capacitor C_1 (i.e. C_{1a} in inverting unity mode part and C_{1b} in step-up unity mode circuit). Therefore, and Fig. 6 also shows that, when Q_1 is turned on, current through Q_1 is the sum of the current through L_{ra} and L_{rb} which is:

$$i_{Q1} = I_{oa}\pi\frac{f_{oa}}{f_S}\sin\omega_{ba}(t-t_0) + I_{ob}\pi\frac{f_{ob}}{f_S}\sin\omega_{bb}(t-t_0) \qquad (13)$$

where $I_{oa} = V_{oa}/R_{La}$, $I_{ob} = V_{ob}/R_{Lb}$, $\omega_{ba} = 1/\sqrt{(L_{ra}C_{1a})}$, $\omega_{ba} = 1/\sqrt{(L_{rb}C_{1b})}$, $T_{oa} = \omega_{oa}/2\pi$ and $f_{ob} = \omega_{ob}/2\pi$.
When Q_2 is turned on, the current through Q_2 is the same as i_{Q1}:

$$i_{Q2} = I_{oa}\pi\frac{f_{oa}}{f_S}\sin\omega_{ba}(t-t_2) + I_{ob}\pi\frac{f_{ob}}{f_S}\sin\omega_{bb}(t-t_2) \qquad (14)$$

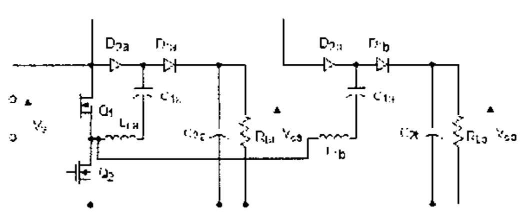
In order to ensure zero-current switching of Q_1 and Q_2, the period of resonant frequency is designed to be equal and

$$\frac{f_o}{f_{oa}} = \frac{f_o}{f_{ob}} < 1 \qquad (15)$$

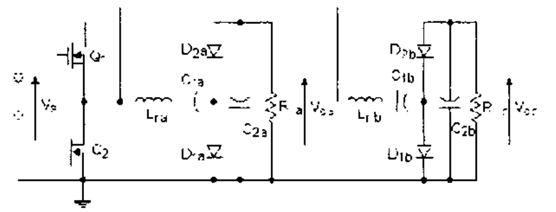
IV OTHER MULTIPLE OUTPUT CIRCUIT

Similarly, other merger of circuit can be possible. Figures 7 a-c show different possibility of the multiple output circuit. It can be seen that Fig 7a is a circuit with two Vo/Vs=2 outputs. The reason of the two outputs with the same voltage is that both outputs can be operated more independently from the other. The cross-talk between the two outputs is less and it is suitable for applications requiring better cross-regulation multiple output system. Fig 7b shows two inverting outputs with unity conversion ratio. Again, both output are the same.

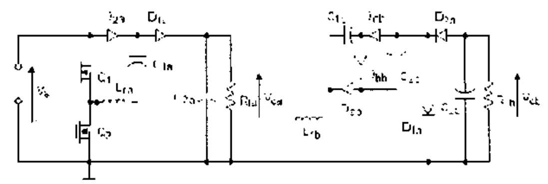
Fig 7c shows a circuit with an integration of the double mode with output V_{oa} and the half-mode inverting [6] with output V_{ob} where V_{oa}/V_s=2 and V_{ob}/V_s = -0.5. The sub-circuit in the left hand side that consists of D_{1b}, D_{2a}, L_{ra}, C_{1a}, C_{2a} and R_{La} is the double mode circuit as shown in Fig 2. The right hand side sub-circuit which consists of L_{rb}, C_{1b}, C_{0b}, C_{1b}, C_{2b}, D_{ab}, D_{bb}, D_{cb}, D_{2b} and R_{Lb} is a higher order inverting-half mode circuit. It uses 3 additional diodes D_{aa}, D_{bb}, D_{cb} and a capacitor C_{1b} to achieve inverting half mode output. In fact, other combination can also be merged together to give a number of zero-current switching switched-capacitor circuits.



(a) Merger of two double mode step-up circuits



(b) Merger of two unity mode inverting circuits



(c) Merger of the double mode and inverting-half mode circuits

Fig 7. Examples of multiple switched-capacitor circuits

IV. PROTOTYPING AND TESTIMG

The circuit shown in Fig 5 is the integration of the inverting and the double mode circuits that give two outputs of inverting and step-up voltage has been designed. The circuit has been prototyped and examined for its characteristics against its theoretical performance. The parameters and the specification of the circuit are respectively shown in Table II and II.

The experimental results of the converter with output power of 50W at the inverting output and 50W at the double mode output is shown in Figs 8 to 11. The voltage developed at the inverting output (V_{oa}) is -48.5V and the output of the double mode (V_{ob}) is 99.2V

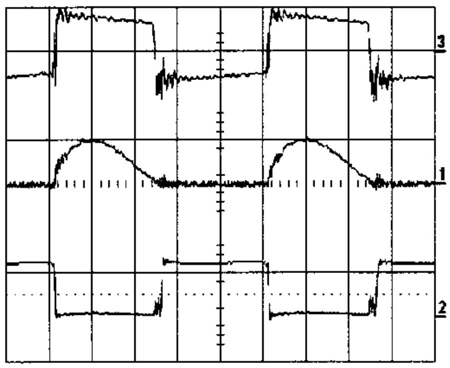
Fig 8 shows the waveforms of gate-source signal (V_{GS}), drain current (I_D) and drain-source voltage (V_{DS}) of the transistor Q_1. It can be seen that the transistors' turn-on and turn-off currents are both operated under zero-current switching. Similar waveforms are shown in Fig 9 for the Q_2. The i-v trajectory is useful to examine the zero-current switching of the devices. Therefore the switching transients of Q_1 and Q_2 are shown in Fig 10 and 11 respectively. It can be seen that the waveforms lie along the x-y axes and the area enclosed by the waveforms and the co-ordination axes is small. This confirms that the zero-current switching condition is achieved.

TABLE II
LIST OF COMPONENTS OF PROTOTYPE OF MULTIPLE OUTPUS INVERTING-AND-STEP-UP CIRCUIT

Components	Parameters/ Part Numbers	Units
C_{1a} and C_{1b}	0.5	μF
C_{2a} and C_{2b}	47	μF
L_{ra} and L_{rb}	1	μH
Q_1 and Q_2	IRF510	
D_{1a}, D_{1b}, D_{2a} and D_{2b}	MBR10100	

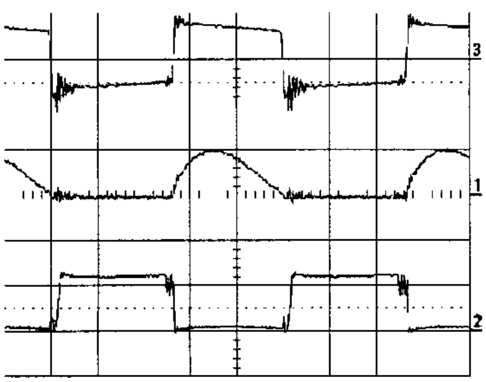
TABLE III
ELECTRICAL SPECIFICATION OF PROTOTYPE OF MULTIPLE OUTPUS INVERTING-AND-STEP-UP CIRCUIT

	Values	Units
Input voltage (V_S)	50	V
Inverting mode output voltage (V_{oa})	-50	V
Inverting mode output power	50	W
Double mode output voltage (V_{ob})	100	V
Double mode output power	50	W
Switching frequency	200	kHz



Time base: 1us
upper: Q1 gate signal, 20V/div
middle: Q1 current, 5A/div
lower: Q1 Vds, 40V/div

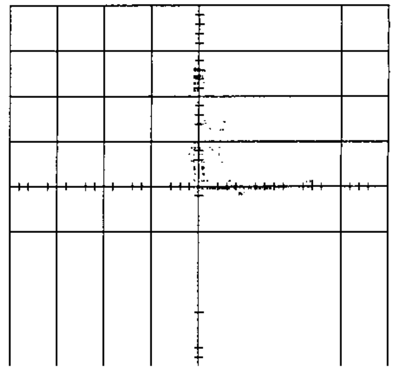
Fig. 8 Experimental results of Q_1 for the double-inverting circuit.



Time base: 1us
upper: Q2 gate signal, 20V/div
middle: Q2 current, 5A/div
Lower: Q2 Vds, 40V/div

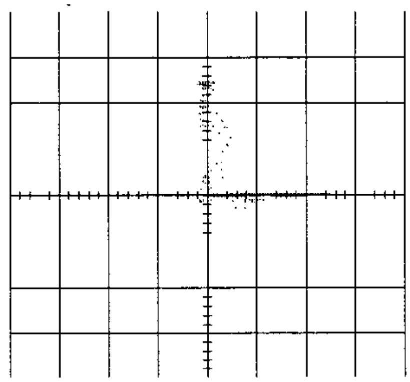
Fig. 9 Experimental results of Q_2 for the double-inverting circuit.

The regulation of the output voltage is very good. It is found that in any one of the outputs, the maximum voltage changes are less than 3% as the power varies between 20-50W. If constant power is drawn from one output, its voltage only varies by less than 1% as the output varies between 20-50W. This is because each of the output has its corresponding switched-capacitor C_1 and zero-current switching diode D_1 and D_2 that do not share with other sub-circuit. The only components affect the cross-regulation are Q_1 and Q_2 which are shared between the two sub-circuits. They can be selected by a lower R_{DS} to minimise the problem. Hence this multiple output converter is very capable for systems requiring simple design and strict regulation. The measurement also confirms the good inter-output regulation.



X: Q1 current, 2A/div
Y: Q1 Vds, 20V/div

Fig. 10 Experimental results of the i-v trajectory of Q_1 for the double-inverting circuit



X: Q2 current, 2A/div
Y: Q2 Vds, 20V/div

Fig. 11. Experimental results of the i-v trajectory of Q_2 for the double-inverting circuit.

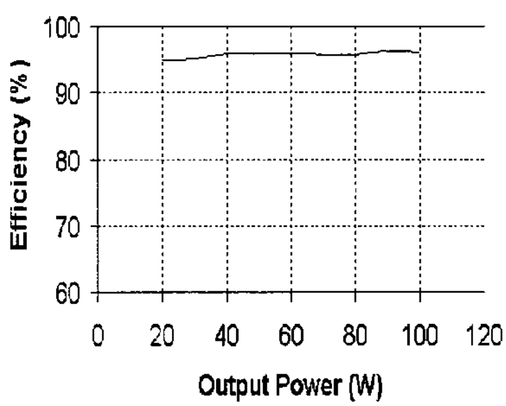


Fig. 12. Measurement efficiency of the double-inverting converter.

The efficiency of the converter has been measured and is shown in Fig. 11. It can be seen that high efficiency of around 95% can be achieved for the power varies between

20-100W. The high efficiency of the converter is because the removal of the inductive components and the zero-current switching of the converter.

VI. CONCLUSION

Three basic switched-capacitor resonant converters, step-up double mode, step-down half mode, and inverting mode circuits, have been presented. Voltage conversion ratio of these circuits are 2, 1/2 and −1, respectively. Theoretical analysis and operation principle have been discussed. This family of circuits has the features of traditional switched-capacitor converters and resonant converters. From the equations of the circuits, it was shown that all circuits are under zero-current switching condition. Each circuit only requires one small inductor for obtaining the zero-current switching.

By simply combining the basic switched-capacitor resonant converter circuits, a multiple output inverting and step-up mode switched-capacitor resonant converter circuit has been designed. Output ports of this multiple output circuit have a common ground. Similar to the basic circuits, only two transistors are needed in the circuit. All transistors are under zero-current switching condition when operating in any power level. Equations of operation are the direct superposition of the original equations of the basic circuits. Operation of the converter is simple. Fixed 50% duty ratio for each transistor can be used, but the duty ratio is not critical. Resonant inductor is very small that it can be made from the PCB track or an air-core.

Simulation results, equations of operation, and experimental results of the multiple output circuit have been presented in this paper. From the experiment, it has been shown that high efficiency can be obtained.

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