New Generation of Switched Capacitor Converters

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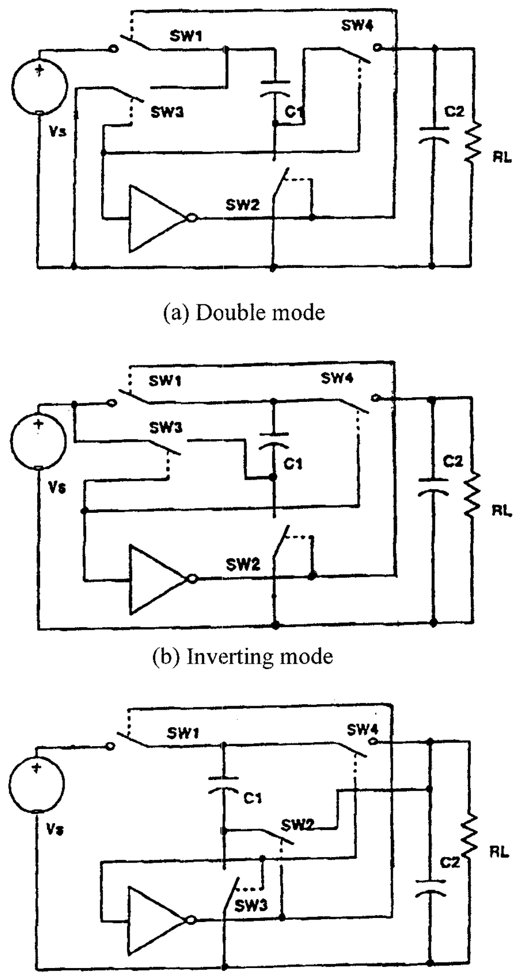
ABSTRACT

This paper is to present a new generation of the switched capacitor converters. These new circuits have used less number of switches. The new family consists of three topologies of circuit which are double, inverting and half the input voltage. All the switching devices are zero-current switching and hence it can operate at high switching frequency. The high switching current has been reduced too.

1. INTRODUCTION

The conventional Switched Mode Power Supplies (SMPS) are using magnetics and capacitors as energy storage. The power conversion is very efficient and has been studied by many engineers. The resonant converters based on this SMPS have been developed [1] and can operate at constant switching frequency however their switching frequencies are not constant and hence the EMI filter cannot be optimised. The extended period quasi-resonant converters have been introduced [2,3]. These converters are able to operate at constant switching frequency and all the switching devices are zero-current or zero voltage switched. On the other hand, the switching capacitor approach combines capacitors and a number of switches. The capacitors are charged and discharged by routing the switching appropriately. The combinations of the switches and capacitors can achieve a number of topologies which achieve different voltage conversion ratio. This converter uses capacitors only as energy storage and is so called switched capacitor converter [4].

The main advantage of these converters is that there is no inductor or transformer and hence the converter size can be smaller and it is possible to fabricate the converter on a semiconductor IC chip such as ASIC. The main disadvantages are that the switching current is very high [4-6] and inducing EMI. The regulation of the output voltage is poor. This converters require a number of switches. Fig. 1 shows a family of the classical switched capacitor converters. These converters have fixed conversion ratio. Fig. 1a shows the double mode where the output voltage is twice the input voltage. Fig. 1b shows the inverting mode where the output voltage is the inverse of the input voltage. Fig. 1c shows the half mode where the output voltage is half the input voltage. It can be seen that each of the converters requires 4 switches.



(a) Double mode

(b) Inverting mode

(c) Half mode

Fig. 1. Classical switched capacitor converters

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Fig 2 shows typical waveforms of the double-mode circuit. The waveforms shown are the currents of the input, SW4, SW1, SW2 and SW3. The input current and the switching device currents are very high, oscillatory and the devices are operated in hard-switching. Because of the switching current, the induced EMI is large. The non zero voltage or non zero current switching also limits the top end of switching frequency and hence the size of capacitor cannot be minimised. This causes a problem to be fabricated into an ASIC. Soft switching switching capacitor approach can be found in Ref. [7] where it combines a number of switching capacitors with quasi-resonant circuits. The circuit is complicated, consists of magnetics and is unable to be fabricated into an IC.

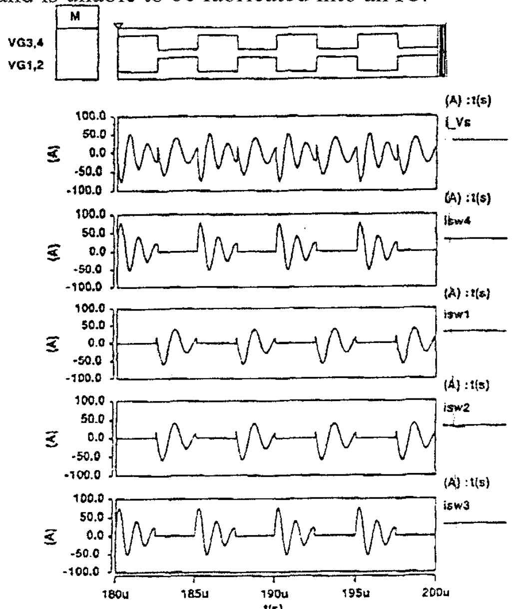
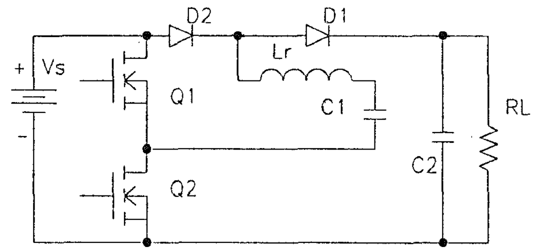


Fig.2. Switching waveforms of the classical switched capacitor

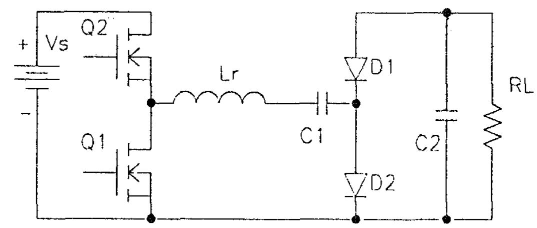
This paper is to propose a new family of the switched capacitor circuits which operates at constant frequency, low switching loss and uses less number of switches. The high switching current can also be reduced. This new generation of circuits has a corresponding topology of each of the classical mode. Analysis, design and experimental results will be used to support this new concept of the converters.

2. THE FAMILY OF THE CIRCUITS

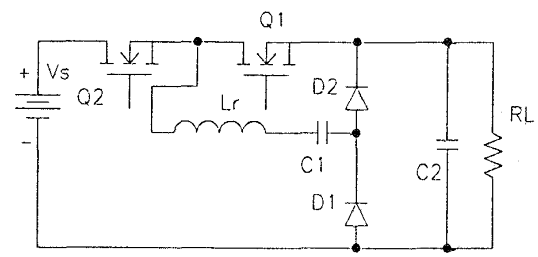
Fig 3 shows a family of the zero current switching switched-capacitor converter. It can be seen that each of the circuits uses only two active switches and only a very small inductor is used to assist resonance in the converter. Complicated resonant techniques [1] has not been considered because it will significantly increase the converter sizes and make it less possible to be fabricated in an IC.



(a) Double mode



(b) Inverting mode



(c) Half mode

Fig. 3. Family of the zero current switching switched capacitor converters

A resonant inductor, L_r, is connected in series with the switching capacitor to create a resonance cycle when each of the switches Q1 or Q2 is switched on. The switches are connected in such a way that when the device is turned on, the instantaneous device current is the same as the inductor current, hence it creates a zero-current turn-on mechanism. After the resonant current resonates to a peak value and then decreases to zero current, it cannot reverse into negative current because there are diodes which stop the current reversing.

The circuit uses less diodes and switches when it is compared to other switched capacitor circuits [4-6].

The switching devices are in half-bridge module configuration and connected across the input source or between the input source and output voltage. This is important when high power switched capacitor converter is constructed because half-bridge module is widely available and high current bus-bar is easily constructed and EMI can be reduced.

Fig 4 shows the idealised waveform of the double mode topology under steady-state conditions. The operation of the circuit can be described in four states of operation. It can be seen that the switching device currents resonate from a zero value and the devices stop conduction when the currents return to zero. This creates the zero-current turn-on and turn-off condition of the two devices. The duty-ratio of the devices are about 50% and are turned on alternatively and can be varied to less than 50% if output voltage is wanted to be adjusted slightly. Q1 is to charge up the switching capacitor C_1 from the source Vs and Q2 is to discharge the switching capacitor to the load R_L. The inductor current is the sum of the devices' current.

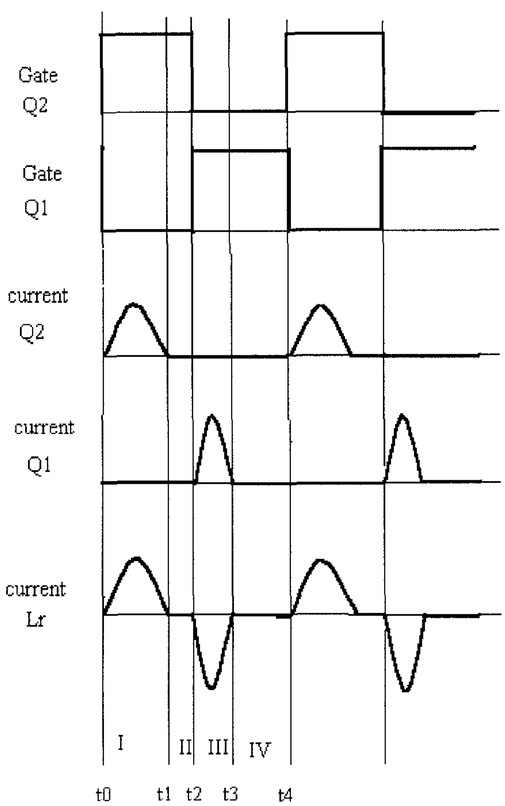


Fig. 4. Idealised waveforms of zero-current switching switched capacitor converter

3. ANALYSIS OF THE CIRCUIT

3.1 States of operation

The circuit can be described in four states of operation as shown in Fig. 5.

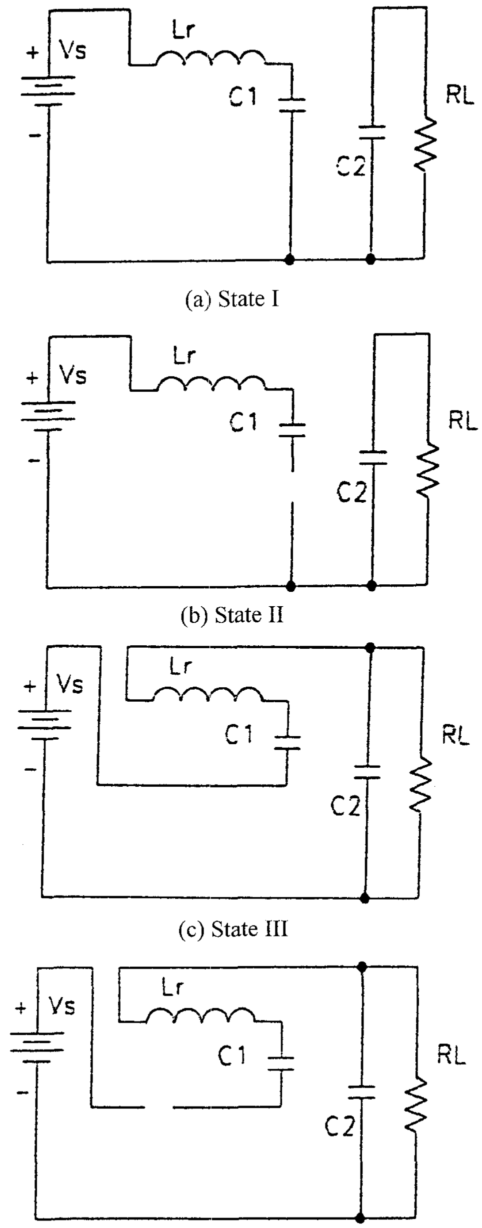


Fig. 5. Equivalent circuit of the double-mode switched capacitor converter.

3.1.1 State I (Fig. 5a) [t0-t1]

When Q2 is turned on at t=t0, with Q1 off, L_r and C_1 resonate. Because of the presence of L_r, Q2 is turned on with zero-current. C_2 is discharged to the load R_L. The state equations are:

$$i_{Lr}=\frac{V_s-V_{clo}}{L_r\omega_1}\sin\omega_1 t$$
$$V_{cl}=V_s+(V_{clo}-V_s)\cos\omega_1 t$$

where V_{c1o} is the initial voltage of C_1 at t=t0 and $\omega_1 = 1/\sqrt{(L_rC_1)}$. L_r and C_1 will resonate for half a cycle and the resonance stops because D_2 and D_1 are reverse biased.

3.1.2 State II (Fig. 5b) [t1-t2]

The device currents and inductor current are zero. C_2 is still discharged to the load. Q2 is switched off at zero current condition at t=t2.

3.1.3 State III (Fig. 5c) [t2-t3]

Q1 is turned on at t=t2, L_r, C_1 and C_2 start to resonate. i_{Lr} increases its value in a resonant manner and hence it operates at zero-current turn-on. The resonance equations of the inductor and capacitors depend on the size of the load. Their equations when R_L is large can be approximated as:

$$i_{Lr}=\frac{V_d}{L_r\omega_n}\sin\omega_n t$$
$$V_{C1}=\frac{V_d}{C_1L_r\omega_n^2}(1-\cos\omega_n t)+V_{C1_o}$$
$$V_{C2}=\frac{V_d}{C_2L_r\omega_n^2}(1-\cos\omega_n t)+V_{C2_o}$$

where $\omega_n = 1/\sqrt{(L_rC_p)}$, $C_p = C_1 // C_2$ and $V_d = (V_S-V_{C1o}-V_{C2o})$

After i_{Lr} resonates back to zero value, D1 and D2 are in reverse biased and this state terminates.

3.1.4 State 4 (Fig.5d) [t3-t4]

i_{Lr} is zero and C_2 is discharged to the load. Q1 is turned off at zero current when t=t4.

3.2 Condition of zero current switching

The Q1 and Q2 are turned on at zero current condition because of the resonance characteristics of the circuit. i_{Lr} returned to zero after approximately half a resonant period, the switching device are turned off after that in order to ensure zero current switching.

If the duty ratio of the Q1 and Q2 are d_1 and d_2 respectively, the condition for zero-current switching of Q1 is:

$$d_1T_s\geq\frac{\pi}{\omega_n}$$

The condition for zero-current switching of Q2 is:

$$d_2T_s\geq\frac{\pi}{\omega_1}$$

where T_s is the period of the switching frequency.

4. SIMULATION OF THE CIRCUITS

The double mode circuit is first studied in a computer simulation using SABER. The model of the circuit is shown in Fig 6. The switching devices were modelled using a simple switch with only on-state and off-state resistances. Fig. 7 shows the simulated waveforms of the output voltage, switching devices' voltage and current. It can be seen that the device voltage during the turn-off is equal to V_S. The device currents are in resonant manner. The waveforms agree generally with the idealised waveforms predicted in Fig. 4.

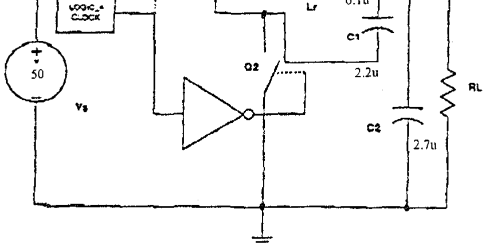
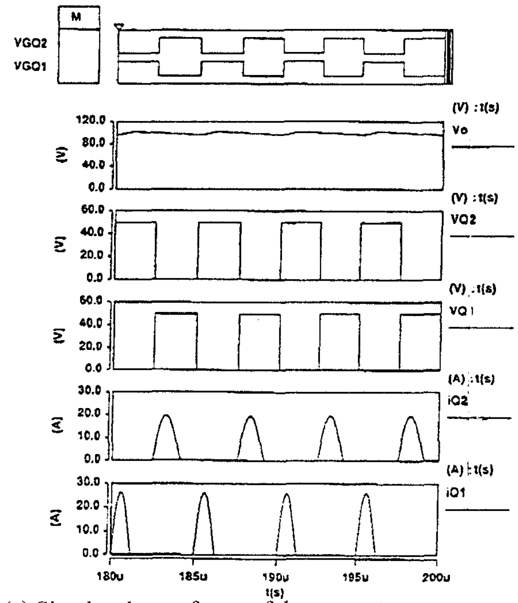
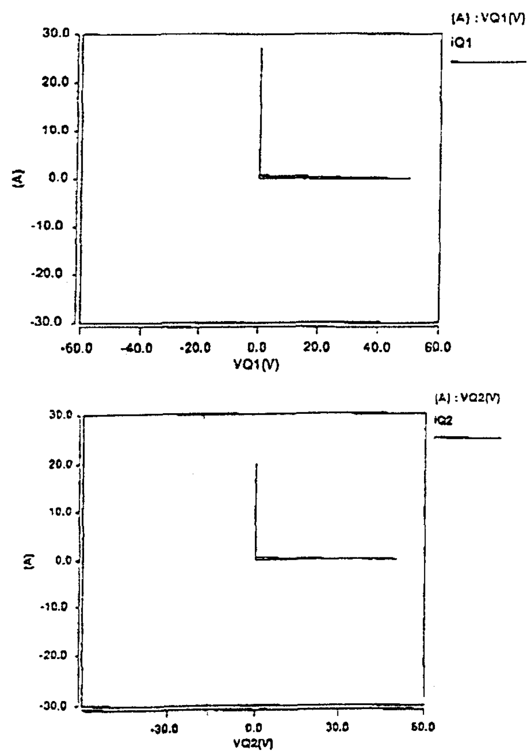


Fig. 6. Simulation model of the converter

The simulated switching trajectories of Q1 and Q2 indicate that the instantaneous operating conditions of the switches lie on the zero voltage or zero-current axes. That means the switching losses are zero. This confirms the zero-current switching conditions of the devices.



(a) Simulated waveforms of the converter



(b) Simulated i-v switching trajectories of Q1 and Q2

Fig. 7. Simulated waveform of the double mode zero current switching switched capacitor converter

5. EXPERIMENTAL VERIFICATION

5.1 Specification

An outline specification for a prototype double-mode switched capacitor converter is given below:

$V_s = 50V$
$f_s = 200kHz$
$V_o = 100V$
$R_L = 16\text{-}100\Omega$

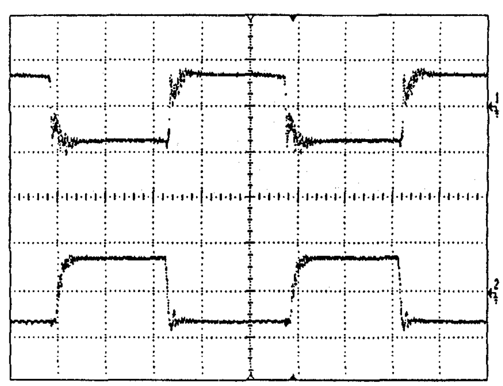
The voltage ratings of the switching devices and diodes are V_s. Power MOSFET and schottky diode are chosen. The capacitors are polypropylene. Electrolytic capacitor, because of the high ESR, cannot be used for the capacitor, especially for C_1. The resonant inductor is an air-core toroid. The components used are given below:

$L_r = 0.1\mu F$
$C_1 = 2.2\mu F$
$C_2 = 2.7\mu F$

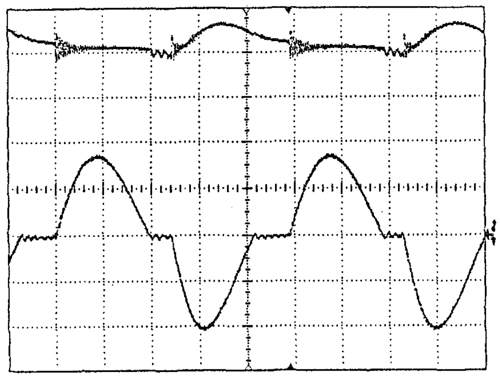
5.2 Steady-state results

Waveforms for the prototype circuit under steady-state conditions are shown in Fig. 8. It can be seen that it agrees with the simulated waveform as shown in Fig. 7. Some ringing effect occurs in the switches when their currents are zero. This is due to the current loops are inserted in order to measure the device currents. The device currents clearly confirm the zero-current switching of the switches.

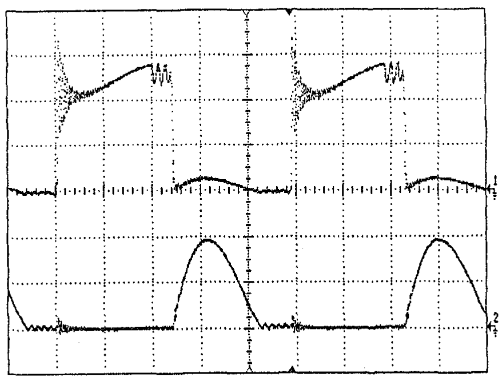
The output voltage is slightly less than twice the V_s because of the power loss in the circuit. This has been predicted in the simulated waveform as shown in Fig. 8.



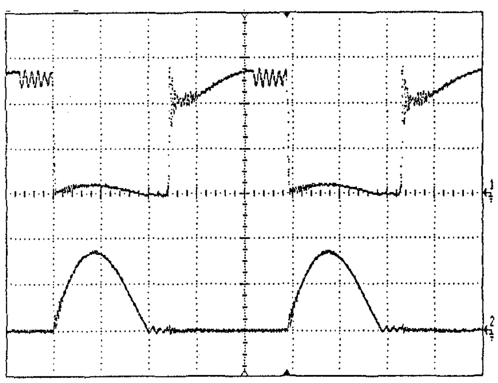
(8a) Upper: V_{GS} of Q1 (20V/div)
Lower: V_{GS} of Q2 (20V/div)



(8b) Upper: V_o (20V/div)
Lower: i_{Lr} (10A/div)



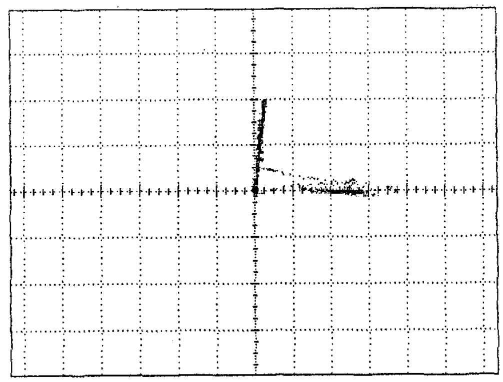
(8c) Upper: V_{DS} of Q1 (20V/div)
Lower: I_D of Q1 (10A/div)



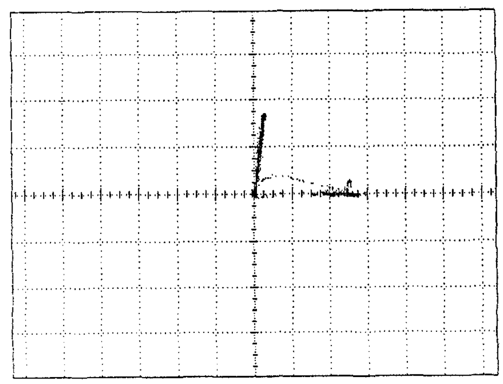
(8d) Upper: V_{DS} of Q2 (20V/div)
Lower: I_D of Q2(10A/div)

Fig. 8. Experimental waveform of the double mode zero current switching switched capacitor converter (1μs/div)

The switching i-v trajectory of Q1 and Q2 are shown in Fig 9. These again confirm that all the switching devices are zero-current switched in this new generation of the switched capacitor circuit.



(9a) Measured i-v switching trajectory of Q1



(9b) Measured i-v switching trajectory of Q2

Fig. 9. Measured i-v switching trajectory of Q1 and Q2 (Y-axis: current 10A/div, X-axis: voltage 20V/div)

It is also found that durations of State I and State III as described in Section 3 are roughly independent of load. It again comfirms the zero current criteria are true for normal load range and operation conditions.

5.3 Efficiency and conversion ratio

Typical measured efficiency and output voltage characteristics of the prototype circuit are shown in Fig. 10. It can be seen that the efficiency rises from 80% at heavy load to 92% at light load.

The output voltage varies from 78V to 96V as the load decrease from heavy to light. It should be noted that the converter is operated in open loop voltage conversion mechanism.

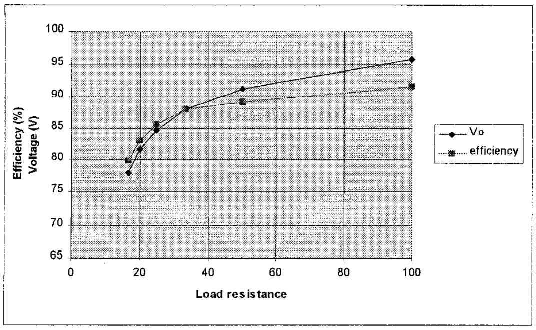


Fig. 10. Output voltage and efficiency

6. CONCLUSIONS

A family of zero-current switching switched capacitor converter is proposed in this paper. These circuits use less number of active switches and diodes when it is compared with the classical switched capacitor converters. All the devices are zero-current switching and hence it can operate at high switching frequency. The high EMI switching current has also been reduced as compared with the other switched capacitor circuits [4-6].

The family of switched capacitor circuits consists of double mode, inverting mode and half mode. Each of the circuits use only two switching devices, two diodes, one resonant inductor, one switching capacitor and one output filter capacitor. One switching device is to charge up the switching capacitor and the other one is to discharge it. The resonant inductor is usually very small and hence does not create problems of design, construction and packaging.

A prototype double mode zero current switching switched capacitor converter was constructed. Experimental results indicate that the converter is suitable for high frequency operation. All the devices are zero-current switching. The efficiency is high and the output voltage is reasonably constant even the load varies by six times. The regulation can be further improved if duty ratios of the switching devices are controlled.

This new generation of switched capacitor converters provides a practical means of realizing a power converter on a semiconductor chip. The characteristic of zero current switching minimises the loss and EMI and hence the switching frequency can be further increased and the size of capacitor can be decreased. For high power application, because of the elimination of magnetic components, the problem such as availability of high flux core, large core and the losses in the winding and core can also be eliminated.

7. REFERENCES

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