IMPROVEMENTS OF SWITCHED-CAPACITOR NETWORKS TO THE PERFORMANCE OF SWITCHING DC-DC CONVERTERS

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ABSTRACT- Three switched-capacitor(SC) networks are presented including series-parallel capacitor set, reversed-switched-capacitor network and push-pull switched-capacitor network., the performances of which are discussed. Combining the SC networks with traditional DC-DC converters, we form several new topologies. Experiment and analyzed results show that the behavior of a DC-DC converter with large voltage ratio can be improved. A wider voltage conversion range is also obtained.

1. INTRODUCTION

As for traditional switching DC-DC converters, such as buck converter and Cuk converter, the power switch has to work with a very small conducting ratio when the input voltage is quite higher than the desired output voltage. In this case, the pulse current is high and the maximum switching frequency is limited due to the small conducting ratio[1].

In another cases, when we use boost converter or Cuk converter to make a voltage step-up conversion, the conducting ratio of the power switch has to be very high when the input voltage is quite lower than the desired output voltage. Very high conducting ratio makes the losses of the converter increase greatly. It is worse that the output voltage of the converter sometimes can not reach the desired value due to the large losses[2].

Above problems are solved by replacing the single capacitor in a traditional converter with a proper switched capacitor network. Combining series-parallel capacitor set or reversed-switched-capacitor (RSC) network or push-pull switched-capacitor network with one of the traditional DC-DC converters, such as buck, boost, Cuk and buck-boost converter, respectively, one can obtain a family of new DC-DC converters.

Experiments and analyzed results indicate that for a DC-DC converter with large voltage ratio, its switching frequency and dynamic behavior can be improved when any topological form among the family is employed. Besides, a wider voltage conversion range can be also obtained.

2. THREE SWITCHED CAPACITOR NETWORKS

The three typical switched-capacitor(SC) networks are shown in Fig.1[3].

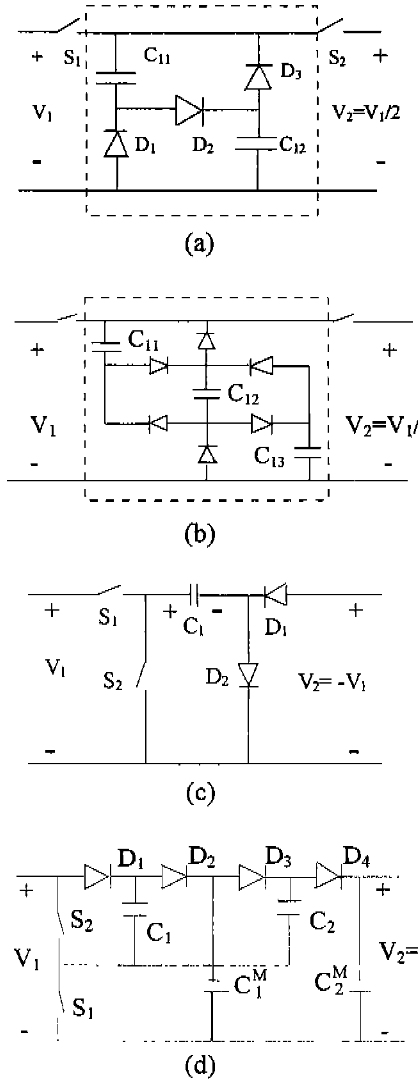

Fig.1 Structure of three SC networks
(a)2-order SP-SC network (b)3-order SP-SC network
(c)RSC network (d)2-stage push-pull SC network

S_1 and S_2 are power switches, they are turned on and off alternately, i.e., when S_1 is on S_2 must be off, when S_1 is off S_2 must be on.

Fig.1(a) and (b) show series-parallel capacitor(SP) sets with 2 order and 3 order, respectively. The order number can be defined as the number of capacitors in the a SP set. The capacitors in a SP set has the behavior of being charged in series while being discharged in parallel. Therefore, in the steady state, the output voltage V_2 and the input voltage V_1 follow Eq.(1).

$$V_2 = \frac{V_1}{n} \tag{1}$$

where, n is the order of the SP set.

Illustrated in Fig.1(c) is a reversed-switched-capacitor(RSC) network, where C_1 can be a single capacitor or a SP set. Eq.(2) describes the relationship of the input voltage and output voltage for a RSC with a n-order SP set.

$$V_2 = -\frac{V_1}{n} \tag{2}$$

A push-pull switched-capacitor network is shown in Fig.1(d), where, C_i can be a single capacitor or a SP set, C_i^M is called the intermediate capacitor, it is usually a single capacitor with a rather large value. The number of the intermediate capacitors in one push-pull switched-capacitor network is called the stage of the structure. The behavior of a m-stage push-pull switched-capacitor network is described as Eq.(3)[4].

$$\frac{V_2}{V_1} = \frac{1+\sum_{i=1}^{m}\prod_{j=1}^{i} n_j}{\prod_{i=1}^{m} n_i} \tag{3}$$

where, n_i is the order of the i-th SP set, i.e., C_i.

3. IMPROVED DC-DC CONVERTERS WITH SWITCHED CAPACITOR NETWORKS

Combining the SC networks with traditional DC-DC converters, we form several new topologies as shown in Fig.2 and Fig.3, respectively.

The performance of the new family of SC based DC-DC converters are analyzed in the cases of Continuous Conducting Mode(CCM) and Discontinuous Conducting Mode(DCM), respectively, with the results summarized in Table 1[4]. that the performance of DC-DC converters with

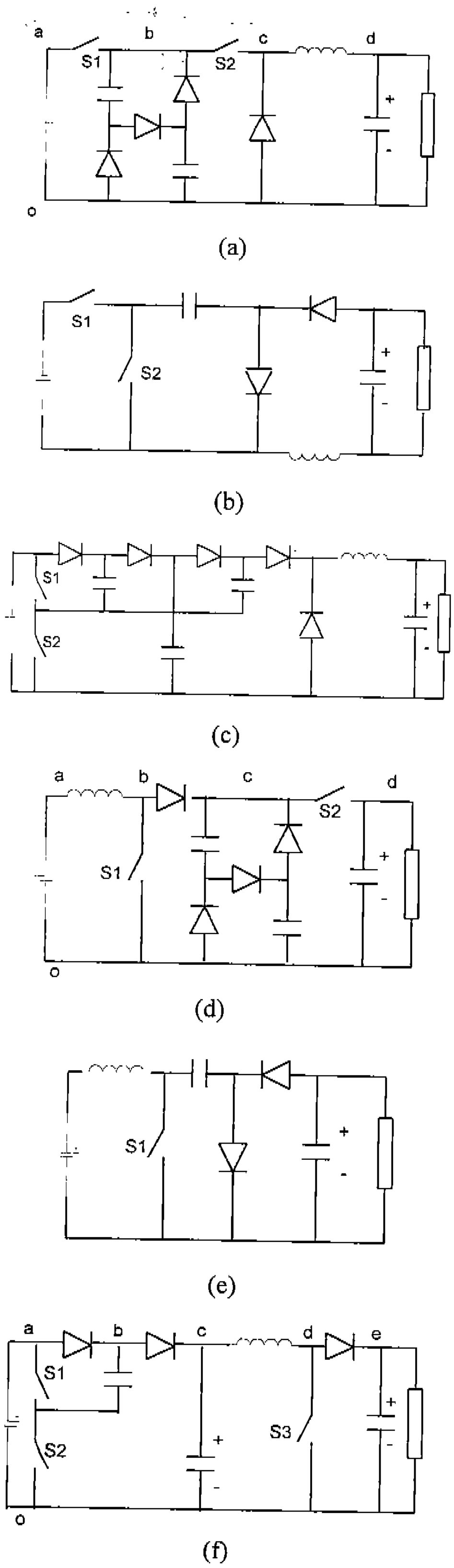

Fig. 2 SC based buck and boost DC-DC converters (a)SP-SC buck (b)RSC buck (c)push-pull SC buck (d)SP-SC boost (e)RSC boost (f)push-pull SC boost

large voltage ratio can be improved. A wider voltage conversion range and a better dynamic behavior is also obtained. Some of the experiment results are shown in Fig.3.

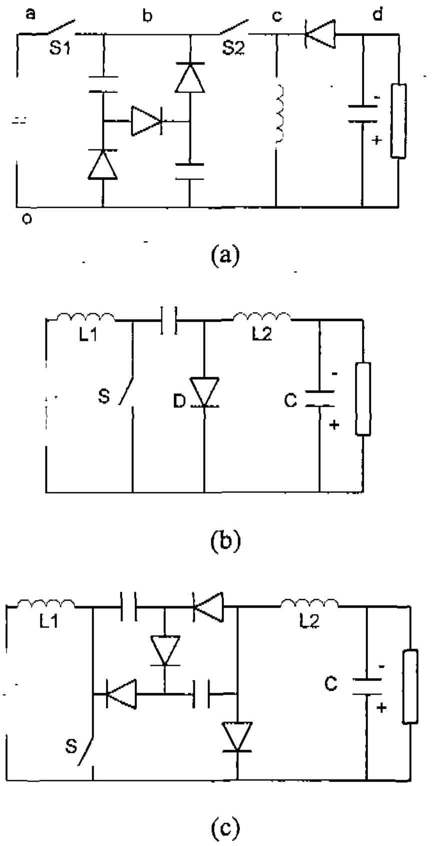

Fig. 3 SC based buck-boost and Cuk DC-DC converters (a)SP-SC buck-boost (b)RSC buck-boost (c)SP-SC Cuk

4. EXPERIMENTS

Fig.4(a) and (b) show the experiment results of a 2-order SP-SC buck DC-DC converter and a 2-order SP-SC Cuk DC-DC converter, respectively.

In the SP-SC buck prototype, S_1 is a P-MOSFET IRF9530, S_2 is a N-MOSFET IRF540. Therefore, the driving circuit is simplified. The diodes are Schottky rectifiers SR150. L is 32μH. The capacitors in the SP set are 33μF, respectively. The output capacitor is 100 μF. The ESR of each capacitor is less than 0.06 Ω. The switching frequency is 60 kHz.

In the SP-SC Cuk prototype, S_1 is a N-MOSFET IRF540. The diodes are Schottky rectifiers SR150. L_1 is 360μH. L_2 is 128μH. The capacitors in the SP set are 47μF, respectively. The output capacitor is 100 μF. The ESR of each capacitor is less than 0.06 Ω. The switching frequency is 100 kHz.

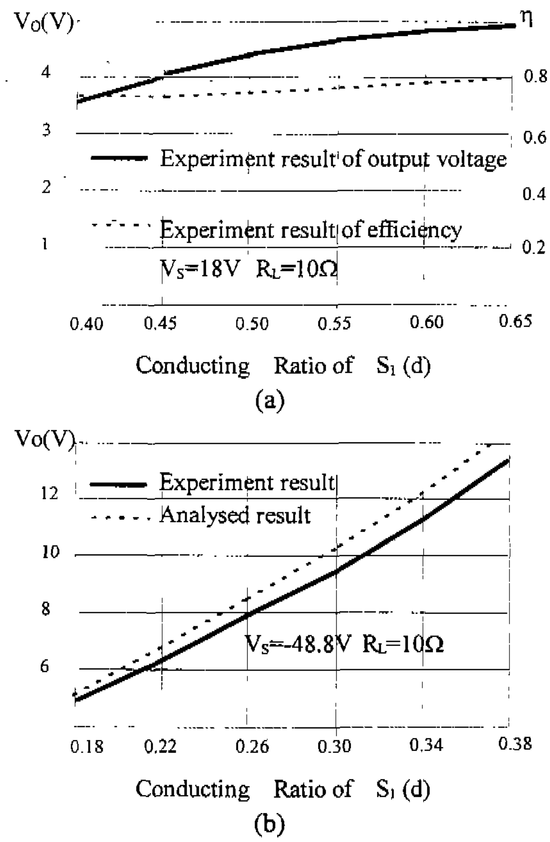

Fig.4 Experiment results of a 2-order SP-SC buck converter (a) and a 2-order SP-SC Cuk converter (b)

5. CONCLUSION

A SP-SC network can improve the performance of a step-down DC-DC converter with a large conversion ratio. A RSC network can reverse the output voltage. A push-pull SC network can improve the performance of a step-up DC-DC converter with a large conversion ratio.

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Table 1 Performance of SC based switching DC-DC converters

Converter Types		$M = V_o / V_S$	Duty ratio	Mode
buck based	buck	D	D=M	CCM
		$\frac{2}{[1+\sqrt{1+\frac{4k}{D^2}}]}$	$D = 2\sqrt{\frac{K}{(\frac{2-M}{M})^2 - 1}}$	DCM
	SP-buck	D_2 / N	D_2=NM	CCM
		$\frac{2}{[1+\sqrt{1+\frac{4k}{D_2^2}}]N}$	$D_2 = 2\sqrt{\frac{K}{(\frac{2-MN}{MN})^2 - 1}}$	DCM
	RSC-buck	$-D_2{}^2$	$D_2 = -M$	CCM
		$\frac{-2}{[1+\sqrt{1+\frac{4k}{D_2^2}}]}$	$D_2 = 2\sqrt{\frac{K}{(\frac{2+M}{M})^2 - 1}}$	DCM
	Push-Pull buck	$(m+1)D_2^2$	$D_2 = M/(m+1)$	CCM
		$\frac{2m+2}{1+\sqrt{1+\frac{4k}{D_2^2}}}$	$D_2 = 2\sqrt{\frac{K}{(\frac{2m+2-M}{M})^2 - 1}}$	DCM
boost based	boost	$1/1-D$	$D_1 = 1 - 1/M$	CCM
		$(1+\sqrt{1+4D^2/K})/2$	$D_1 = \sqrt{KM(M-1)}$	DCM
	SP-boost	$\frac{1}{N(1-D_1)}$	$D_1 = 1 - \frac{1}{MN}$	CCM
		$\frac{1+\sqrt{1+4D_1^2/K}}{2N}$	$D_1 = \sqrt{KMN(MN-1)}$	DCM
	RSC-boost	$-\frac{1}{1-D_1}$	$D_1 = 1 + \frac{1}{M}$	CCM
		$-\frac{1+\sqrt{1+4D_1^2/K}}{2}$	$D_1 = \sqrt{KM(M+1)}$	DCM
	Push-Pull boost	$\frac{m+1}{1-D_3}$	$D_3 = 1 - \frac{m+1}{M}$	CCM
		$\frac{(m+1)(1+\sqrt{1+4D_3^2/K})}{2}$	$D_3 = \sqrt{K\frac{M}{m+1}(\frac{M}{m+1} - 1)}$	DCM
buck-boost based	buck-boost	$D/(1-D)$	$D_2 = M/(1+M)$	CCM
		$D/\sqrt{K}$	$D_2 = M\sqrt{K}$	DCM
	SP buck-boost	$\frac{D_2}{N(1-D_2)}$	$D_2 = \frac{MN}{1+MN}$	CCM
		$D_2/N\sqrt{K}$	$D_2 = MN\sqrt{K}$	DCM
Cuk based	Cuk	$\frac{D}{1-D}$	$D = \frac{M}{1+M}$	CCM
		$D/\sqrt{K_e}$	$D = M\sqrt{K_e}$	DCM
	SP-Cuk	$\frac{D}{N(1-D)}$	$D = \frac{MN}{1+MN}$	CCM
		$D/N\sqrt{K_e}$	$D = MN\sqrt{K_e}$	DCM

Note: $K = \frac{2L}{R_L T_s}$, $Ke = 2(L_1//L_2)/R_L T$