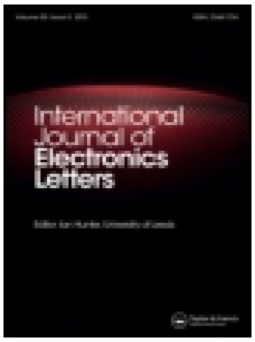

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High efficiency two-phase switched-capacitor converter with seven distinct negative voltage ratios for power saving applications

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ABSTRACT

In this letter, a reconfigured switched-capacitor converter (SCC) is proposed that is capable of achieving seven negative voltage conversion ratios (VCRs) using only three flying capacitors and minimum number of switches. The proposed converter is used to drive a white-LED backlight (WLB) in cellular phones for various backlight conditions. The negative VCR is realized with a single-input single-output structure using 10 CMOS switches and three flying capacitors. The reconfigured SCC has an advantage of choosing buck/boost voltages to drive the WLBs for various black light conditions. The proposed converter is tested experimentally with a low input voltage of 10 mV to 0.5 mV, and it maintains a high efficiency of 85%-95% with an output voltage that varies from −1 mV to −0.1 V.

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KEYWORDS
Negative Switched-capacitor Converter (NSCC); inductorless converters; DC-DC switched-capacitor converters; charge pump white-LED backlight applications

1. Introduction

Charge pump (CP) is a voltage regulator which converts positive/negative dc-dc voltages. White-LED (WLED) Burgyan and Prinz (2004) provides an ideal backlight colour display for cellular phones and electronic displays. The WLED drivers can be designed using switched capacitor converter (SCC) or a switched inductor converter (SIC). Obviously, SIC is bulky size, high cost and consumptions of more space for on-chip fabrication Richardson (2007). Therefore, reconfigured SCC is employed in this paper. The reconfigured, Negative switched-capacitor converter (NSCC) is used for varying the backlight in cellular phones when phones are in idle conditions Subburaj et al. (2018). A few real-time commercial products of NSCCs is available in the market. TLC555 switched converter is used to protect the reverse voltages which is developed by Texas. Indeed, basic diodes can be used for limiting the reverse voltage but it causes voltage drop and provides low efficiency. On the other hand, Analogue devices developed a charge pump (LT3260) which is used to operate both positive/negative voltages for low power applications. Recently, voltage doubler circuit is designed by MAXIM. Moreover, inverted variable voltage regulator (MAX1673) is developed using fixed frequency control. Shin, Hong, and Kwon (2018) proposed a buck-boost negative converter for organic LEDs

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(OLEDs) to operate for a wide load and various current range using inductors and capacitors. Generalized switched capacitor analysis is discussed in Butzen and Steyaert (2018) using voltage domain analysis. The method to find coefficients for R_{eq} (square of the ratio between the topology current and output current) was developed in my Kushnerov (2010); Kushnerov and Ben-Yaakov (2011) and the detailed analysis of inverted SCC are discussed in Subburaj et al. (2018). In this paper, a reconfigured NSCC is proposed using a series-parallel structure. The proposed converter provides seven distinct voltage conversion ratios (VCRs) with only two flying capacitors and 10 switches. The validation of the proposed converter has been confirmed by mathematical, simulation and hardware prototype results. Those results are in good agreement to each other for different input voltages and load conditions.

2. The reconfigured generalized NSCC

The schematic and model of NSCC is depicted in Figure 1. The converter uses only 10 switches and three capacitors Mahnashi and Peng (2017). ϕ_1 and ϕ_2 are non-overlapping 50% duty cycle clocks, where ϕ_1 and ϕ_2 are charging/discharging the capacitors. The voltage conversion ratio (VCR) of the negative outputs can be quantified and the proper boundary for NSCC is defined: $-Q/S; 1 \leq max|Q, S| < F_{i+2}$

where Q and S follow Fibonacci series, and F_i is a Fibonacci number. The number of converter stages is selected accordingly. i.e. F_{i+2} where i denotes the number of flying capacitors. Mahnashi and Peng (2017) discussed negative VCRs (−1, −1/2, −2) using two capacitors and multiple inputs. In the proposed work, seven VCRs are achieved using only three capacitors. To generate the negative VCRs, the flying capacitors (C_1 to C_3) are connected to the negative terminal and disconnected via positive terminal. In Table 1, the look-up-table of seven negative VCRs is presented. For each state, individual switching sequence is selected to control the CMOS switches. For simplicity, the fifth and sixth option are considered to illustrate the operation. For the fifth option, switches 2, 3 and 8 are connected to charge the flying capacitors in negative direction and discharge them using switches 1, 4, 5, 6 and 9.

The equivalent circuits of charging and discharging operations for the fifth option are shown in Figure 2(a) and (b), where bidirectional switches are closed. The average capacitor current in charging and discharging phase is connected to the I_o, given by, Abraham et al. (2017). During charging ($R_{\phi_{c1}}$) and discharging ($R_{\phi_{t2}}$) period, equivalent resistance R_{eq} is given by:

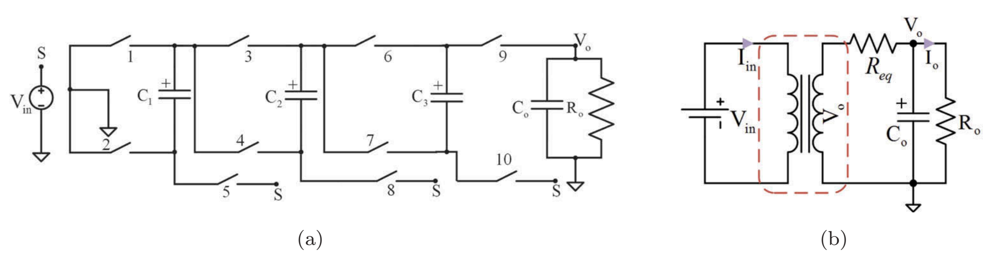


Figure 1. The NSCC: (a) circuit implementation, adapted from Mahnashi and Peng (2017), (b) state model, adapted from Abraham et al. (2017).

Table 1. Negative voltage ratios.

		Switches									
States	VCRs	1	2	3	4	5	6	7	8	9	10
1	$-1/2 * V_{in}$	ϕ_1	ϕ_2	1	–	ϕ_1	1	0	1	ϕ_2	Φ_1
2	$-1/3 * V_{in}$	ϕ_1	ϕ_2	1	–	ϕ_1	1	–	1	ϕ_2	1
3	$-1/4 * V_{in}$	ϕ_1	ϕ_2	ϕ_2	ϕ_1	ϕ_1	ϕ_1	ϕ_2	–	ϕ_2	Φ_1
4	$-1 * V_{in}$	ϕ_1	ϕ_2	ϕ_2	–	ϕ_1	ϕ_2	–	–	ϕ_2	–
5	$-2 * V_{in}$	ϕ_1	ϕ_2	ϕ_2	ϕ_1	Φ_1	ϕ_1	–	ϕ_2	ϕ_1	–
6	$-3 * V_{in}$	ϕ_1	ϕ_2	ϕ_1	ϕ_2	ϕ_1	ϕ_1	ϕ_2	ϕ_1	ϕ_2	ϕ_1
7	$-4 * V_{in}$	ϕ_1	ϕ_2	ϕ_2	ϕ_1	ϕ_1	ϕ_1	ϕ_2	ϕ_2	ϕ_2	ϕ_1

$$R_{\phi_{c1}} = \frac{\coth\left(\frac{2}{(3R_d+2ESR)C}\right)}{2Cf} \tag{1}$$

$$R_{\phi_{t2}} = \frac{\coth\left(\frac{C+C_o}{(5R_d+2ESR)CC_o}\right)}{4Cf} \tag{2}$$

Combining (1) and (2), as in Abraham et al. (2017), we obtain the total R_{eq} . Using, R_{eq} and Figure 1(b), V_o can be calculated. Table 2 shows the calculated values of V_o for different switching frequencies for the fifth option.

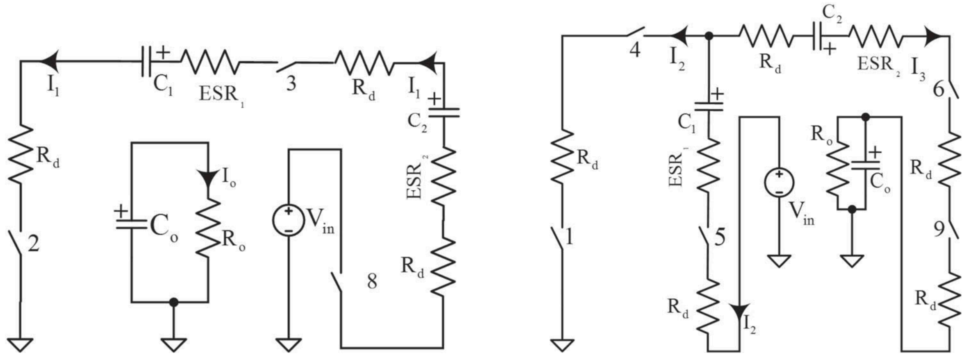
3. Results and discussion

The proposed converter is validated using MAX4567 switches with turn-on resistance, (R_d), of 0.3 Ω. For the capacitors, 22 μF flying capacitors and 220 μF output capacitor are used, with ESR equals to 100 mΩ. The load current varies between 0.01 μA to 1 μA. PIC16F controller is used for generating the switching pulses for bidirectional switches, and a small LCD display is used to show the current state of the VCRs. Figure 3 shows the comparison between experimental, the theoretical (model), and simulation results for different inputs and two different states. Figure 4(a) A shows the overall prototype of the proposed NSCC test bench. Implementation results for the fifth option with different load conditions are shown in Figure 4(b), where the V_{in} and V_o are $\approx$ 0.01 V and –0.019 V. Similarly, voltage ripple is shown in Figure 4(b). It can be seen that the simulation and experimental results are in good agreement with the proposed model.

On the other hand, experiment testing for the sixth option is also performed and shown in Figure 4(a) B, where the V_{in} and V_o are 16 mV and –40 mV. It shows a good agreement with the expected value, i.e. ($-3 * V_{in}$), even at maximum load. Comparison of all output voltage VCRs model, simulated and hardware results are discussed in Figure 5 and one can notice that all the results are close to each other. Efficiency and output voltage are plotted for various load conditions for the sixth option. NSCC has the capability to withstand maximum load where the efficiency is almost 80 % as shown in Figure 6. Table 2 provides the simulation and hardware

Table 2. NSCC performance with different switching frequencies.

f (Hz)	$R\phi_{c1}$	$R\phi_{t2}$	R_{eq}	V_o model	V_o simulation	V_o hardware	η
100k	0.12	0.54	0.668	–0.02	–0.0198	–0.019	95%
50k	0.22	0.962	1.19	–0.02	–0.019	–0.018	90%
10k	1.136	4.77	5.9	–0.019	–0.018	–0.017	85%



(a) Charging Phase ϕ_1 (b) Discharging Phase ϕ_2

Figure 2. The equivalent circuit of the proposed converter for the fifth option.

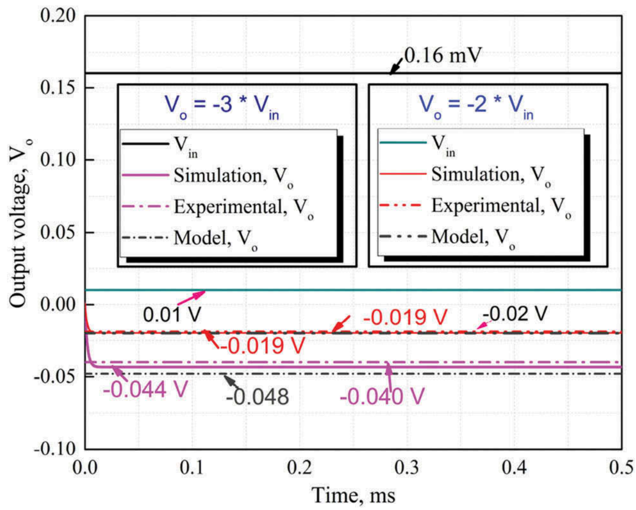
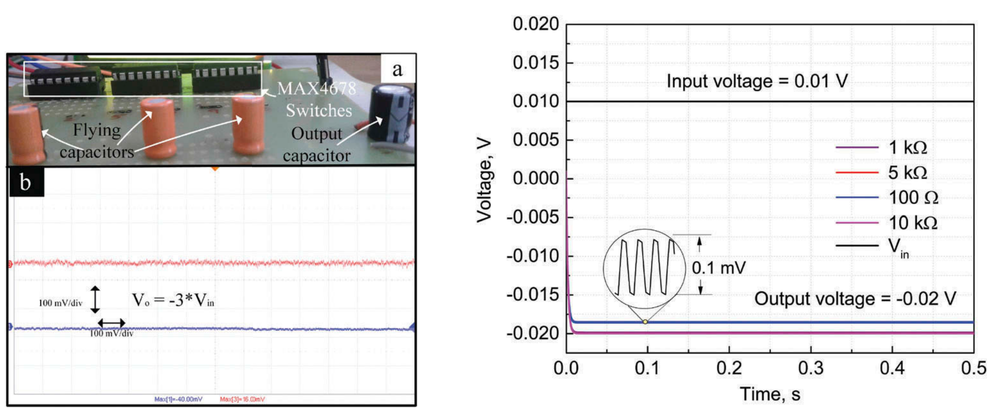


Figure 3. Comparison between experiment, simulation and model results for fifth and sixth states.



(a) Overall prototype. (b) Load variation and ripple of NSCC

Figure 4. The experimental results for the 5^{th} and 6^{th} states.

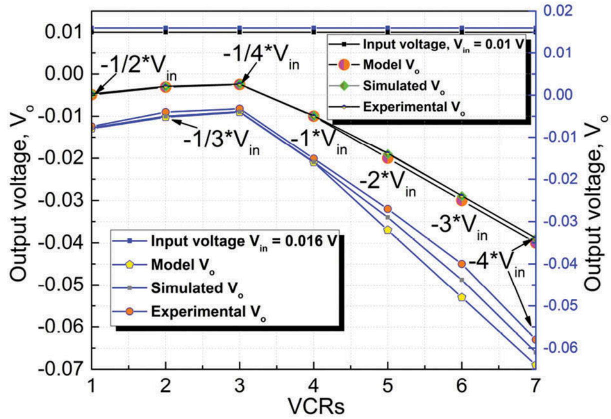


Figure 5. Comparison between the theoretical, simulated and experimental results.

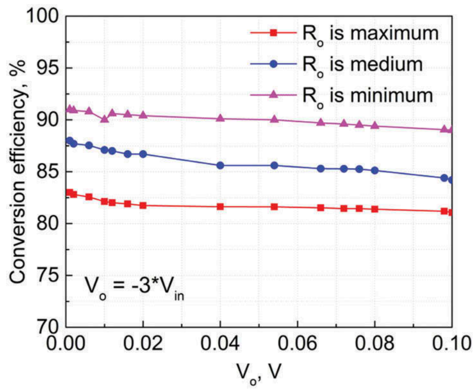


Figure 6. The efficiency versus the output voltage for different load conditions for the sixth state.

Table 3. Comparison with different NSCC.

Parameters	Shin et al. (2018)	Mahnashi and Peng (2017)	This work
VCR	–	4	7
Input voltage, V_{in}	1.8 V	1 V	maximum 0.5 V
Output voltage, V_o	−4 V	−1, 1, 2	maximum −1.5 V
Frequency, kHz	500	500	100
Flying capacitors	Nil	2	3
Efficiency	81.9%	Nil	85–95%

results for the fifth option. It validates the efficiency of the proposed converter at different switching frequencies. Finally, the comparison results of recent works related to NSCC are discussed in Table 3.

4. Conclusion

Negative converters are mostly used in cellular phones in changing the backlight for improving the battery life. This proposed NSCC is capable of controlling the dim lighting for cellular devices by providing negative voltages. Compared to all NSCC circuits, the reconfigured NSCC provides peak efficiency and generates maximum VCRs. The proposed NSCC is designed using only 10 CMOS bidirectional switches and three capacitors which provides seven VCRs and achieves high efficiency.

Disclosure statement

No potential conflict of interest was reported by the authors.

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