SWITCHED-CAPACITOR POWER CONVERTERS*
(BASICS AND OVERVIEW)

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Summary *- A brief theoretical background of the switched-capacitor power conversion is presented. The known-by-now switched-capacitor power converters are classified. Several representative examples are presented and the mostly used methods for their analysis are pointed-out.*

1. INTRODUCTION

"Once upon a time" in 1987 one of the rare switched-capacitor power converter ICs was Intersil's unregulated voltage inverter/doubler ICL7660. Soon, in the decade 1990/2000, Linear Technology alone offered eight IC families of unregulated and regulated switched-capacitor power converters (10xx, 11xx, 12xx, 14xx, 15xx, 16xx, 17xx, 32xx) [1]. They are aimed for supplying battery powered equipment (cellular phones, pagers, handheld medical instruments), PCMCIA local supply, smart card readers and battery back up supplies (NiMH or Li-Ion). Their wide application in miniature electronic equipment is a strong motivation for studying these converters (configurations, characteristics, and regulation) and also for exploring new applications.

2. THE CIRCUIT THEORY FUNDAMENTALS

Deeper understanding of the operation of switched-capacitor power converters (SCPC) needs reexamining of some basic phenomena concerning charging and discharging of capacitors.

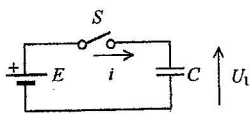

Fig. 1. Ideal voltage generator and ideal switch

2.1 Ideal capacitor charged from ideal voltage source through ideal switch

Let a capacitor C with voltage U_1 be connected to an ideal voltage source with EMF E ($>U_1$) (Fig. 1). It can easily be shown [2] that the energy efficiency is:

$$\eta_W = \frac{\Delta W_C}{\Delta W_E} = \frac{E+U_1}{2E}, \qquad (1)$$

where ΔW_C is the capacitor energy increase and ΔW_E is the energy drawn from the source.

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It should be noted that the energy efficiency depends solely on the voltage ratio. It will be shown later that this property is fundamental for the SCPCs.

2.2 Ideal capacitor charged from ideal voltage source through ideal current conveyer

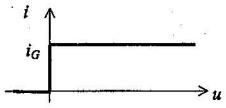


Fig. 2. *U-I* characteristic of the current conveyer

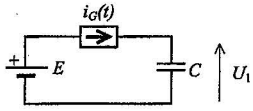


Fig. 3. Ideal EMF source and current conveyer

Let a capacitor C with voltage U_1 be connected to an ideal voltage source with EMF E ($>U_1$) through a current conveyer (e.g. ideal transistor with current-voltage characteristics as in Fig. 2) with current $i_G(t)$ (Fig. 3) during time interval T, and let it's voltage change to value U_2.

Again the energy-transfer efficiency depends solely on the voltages ratio [2]:

$$\eta_W = \frac{\Delta W_C}{\Delta W_E} = \frac{U_1 + U_2}{2E}. \tag{2}$$

Since the waveform of the current is irrelevant in the previous equation [2], an exponential current waveform can be applied. In this case the current conveyer behaves as a resistor, so charging through current conveyer is a general case that includes the charging through a resistor.

2.3 Charging ideal capacitor from ideal capacitor through ideal switch

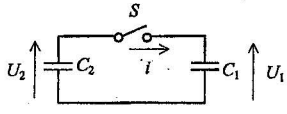


Fig. 4. Capacitor-to-capacitor charging

Let a capacitor C_1 with voltage U_1 be connected to a capacitor C_2 with voltage U_2 through ideal switch (Fig. 4). Let the voltage after connection be U. The efficiency now is:

$$\eta_W = \frac{\Delta W_{C1}}{-\Delta W_{C2}} = \frac{1+u+2ru}{2+r+ru}, \tag{3}$$

where $u = \frac{U_1}{U_2} \in [0,1]$ and $r = \frac{C_1}{C_2} \in (0,\infty)$.

The function $\eta_W(u)$ with r as parameter is shown in Fig. 5. The diagram shows weak dependence of the efficiency on capacitance ratio and strong dependence on the voltage ratio. And more: at voltage ratios greater than 0.7 the efficiency is nearly independent on capacitance ratio and is higher than 80%.

Generally:

1. The energy losses in SCPC are inevitable even with ideal components.
2. The energy losses are predominantly dependent on the voltage difference in the charge-transfer path.

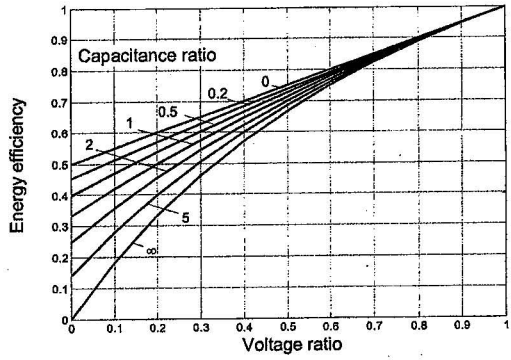


Fig. 5 Energy efficiency for capacitor-to-capacitor charging

3. SCPC CLASIFICATION

Depending on input and output quantities there are:

1. DC voltage/current to DC voltage/current converters [3-6],
2. AC voltage/current to DC voltage/current converters [7],
3. DC voltage/current to AC voltage/current converters [8,9],
4. AC voltage/current to AC voltage/current converters [10, 11].

Depending on the input quantity there are two SCPC categories:

- voltage-to-voltage converters,
- current-to-current converters.

The first category draws the charge directly from the voltage source while the second one does it through a current conveyer. Although in the literature both categories are treated with voltage output, the author insists that the second one has actually a current output as a direct consequence of the charge balance principle.

Depending on the regulation SCPC can be classified as:

- unregulated SCPC or so called SC-transformers, [3]
- regulated SCPC, which can be by:
  - frequency modulation [2],
  - pulse-width modulation [4,6],
  - current modulation [5],
  - resistance modulation [3].

Depending on the number of steps in one cycle (number of states of the converter during one cycle) SCPC can be:

- two-step,
- multistep, [13]
- quasi-multistep (actually two-step with interstates).

Depending on the configuration SCPCs can have the following voltage ratios:

- whole number step-up ($\pm n$ where n is natural number) – also known as voltage multipliers,
- whole number step-down ($\pm 1/n$ where n is natural number),
- fractional ratio ($\pm m/n$ where m and n are natural numbers). [6]

Two-step DC-to-DC SCPC can be:

- optimal on capacitor number (Fibonacci), [12]
- with series-parallel capacitor connections (or classical).

4. SCPC EXAMPLES

4.1 DC-to-DC SCPC

The most interesting classical DC-to-DC SCPCs are: the voltage halver, the voltage doubler and the inverter [3]. They are shown in Fig. 6 together with their switch-control waveforms.

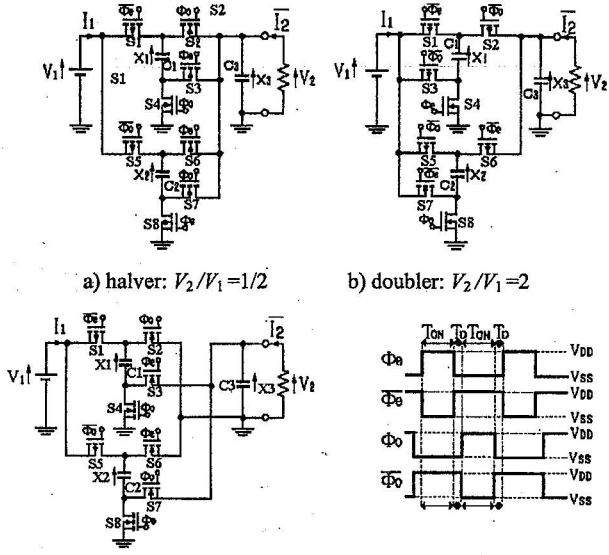


Fig. 6 Symmetrical DC-to-DC voltage transformers

The analysis is performed by solving the state equations. With all capacitors C equal and switch-resistance r_{on} equal, the average output voltage for the voltage halver is:

$$\overline{V}_2 = \frac{V_1}{2}\frac{R_L}{R_L + r_{on}/2D}. \tag{4}$$

This shows that the converter behaves at the output as voltage source with EMF=$V_1/2$ and internal resistance $r_{on}/2D$, where D is the duty cycle. Similarly it can be shown that the voltage doubler has EMS=$2V_1$ and internal resistance $2r_{on}/D$ while the inverter has EMF=$-V_1$ and internal resistance $2r_{on}/D$.

The (power) efficiency can be determined by applying the charge-balance method. For example, it can be shown [2] that the average input and output currents of the voltage halver satisfy the relation:

$$\overline{I}_2 = -2\overline{I}_1, \tag{5}$$

from where it follows:

$$\eta = \frac{P_2}{P_1} = \frac{R_L \overline{I}_2^2}{V_1 \overline{I}_1} = 2\frac{-R_L \overline{I}_2}{V_1} = 2\frac{\overline{V}_2}{V_1}, \tag{6}$$

This shows that the efficiency is as close to 100% as is the output voltage closer to the value for unloaded converter. Output voltage regulation (at any lower value [4]) inevitably reduces the efficiency.

4.2 AC voltage SCPC

Little research has been done by now with these converters probably due to:

- hudge number of well known rectifiers (for AC-to-DC conversion) and impossibility to obtain good galvanic isolation from the power source with SCPC;
- very complex structures needed to synthesize sine-wave (DC-to-AC converters);
- both of the previous reasons for AC-to-AC conversion.

Nevertheless, if galvanic isolation is not mandatory, and the complexity can be accepted (integrated circuit) these converters can be applied.

Fig. 7 is an example of an AC SCP inverter for electrolumminiscent light [8].

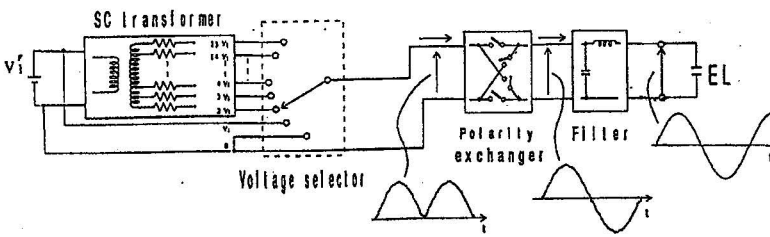
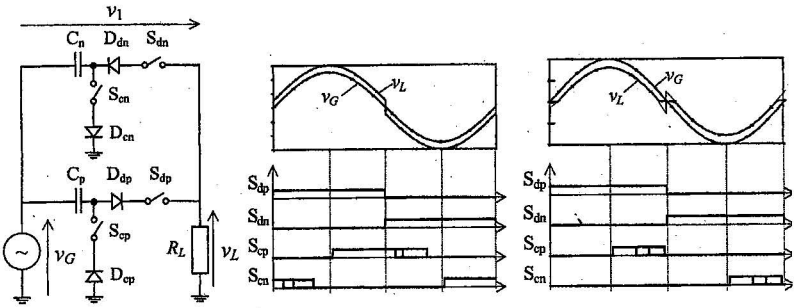


Fig. 7 Block-diagram of an DC-to-AC SCPC for electroluminiscent light

The simplest AC voltage SCP regulator (inductorless autotransformer) [11] is shown in Fig. 8.



a) Circuit diagram b) Voltage step-up c) Voltage step-down

Fig. 8 The simplest inductorless AC autotransformer

The analytical THD equations and their numerical analysis show that the optimal capacitance value is [11]:

$$C_{OPT} \approx \frac{1.5}{fR_L}. \tag{7}$$

5. CONCLUSION

SCPCs has long been marginally researched and were a little bit exotic circuits in power electronics. Nevertheless, in the latest decade this has changed significantly. A plethora of configurations, analysis and design methods, voltage or current regulation methods, are open research fields. Therefore, the basic theoretical knowledge of their fundamental limitations is mandatory.

6. LITERATURE

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