A New Visit to an Old Problem in Switched-Capacitor Converters

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***Abstract*—The energy-efficiency issue of the switched-capacitor converters is still a highly controversial topic that requires a more in-depth exploration. This paper will address the issue by dissecting the analysis of the entire efficiency problem into two parts. In the first part, the efficiency analysis of charging the capacitor of an RC circuit under different aspects (partial charging, full charging, at zero capacitor voltage, at non-zero capacitor voltage, etc.) will be conducted. In the second part, the efficiency analysis of discharging the capacitor of an RC circuit with resistive and capacitive loads will be covered. A complete evaluation of the overall efficiency is then performed in terms of both the charging and discharging efficiencies of the capacitor. Additionally, it is shown in this paper that the claim that quasi-switched-capacitor converters are more lossy than switched-capacitor converters is a common misconception.**

I. INTRODUCTION

The overall energy efficiency of the switched-capacitor (SC) circuits and converters is frequently discussed and debated by many researchers [1]-[12]. Careful review of the literature shows that there are still many contradictory viewpoints and discrepancies on the issue. For example, in [3], it is claimed that a higher efficiency could be obtained by reducing the turn-on resistance $R_{\mathrm{DS(on)}}$ of MOSFETs. In [4], it is emphasized that the insertion of a series sensing resistor could result in large power loss. In [5], it is argued that by operating the MOSFET device of an SC converter in the active region, a constant current source is created to charge the capacitor and the converter becomes a quasi-switched-capacitor (QSC) converter [6], [7], will lead to the converter being highly inefficient.

On the other hand, the discussion in [8] reflected that efficiency is resistance-independent and that the efficiency of QSC converter is the same as that of the conventional SC converter. Moreover, against conventional understanding that power loss is caused mainly by resistance and hard-switching actions, there are also controversial claims that a bigger capacitance and a higher switching frequency can improve the overall efficiency of SC converter [9]. Also worth mentioning is that while many power-electronics practitioners still believe that SC converters are but a class of highly inefficient converters, the IC manufacturing companies are contradicting this belief by producing SC converter ICs of an extremely high efficiency of up to 98% [13].

In this paper, we attempt to address these issues by systematically analyzing from a circuit and then a system perspective, the efficiency of each individual component of the RC circuit, in the charging operation, the discharging operation, and then the entire charging-discharging operation. The discussion considers the different aspects of the operating conditions possible and pinpoints the main difference in efficiency between these aspects. Conclusive remarks on how high-efficiency SC converters can be obtained will be provided.

II. EFFICIENCY OF RC CHARGING CIRCUITS

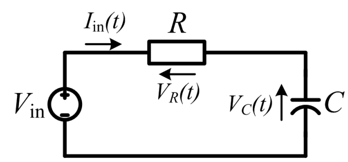


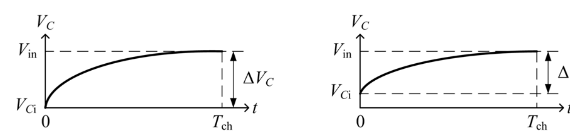
Fig. 1. An equivalent circuit of the charging process.

In SC converters, the charging circuit contains only power switches and flying capacitors, which can be equivalently represented by an RC circuit [10], [11] (see Fig. 1). The instantaneous voltages and current can be given by

$$\begin{cases} V_C(t) &= (V_{\mathrm{in}} - V_{C\mathrm{i}})(1 - e^{\frac{-t}{RC}}) + V_{C\mathrm{i}} \\ V_R(t) &= V_{\mathrm{in}} - V_C(t) \\ I_{\mathrm{in}}(t) &= \frac{V_{\mathrm{in}} - V_{C\mathrm{i}}}{R}\left(e^{\frac{-t}{RC}}\right) \end{cases} . \quad (1)$$

The energy profile and efficiency of this circuit can be classified into two categories – full charging and partial charging.

A. *Efficiency of Full-Charging RC Circuit*



(a) $V_{C\mathrm{i}}$ = 0 V (b) 0 V $< V_{C\mathrm{i}} < V_{\mathrm{in}}$

Fig. 2. The capacitor voltage waveforms of a full-charging process with (a) zero initial capacitor voltage and (b) non-zero initial capacitor voltage.

In full charging, the capacitor is charged to the value of the input voltage, i.e. $V_{C\mathrm{f}} = V_{\mathrm{in}}$. The energy profile and the charging efficiency over a charging cycle can be expressed as

$$\begin{cases} \Delta E_C &= \int_0^{T_{\mathrm{ch}}} V_C(t) \cdot I_{\mathrm{in}}(t)dt = \frac{C}{2}({V_{\mathrm{in}}}^2 - {V_{C\mathrm{i}}}^2) \\ \Delta E_R &= \int_0^{T_{\mathrm{ch}}} V_R(t) \cdot I_{\mathrm{in}}(t)dt = \frac{C}{2}(V_{\mathrm{in}} - V_{C\mathrm{i}})^2 \\ \Delta E_{\mathrm{in}} &= \int_0^{T_{\mathrm{ch}}} V_{\mathrm{in}} \cdot I_{\mathrm{in}}(t)dt = CV_{\mathrm{in}}(V_{\mathrm{in}} - V_{C\mathrm{i}}) \end{cases} ; \quad (2)$$

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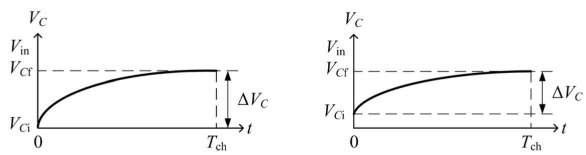
$$\eta_{\mathrm{ch(full)}} = \frac{\Delta E_C}{\Delta E_{\mathrm{in}}} = \frac{1}{2}\left(1 + \frac{V_{C\mathrm{i}}}{V_{\mathrm{in}}}\right). \tag{3}$$

The charging process can start with two different initial conditions, zero (Fig. 2(a)) or non-zero (Fig. 2(b)) initial capacitor voltage, respectively. **For $V_{C\mathrm{i}}$ = 0 V, the charging efficiency is 50%** and is independent of resistance R in the charging path, as pre-discussed in [8], [12]. However, **for $V_{C\mathrm{i}} > 0$ V, the charging efficiency will be greater than 50%**. Obviously, from (3), the best way of achieving a high charging efficiency is to keep $V_{C\mathrm{i}}$ as close to V_{in} as possible.

B. Efficiency of Partial-Charging RC Circuit



(a) $V_{C\mathrm{i}}$ = 0 V (b) 0 V $< V_{C\mathrm{i}} < V_{\mathrm{in}}$

Fig. 3. The capacitor voltage waveform of a partial-charging process with (a) zero initial capacitor voltage and (b) non-zero initial capacitor voltage.

In partial charging, the capacitor is charged to a voltage less than the input voltage, i.e. $V_{C\mathrm{f}} < V_{\mathrm{in}}$. The energy profile and charging efficiency over a charging cycle are respectively

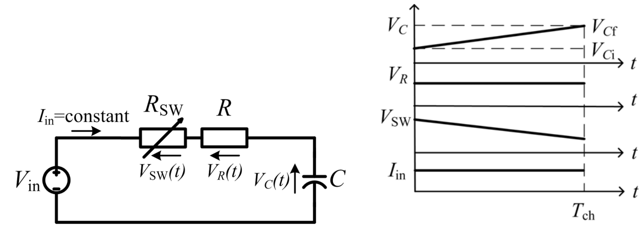
$$\begin{cases} \Delta E_C &= \int_0^{T_{\mathrm{ch}}} V_C(t)\cdot I_{\mathrm{in}}(t)dt = \frac{C}{2}({V_{C\mathrm{f}}}^2 - {V_{C\mathrm{i}}}^2) \\ \Delta E_R &= \int_0^{T_{\mathrm{ch}}} V_R(t)\cdot I_{\mathrm{in}}(t)dt \\ &= \frac{C}{2}[(V_{\mathrm{in}} - V_{C\mathrm{i}})^2 - (V_{\mathrm{in}} - V_{C\mathrm{f}})^2] \\ \Delta E_{\mathrm{in}} &= \int_0^{T_{\mathrm{ch}}} V_{\mathrm{in}}\cdot I_{\mathrm{in}}(t)dt = CV_{\mathrm{in}}(V_{C\mathrm{f}} - V_{C\mathrm{i}}) \end{cases}; \tag{4}$$

$$\eta_{\mathrm{ch(partial)}} = \frac{\Delta E_C}{\Delta E_{\mathrm{in}}} = \frac{1}{2}\left(\frac{V_{C\mathrm{i}} + V_{C\mathrm{f}}}{V_{\mathrm{in}}}\right) \approx \frac{\overline{V_C}}{V_{\mathrm{in}}}. \tag{5}$$

It can also start with a zero (Fig. 3(a)) or non-zero (Fig. 3(b)) initial capacitor voltage. From (5), for $V_{C\mathrm{i}}$ = 0 V, the charging efficiency is always less than 50% and it increases with a higher value of $V_{C\mathrm{f}}$. For $V_{C\mathrm{i}} > 0$ V, the charging efficiency can be made very high by keeping $(V_{\mathrm{in}} - V_{C\mathrm{i}})$ and $(V_{\mathrm{in}} - V_{C\mathrm{f}})$ small. This implies that $\Delta V_C (= V_{C\mathrm{f}} - V_{C\mathrm{i}})$ should also be small.

From the analysis and comparison of the charging efficiencies in the different conditions, some key points can be summarized.

- **The charging efficiency is independent of R in the charging path**. R affects only the time constant ($\tau_{\mathrm{ch}} = RC$) of the charging circuit, and the instantaneous peak current value of the charging response. Therefore, although changing R does not affect the charging efficiency, a bigger R can suppress the peak current value while lengthening the charging duration.
- 50% charging efficiency only appears under full charging with $V_{C\mathrm{i}}$ = 0 V. An efficiency lower than 50% occurs under partial charging when $V_{C\mathrm{i}} + V_{C\mathrm{f}} < V_{\mathrm{in}}$.
- **A higher charging efficiency is obtained when ΔV_C is smaller and $\overline{V_C}$ is nearer to V_{in}.**



(a) (b)

Fig. 4. (a) An equivalent charging circuit of a QSC converter and (b) its theoretical voltage and current waveforms.

III. Charging Efficiency of QSC Converters

For QSC converters, the MOSFET switch in the charging path is operated in the active region making it a constant current source [6], [7]. This is possible via the control of the gate voltage of the switch. Theoretically, the control of current flow through the switch is equivalently the control of its internal resistance. Hence, to have a constant current I_{in} flowing through the RC circuit from a constant voltage source, the resistance of the switch R_{SW} should be time-varying. Fig. 4(a) shows the equivalent charging circuit of the QSC converters. The theoretical voltage and current waveforms are given in Fig. 4(b). The instantaneous voltages and current, energy profile and the charging efficiency of QSC converters over a charging cycle can be expressed as

$$\begin{cases} V_C(t) &= \frac{V_{C\mathrm{f}} - V_{C\mathrm{i}}}{T_{\mathrm{ch}}}(t) + V_{C\mathrm{i}} \\ V_R(t) &= I_{\mathrm{in}}\cdot R \\ V_{\mathrm{SW}}(t) &= I_{\mathrm{in}}\cdot R_{\mathrm{SW}}(t) \\ I_{\mathrm{in}}(t) &= I_{\mathrm{in}} \end{cases}; \tag{6}$$

$$\begin{cases} \Delta E_C = \int_0^{T_{\mathrm{ch}}} V_C(t)\cdot I_{\mathrm{in}}dt = \frac{C}{2}({V_{C\mathrm{f}}}^2 - {V_{C\mathrm{i}}}^2) \\ \Delta E_{(R+R_{\mathrm{SW}})} = \int_0^{T_{\mathrm{ch}}} (V_R(t) + V_{\mathrm{SW}}(t))\cdot I_{\mathrm{in}}dt \\ \qquad = \frac{C}{2}[(V_{\mathrm{in}} - V_{C\mathrm{i}})^2 - (V_{\mathrm{in}} - V_{C\mathrm{f}})^2] \\ \Delta E_{\mathrm{in}} = \int_0^{T_{\mathrm{ch}}} V_{\mathrm{in}}\cdot I_{\mathrm{in}}dt = CV_{\mathrm{in}}(V_{C\mathrm{f}} - V_{C\mathrm{i}}) \end{cases}; \tag{7}$$

$$\eta_{\mathrm{ch(QSC)}} = \frac{\Delta E_C}{\Delta E_{\mathrm{in}}} = \frac{1}{2}\left(\frac{V_{C\mathrm{i}} + V_{C\mathrm{f}}}{V_{\mathrm{in}}}\right). \tag{8}$$

Three important points can be concluded.

- Even though the charging trajectories are different, with SC converters being exponential and QSC converters being linear, their charging efficiency are identical (see (5) and (8)). This is because charging efficiency is independent of R and the use of MOSFET in the active region merely alters its internal resistance, whereas its resistance is fixed at $R_{\mathrm{DS(on)}}$ when being as a static switch. Hence, **QSC converter is not more lossy than conventional SC converter**, which is consistent to the comments in [8].
- QSC converter has a flat and continuous input current flow which means that it does not generate electromagnetic radiation. However, the precise control of the current level is difficult especially for a varying output power.
- The switching loss (due to voltage-current crossing) of non-ideal "on-off" switches of conventional SC converter is also a form of time-varying resistance, R_{SW} [14]. Hence, the switching loss does not affect the overall

charging efficiency. **Application of soft-switching will not improve the charging efficiency of SC converters**.

IV. Energy Loss Distribution

Assume that R is the total equivalent resistance in the charging path and it is made up of the equivalent series resistance (ESR) of capacitor R_{ESR}, the $R_{\mathrm{DS(on)}}$, and the resistance due to switching loss R_{SW}. The total energy loss is $\Delta E_{\mathrm{Total}} = \Delta E_{R_{\mathrm{ESR}}} + \Delta E_{R_{\mathrm{DS(on)}}} + \Delta E_{R_{\mathrm{SW}}}$. Consider two charging circuits having the same $V_{C\mathrm{i}}$ and $V_{C\mathrm{f}}$ (same charging efficiency), but a different R (one is R_{eq1} and the other is R_{eq2} = $10R_{\mathrm{eq1}}$ (by increasing only R_{SW})). Hence, $\Delta E_{\mathrm{Total1}} = \Delta E_{\mathrm{Total2}}$ as the total energy loss in the charging process is independent of R. However, with R_{eq2} = $10R_{\mathrm{eq1}}$, the average current flow of each circuit will be ${I_{\mathrm{in1}}}^2 = 10{I_{\mathrm{in2}}}^2$. (9) and (10) give the energy loss in the two circuits respectively.

$$\begin{cases} \Delta E_{\mathrm{Total1}} = \Delta E_{R_{\mathrm{ESR1}}} + \Delta E_{R_{\mathrm{DS(on)1}}} + \Delta E_{R_{\mathrm{SW1}}} \\ \Delta E_{R_{\mathrm{ESR1}}} = \int_0^{T_{\mathrm{ch}}} {I_{\mathrm{in1}}}^2(t) \cdot R_{\mathrm{ESR}} dt \\ \Delta E_{R_{\mathrm{DS(on)1}}} = \int_0^{T_{\mathrm{ch}}} {I_{\mathrm{in1}}}^2(t) \cdot R_{\mathrm{DS(on)}} dt \\ \Delta E_{R_{\mathrm{SW1}}} = \Delta E_{\mathrm{Total1}} - \Delta E_{R_{\mathrm{ESR1}}} - \Delta E_{R_{\mathrm{DS(on)1}}} \end{cases} \tag{9}$$

$$\begin{cases} \Delta E_{\mathrm{Total2}} = \Delta E_{R_{\mathrm{ESR2}}} + \Delta E_{R_{\mathrm{DS(on)2}}} + \Delta E_{R_{\mathrm{SW2}}} \\ \Delta E_{R_{\mathrm{ESR2}}} = 0.1 \int_0^{T_{\mathrm{ch}}} {I_{\mathrm{in1}}}^2(t) \cdot R_{\mathrm{ESR}} dt \\ \Delta E_{R_{\mathrm{DS(on)2}}} = 0.1 \int_0^{T_{\mathrm{ch}}} {I_{\mathrm{in1}}}^2(t) \cdot R_{\mathrm{DS(on)}} dt \\ \Delta E_{R_{\mathrm{SW2}}} = \Delta E_{\mathrm{Total1}} - 0.1(\Delta E_{R_{\mathrm{ESR2}}} + \Delta E_{R_{\mathrm{DS(on)2}}}) \end{cases} \tag{10}$$

It can be shown that the loss in both R_{ESR} ($\Delta E_{R_{\mathrm{ESR}}}$) and $R_{\mathrm{DS(on)}}$ ($\Delta E_{R_{\mathrm{DS(on)}}}$) are decreased while that of R_{SW} ($\Delta E_{R_{\mathrm{SW}}}$) is increased when R_{SW} increases. This indicates that **while the change of a resistance component in the charging path does not affect the total charging efficiency, the energy loss among the individual resistive components in the charging path will be changed**. Therefore, by inserting an external resistor in the charging path, the energy loss across the electronic components (power switch and capacitor etc.) will be diverted to the external resistor, hence improving the thermal condition of the components with no penalty on the overall efficiency of the converter.

V. Efficiency of RC Discharging Circuits

The equivalent discharging circuit of an SC converter can also be represented by an RC circuit. Two types of loading, namely resistive and capacitive loads, are considered.

A. Discharging Efficiency with Resistive Load

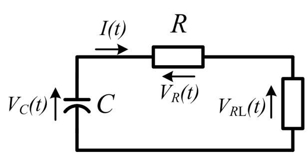


Fig. 5. The equivalent RC discharging circuit with a resistive load.

Fig. 5 shows the equivalent discharging circuit with the resistive load. The instantaneous voltages and current, energy profile and the discharging efficiency of this circuit over a discharging cycle are

$$\begin{cases} V_C(t) &= V_{C\mathrm{i}} \cdot \left(e^{\frac{-t}{(R+R_{\mathrm{L}})C}}\right) \\ I(t) &= \frac{V_{C\mathrm{i}}}{(R+R_{\mathrm{L}})} \cdot \left(e^{\frac{-t}{(R+R_{\mathrm{L}})C}}\right) \end{cases}; \tag{11}$$

$$\begin{cases} \Delta E_C = \int_0^{T_{\mathrm{dis}}} V_C(t) \cdot I(t) dt = \frac{C}{2}({V_{C\mathrm{i}}}^2 - {V_{C\mathrm{f}}}^2) \\ \Delta E_{R_{\mathrm{L}}} = \int_0^{T_{\mathrm{dis}}} V_{R_{\mathrm{L}}}(t) \cdot I(t) dt = \frac{C}{2}({V_{C\mathrm{i}}}^2 - {V_{C\mathrm{f}}}^2)\left(\frac{R_{\mathrm{L}}}{R+R_{\mathrm{L}}}\right) \\ \Delta E_R = \int_0^{T_{\mathrm{dis}}} V_R(t) \cdot I(t) dt = \frac{C}{2}({V_{C\mathrm{i}}}^2 - {V_{C\mathrm{f}}}^2)\left(\frac{R}{R+R_{\mathrm{L}}}\right) \end{cases}; \tag{12}$$

$$\eta_{\mathrm{dis(Rload)}} = \frac{\Delta E_{R_{\mathrm{L}}}}{\Delta E_C} = \frac{R_{\mathrm{L}}}{R+R_{\mathrm{L}}}. \tag{13}$$

From (13), **the total equivalent resistance in the discharging path R (sum of R_{ESR}, $R_{\mathrm{DS(on)}}$ and R_{SW}) will degrade the discharging efficiency**, irrespective of full ($V_{C\mathrm{f}}$ = 0 V) or partial ($V_{C\mathrm{f}} > 0$ V) discharging conditions. This is consistent with what has been reported in [15]. It is important to keep $R \ll R_{\mathrm{L}}$ to maintain a high discharging efficiency.

B. Discharging Efficiency with Capacitive Load

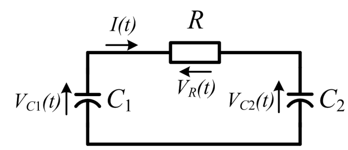


Fig. 6. The equivalent RC discharging circuit with a capacitive load.

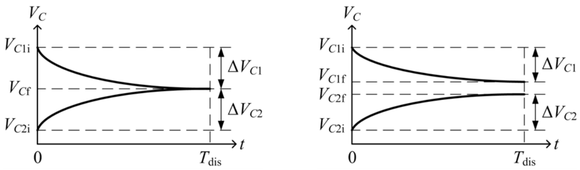
Energy transfer from one capacitor to another is a very common process in SC converters. The equivalent circuit is given in Fig. 6. When two capacitors with different voltages are connected in parallel, charges will be redistributed and energy will be lost (called the charge redistribution loss) [16]. Two different final conditions, full discharging (Fig. 7(a)) and partial discharging (Fig. 7(b)), will be discussed. The instantaneous voltages and current, energy profile and the efficiencies of full and partial discharging processes over a discharging cycle are respectively given in (14) and (15).

$$\begin{cases} V_{C1}(t) &= V_{C1\mathrm{i}} - (V_{C1\mathrm{i}} - V_{C2\mathrm{i}})\left(\frac{C_{\mathrm{E}}}{C_1}\right)\left(1 - e^{\frac{-t}{RC_{\mathrm{E}}}}\right) \\ V_{C2}(t) &= V_{C2\mathrm{i}} - (V_{C1\mathrm{i}} - V_{C2\mathrm{i}})\left(\frac{C_{\mathrm{E}}}{C_2}\right)\left(1 - e^{\frac{-t}{RC_{\mathrm{E}}}}\right) \\ I(t) &= \frac{V_{C1\mathrm{i}} - V_{C2\mathrm{i}}}{R}\left(e^{\frac{-t}{RC_{\mathrm{E}}}}\right) \\ C_{\mathrm{E}} &= C_1 // C_2 \end{cases} \tag{14}$$

$$\begin{cases} \Delta E_{C_1} &= \int_0^{T_{\mathrm{dis}}} V_{C1}(t) \cdot I(t) dt \\ &= \frac{C_{\mathrm{E}}}{2}(V_{C1\mathrm{i}} - V_{C2\mathrm{i}})\left(1 - e^{\frac{-T_{\mathrm{dis}}}{RC_{\mathrm{E}}}}\right)(V_{C1\mathrm{f}} + V_{C1\mathrm{i}}) \\ \Delta E_{C_2} &= \int_0^{T_{\mathrm{dis}}} V_{C2}(t) \cdot I(t) dt \\ &= \frac{C_{\mathrm{E}}}{2}(V_{C1\mathrm{i}} - V_{C2\mathrm{i}})\left(1 - e^{\frac{-T_{\mathrm{dis}}}{RC_{\mathrm{E}}}}\right)(V_{C2\mathrm{f}} + V_{C2\mathrm{i}}) \\ \Delta E_R &= \int_0^{T_{\mathrm{dis}}} V_R(t) \cdot I(t) dt \\ &= \frac{C_{\mathrm{E}}}{2}(V_{C1\mathrm{i}} - V_{C2\mathrm{i}})^2\left(1 - e^{\frac{-2T_{\mathrm{dis}}}{RC_{\mathrm{E}}}}\right) \end{cases} \tag{15}$$

$$\eta_{\mathrm{dis}_{\mathrm{Cload(full)}}} = \frac{\Delta E_{C2}}{\Delta E_{C1}} = \frac{V_{C\mathrm{f}} + V_{C2\mathrm{i}}}{V_{C\mathrm{f}} + V_{C1\mathrm{i}}}; \tag{16}$$

$$\eta_{\mathrm{dis}_{\mathrm{Cload(partial)}}} = \frac{\Delta E_{C2}}{\Delta E_{C1}} = \frac{V_{C2\mathrm{f}} + V_{C2\mathrm{i}}}{V_{C1\mathrm{f}} + V_{C1\mathrm{i}}}. \tag{17}$$



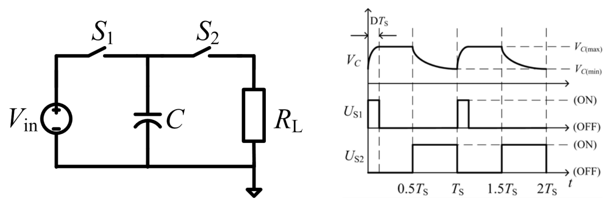
(a) Full discharging (b) Partial discharging

Fig. 7. The capacitor voltage waveform under two different discharging processes.

(16) and (17) indicate that the discharging efficiency is independent of R, but dependent on ΔV_C. The difference between $V_{C2\text{i}}$ and $V_{C1\text{i}}$, and hence **both $\Delta V_{C1} (= V_{C1\text{i}} - V_{C1\text{f}})$ and $\Delta V_{C2} (= V_{C2\text{f}} - V_{C2\text{i}})$, should be kept small for a higher discharging efficiency**.

VI. Overall Efficiency of SC Converters

Combining the circuit analysis from the charging and discharging operations, the overall converter efficiency can be analyzed at a system's level using a simple SC converter circuit shown in Fig. 8(a). Its timing diagram is given in Fig. 8(b).



(a) (b)

Fig. 8. (a) A complete SC converter circuit with (b) its timing diagram.

Since at steady state, energy is balanced on the capacitor, i.e., $\Delta E_{C_{(\text{ch})}} = \Delta E_{C_{(\text{dis})}}$, the overall efficiency of converter over a complete charging and discharging cycle is

$$\eta_{\text{SC}} = \frac{\Delta E_{R_\text{L}}}{\Delta E_{\text{in}}} = \Big(\frac{\Delta E_{C_{(\text{ch})}}}{\Delta E_{\text{in}}}\Big)\Big(\frac{\Delta E_{R_\text{L}}}{\Delta E_{C_{(\text{dis})}}}\Big) = \eta_{\text{ch(partial)}} \cdot \eta_{\text{dis(Rload)}}. \quad (18)$$

(19) can also be derived by (5) and the voltage divider property in Fig. 5 to reach the same result in [10], [11].

$$\frac{\overline{V_\text{O}}}{V_{\text{in}}} = \eta_{\text{ch(partial)}} \cdot \eta_{\text{dis(Rload)}}. \quad (19)$$

Additionally, with the converter operating as a system that toggles between the charging and discharging operations, the capacitor size and switching frequency are important components that influence the energy efficiency. A bigger capacitance and a higher switching frequency f_{SW} will reduce the charging/discharging capacitor voltage ripple ΔV_C, leading to a higher efficiency.

VII. Conclusions

A thorough discussion on the charging, discharging and overall efficiencies of SC converters have been presented. The following are the main conclusions.

- R in the charging circuit does not affect the charging efficiency, but R in the discharging circuit does affect the discharging efficiency.
- QSC converters have a similar loss to SC converters.
- A change in resistance of one resistive component will redistribute the energy loss of other resistive components without affecting the overall efficiency.
- ΔV_C, f_{SW}, and C affect the overall energy efficiency.

With this understanding, the rules of thumb toward designing a highly efficient SC converter are provided as follows.

- ΔV_C should be small and $\overline{V_C}$ should be near V_{in} in the charging and discharging processes during steady state.
- R in the discharging path should be kept as small as possible to maximize the discharging efficiency.
- For capacitors sharing charges, ΔV_{C1} and ΔV_{C2} should be small. It implies that a high f_{SW} and C can be used to minimize ΔV_C.

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