

## Comments on “Unified Analysis of Switched-Capacitor Resonant Converters”

Adrian Ioinovici, Henry S. H. Chung, Marek S. Makowski, and Chi K. Tse

**Abstract**—The realization of line and load regulation in switched-capacitor (SC)-based converters is discussed. A duty-cycle control is based on partial charging of the capacitors in the circuit. The influence on the efficiency is pointed out. The use of inductors in SC-based converters is discussed.

**Index Terms**—Efficiency, switched-capacitor (SC) converter, voltage regulation.

In the above paper [1], a way of realizing soft switching in switched-capacitor (SC) converters by inserting small inductors in series with the switching capacitors has been discussed. Consequently, the proposed circuit behaves like a quasi-resonant converter, with turn-on and turn-off of the transistors under zero current switching. The extent of high-current spikes arising from charging the capacitors is limited, the EMI emission is reduced, and by fully charging the switching capacitors, the maximum available efficiency is attained. In this paper, we wish to comment on the technical feasibility of the work reported in [1] and point out some possible unintentional omissions of important prior developments by the authors. Our primary objective is to clarify the operation of state-of-the-art SC power supplies in relation to the ability to regulate output voltage and the attainable efficiency.

- 1) As should be widely known, prior developments of SC power supplies [1, [4], [6]–[8]], have already advanced to a point where full output voltage regulation has been achieved in a versatile manner. The paper by Yeung *et al.* [1] has, however, devoted itself to the historical case of open-loop SC circuits, where switching capacitors are fully charged in each intermediate step. Obviously, the key advancement as documented in those prior works has been omitted or imprecisely interpreted. We therefore feel the need to clarify the following important technical issues:
  - a) In the cited prior works [1, [4], [6]–[8]], the switching capacitor(s) is (are) “partially” charged in each intermediate charging stage and never fully charged to the voltage level(s) applied to the capacitor(s) concerned during that immediate stage. The successful development of SC power supplies by prior researchers has underlined that the nominal operating point, as far as the charging of capacitors is concerned, has to be in the middle of the linear part of the (time) charging characteristic of the capacitors. This permits sufficient headroom for the operating point to “maneuver” around the operating point and, hence, to decrease or increase the capacitor charging time for the purpose of output voltage regulation in the event of line or load variations. Moreover,

by charging only partially the capacitors, the efficiency is lowered as pointed out in [1, [6]]; however, this is the price to be paid for having line and load regulation.

- b) The on-resistances of the transistors and the equivalent series resistances of the capacitors do not influence the efficiency, in contrary to what [1] has described. The losses are not dependent upon the charging/discharging capacitor current trajectories either. In fact, they depend only on the difference between the line and the switching capacitor voltage and that between the switching capacitor voltage and output voltage. See also [2]. Finally, for a given number of switching capacitors  $n$ , the efficiency depends only on the ratio of the input voltage  $V_i$  and output voltage  $V_o$ ; specifically, it depends on  $nV_o/V_i$  for step-down converters and  $V_o/[(n+1)V_i]$  for step-up converters. A tutorial exposition can be found in [3].
- 2) The development of SC power supplies has been motivated by the power supply requirements of portable electronic equipment. Inductive elements have been purposely removed in order to facilitate integrated-circuit implementation. Hence, at first sight, inserting inductors in SC converters could be a contradiction in itself. Moreover, one may still argue that parasitic inductances present in the circuit can be advantageously exploited as resonant inductors to ease switching, as proposed by Yeung *et al.* [1]. However, for this to be technically feasible, the operating frequency must be raised to tens of megahertz, and the demonstration at 200 kHz given in [1], using 1- $\mu$ H inductors, remains uninteresting and inconsistent with what has been promised in [1, Table 1]. Perhaps, interested readers or the authors themselves may wish to verify the proposed resonant switchings at a sufficiently high frequency, provided that no further complications of other components occur at such a high frequency.
- 3) Given the rich possibilities of applications and the wide variety of commercial specifications, perhaps no researchers can make full justification to reject the usefulness of a particular design. However, for SC power supplies, it seems that the main quest is good output regulation against load and input variations; otherwise, conventional voltage multipliers (which are actually SC circuits) or charge-pump circuits, which operate with a constant input-to-output voltage ratios and are integrable, would be satisfactory. Thus, for any available SC converter, the main issue is how to fulfill the fundamental regulation requirement, which has been the subject of research in the past two decades (see also [4]). As the proposed circuit [1] lacks the faculty of regulation, although with improved efficiency, its application could be limited. It should be noted that using an unregulated SC converter as a post-regulator, as proposed in [1], can be highly disputable since postregulation should, for most applications, meet a very tight output regulation requirement. In fact, for most applications using SC power supplies, more than 1% variation of the output voltage is already inadmissible, and the 10% output variation under a moderately wide load range as reported in [1] is far from being practical.

The development of SC power supplies has gone through several stages of advancements, beginning from the conventional voltage multipliers and charge-pump circuits, to precision voltage step-up and step-down converters, and eventually to integrable SC power supplies. As the field continues to advance, we believe it is timely to review the salient achievements to date and perhaps to clear up misconceptions. In conclusion, as triggered from our foregoing discussion of [1], many technical aspects of the design of SC power supplies are worth

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exploring further, including the tradeoff between “regulability” and efficiency, soft switching at high frequencies with parasitic inductances, etc.

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**Comments on “Elimination of the Stator Resistance and Voltage Sensor Requirement Problems for DFO Control of an Induction Machine”**

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**Abstract**—It is shown that in the paper by Rehman (2005) the proposed method for a stator flux estimation does not have an advantage over a current model.

**Index Terms**—Induction machine, sliding mode, voltage model flux observer.

It has been proposed in [1] to use a slide-mode observer for a stator flux estimation in such a way that the necessity of the information about stator resistance is excluded. The next comments can be drawn in connection with this paper.

It is proved in this paper, that in the constructed observer the estimated stator current converges to the measured one and, hence a deduction is made that an estimated stator flux converges to the actual one by an integration of the sliding-mode functions  $\Psi_{s\alpha}$  and  $\Psi_{s\beta}$ . However, it takes place not under any conditions. Let the  $R_r$ —rotor resistance, its estimation  $R_{re} \ll R_r$ ,  $\Delta R_r = R_{re} - R_r$ .

The equation for a current [1, eq. (1)], we write as follows:

$$\frac{d\mathbf{I}_s}{dt} = K_1(\mathbf{V}_s - R_s\mathbf{I}_s) + K_1\mathbf{A}_1\Phi_s + \mathbf{A}_2\mathbf{I}_s$$

$$\mathbf{A}_1 = \begin{bmatrix} \eta & \omega_r \\ -\omega_r & \eta \end{bmatrix}, \quad \mathbf{A}_2 = \begin{bmatrix} \frac{\eta}{\sigma} & -\omega_r \\ \omega_r & \frac{-\eta}{\sigma} \end{bmatrix}. \quad (1)$$

The equation for current estimation is

$$\frac{d\hat{\mathbf{I}}_s}{dt} = K_1\Psi_s + K_1\hat{\mathbf{A}}_1\hat{\Phi}_s + \hat{\mathbf{A}}_2\hat{\mathbf{I}}_s$$

$$\Psi_s = -u_0\text{sign}(\hat{\mathbf{I}}_s - \mathbf{I}_s). \quad (2)$$

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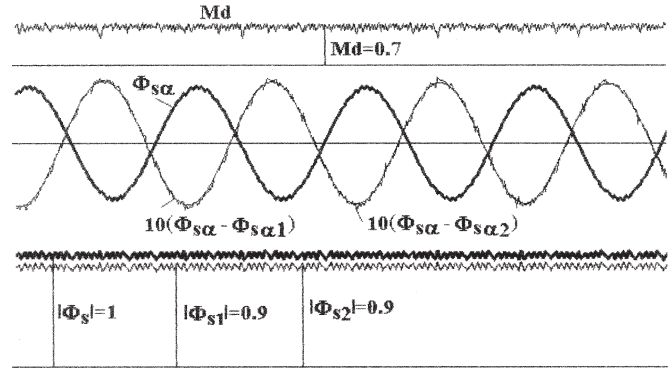


Fig. 1. Comparison of the sliding-mode observer {1} with a current model observer.

The error equation is

$$\frac{d\Delta\mathbf{I}_s}{dt} = K_1[\Psi_s - (\mathbf{V}_s - R_s\mathbf{I}_s)] + K_1(\mathbf{A}_1\Delta\Phi_s + \Delta\mathbf{A}_1\hat{\Phi}_s) + \mathbf{A}_2\Delta\mathbf{I}_s + \Delta\mathbf{A}_2\hat{\mathbf{I}}_s$$

$$\Delta\mathbf{A}_1 = \Delta\eta\mathbf{I}, \quad \Delta\mathbf{A}_2 = \frac{-\eta}{\sigma}\mathbf{I}$$

$$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \Delta\eta = \frac{\Delta R_r}{L_r}. \quad (3)$$

In a sliding-mode, not only  $\Delta\mathbf{I}_s \rightarrow 0$ , but  $d\Delta\mathbf{I}_s/dt \rightarrow 0$  as well [2]. From (3), it follows:

$$\Psi_s = \mathbf{V}_s - R_s\mathbf{I}_s - \mathbf{A}_1\Delta\Phi_s - \Delta\eta\hat{\Phi}_s + \Delta\eta L_s\hat{\mathbf{I}}_s. \quad (4)$$

According to [1, eqs. (2) and (4)]

$$\frac{d\Phi_s}{dt} = \mathbf{V}_s - R_s\mathbf{I}_s, \quad \frac{d\hat{\Phi}_s}{dt} = \Psi_s,$$

$$\frac{d\Delta\Phi_s}{dt} = -\mathbf{A}_1\Delta\Phi_s - \Delta\eta\hat{\Phi}_s + \Delta\eta L_s\hat{\mathbf{I}}_s. \quad (5)$$

Thus, only under  $R_{re} = R_r$ , the error  $\Delta\Phi_s \rightarrow 0$ .

Because this observer requires a speed sensor, it is reasonable to compare it with a current model flux observer. Its equation is [3]

$$\frac{d\Phi_r}{dt} = -\mathbf{A}_1\Phi_r + \eta L_m\mathbf{I}_s. \quad (6)$$

The equation for error

$$\frac{d\Delta\Phi_r}{dt} = -\mathbf{A}_1\Delta\Phi_r - \Delta\eta\hat{\Phi}_r + \eta\Delta L_m\hat{\mathbf{I}}_s. \quad (7)$$

Comparing (7) with (5) and keeping in mind, that  $\Delta\Phi_s \approx K_r\Delta\Phi_r$  and  $L_m \approx L_r \approx L_s$ , we obtain

$$\Delta\Phi_s \approx \Delta\Phi_r.$$

Fig. 1 shows the simulation results in p.u. of the DTC-IM drive with the observer under consideration. IM parameters:  $R_s = R_r = 0.024$ ,  $L_r = 2$ ,  $K_1 = 5$ ,  $\sigma = 0.1$ . IM rotates with a speed  $\omega_r = 0.95$ . It is supposed that stator flux components  $\Phi_{s\alpha}$  and  $\Phi_{s\beta}$  and magnitude