Switching Cell And Measurements In Converter Averaged Models

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Abstract

This paper shows that the parameters of advanced averaged models of power converters to represent the non-linearities of semiconductor devices are independent of DC-DC converter structures, thus they may be identified experimentally on a unique simple circuit. Experimental results on various converters are compared to accurate simulations. Traditional converters DC-DC can well be simplified on a cell converter, concept largely frequently and offered by the perfect switches concept [2]. We show’s that a so-called switching cell be easily identified from the converter circuit and we demonstrate that power device has the same behavior during cell and the original converter.

Key words: Converter, Averaged model, power, losses.

INTRODUCTION

Integrated power systems are expecting a tremendous development with the area of all-portable devices, intelligent in the cars or energy-efficient systems. With this type of technology, the design prototypes become increasingly difficult. For this reason, it is more and more often necessary to refer to the simulation of converters. On the one hand soldering and bonding of components on the same substrate and inside one same package produce a hybrid power system. On the other hand, monolithic integration on silicon is under development. In both cases, integration means a lot of advantages but also a lot of problems like the high coupling between electro-magnetic-thermal and mechanical phenomena. Modeling and simulation at various time-scales are then necessary. Moreover the simulation of the power converter must take into account the power semiconductor device effects: the delays with respect to the driving signals, the dynamic power losses or the non-linear I-V characteristics. So it is possible to optimize the system control loop or to analyze the thermal behavior of the semiconductor devices. Unfortunately the cost of this long time-range simulation is too high for CAE if accurate semiconductor device models are used (several days of CPU-time). Practically the power device transients constrain the integration time-step to a small value. A classical simplification is possible when using ideal switches instead of semiconductor device models. The simulation cost is only slightly reduced while it does no longer include the semiconductor device effects, mainly the power losses. Another level of simplification is to use an averaged model of the converter including the
semiconductor devices. Numerous studies about averaged modeling address ideal converter representation [15]. So the simulation including semiconductor device effects for the power system analysis is not possible.

In [14] it has been presented an algorithm based on an extended causality analysis (algebraic causality analysis, ACA) [16], that guides formally the construction of the averaged model of a given power converter. The algorithm applies to the switched bond graph structure of the converter. The present paper covers the application of the previously published algorithm to converters.

An application of the algorithm to the construction of the converter-averaged model in case of Boost, Buck, and the simple cell converters is done. Virtual switching delays and power losses are introduced to take care of the power device transient behaviors.

On the other hand, in the case of the “arm converter” it has showed a significant variation compared to commutation in circuits DC-DC, This has considerable consequences on the losses during a PiN diode turn-off [2].

A discussion about the obtained averaged model will be done. Especially it will be output port variables $Y=\{v_e, i_s\}$. It may be noted the driving circuit ($r_g$, $l_g$, $G_{\text{PWM}}$) that has been replaced by an ideal source leading to the same causality, seen from the SB.

shown that the same virtual switching delay and losses functions may be used for various DC-DC converter structures. This property will be applied to the measurement of such characteristics and the simplest converter circuit: The Switching Cell.

Many textbooks teach that a DC-DC converter may be easily simplified to a switching cell with regard to the power device behavior during transients. If the concept of switching cell is affordable, the definition of the switching cell especially for power electronic designers has not been clearly demonstrate yet that be it done in this paper.

**AVERAGE MODELING OF A NON-IDEAL BOOST CONVERTER**

The averaged modeling technique may be applied identically as to the ideal boost converter and the other converters will follow [6]. The step A establishes the Switching Block (SB). It is important to note that the wiring inductance $L_d$ belongs to the SB because of its changing causality. Moreover it proves its influence on the averaged model (AM) behavior. Steps B and C lead to identify the input port variables of the SB as $U=\{V_s, I_c\}$, and the

![Figure 1. Schematic of the non-ideal boost converter.](image)
Figure 2. Typical voltage waveform during a PiN diode turn-off.

An equivalent ideal signal is pictured to illustrate the virtual switching time $\delta_{\text{ID}}^{\text{off}}$. Then the virtual switching times $\delta_{\text{ID}}^{\text{off}}$, $\delta_{\text{on}}$ are characteristics of boost converter, including the gate drive circuit, and function of $(V_R, I_F, L_d)$ mainly.

Figure 3. Simplified schema of the non-ideal boost converter.

Fig 3 pictures the simplified circuit from which is computed the non-ideal boost AM. To build the non-ideal boost averaged model as an extension of the ideal boost averaged model an approximation is used to consider the semiconductor devices described by static state equation before and after the switching phase. Fig. 2 pictures the typical waveform of $i_D$ during the diode turn-off. Before $t=t_0$, The power Mosfet is considered in off-state and the diode is considered in on-state. After $t=t_1$, the Mosfet is considered in state on-state and the diode is considered in off-state. Between $t_0$ and $t_1$ static equations cannot be applied, so virtual delays are defined to represent averaged value of the needed value.

The idea is to replace the real semiconductor by an ideal switch, featuring the same current (respectively voltage) average one $(t_0, t_1)$ and over $(t_1, t_2)$, so the device current (respectively voltage) wave-form is replaced by a virtual ideal signal that switches between the same value current (respectively voltage). The method was more detailed in [6].

So the average model of the boost converter is given by:

$$<i_D> = I_F [1 - \rho + \delta_{\text{off}}^{\text{Boost}}]$$

where $\rho$ is the duly ratio, $T$ the period switching, $\delta = \delta_{\text{ID}}^{\text{off}} - \delta_{\text{on}}$.

$$<i_D> = I_F [\rho + \delta_{\text{on}}^{\text{Boost}}]$$

The virtual energies $E_{\text{pm}}$ and $E_{\text{pd}}$ are defined as:

$$<P_{\text{mosfet}}> = v_D^{\text{loss}} I_F \cdot \rho + \left[\frac{E_{\text{pm}}^{\text{Boost}}}{T}\right]$$

$$<P_{\text{diode}}> = v_D^{\text{loss}} I_F \cdot (1 - \rho) + \left[\frac{E_{\text{pd}}^{\text{Boost}}}{T}\right]$$

Obviously $\delta_{\text{off}}^{\text{Boost}} (v_D^{\text{on}}=v_e)$ and $\delta_{\text{ID}}^{\text{Boost}} (i_D=i_s)$ are function of the forward current $I_F$, and the reverse voltage $V_R$. For given Boost converter on they depend (Mosfet: IRF740 [2], Diode: BYT12PI600 [3], a global parasitic inductance $L_d$ of 100nH, and a gate drive circuit.) These functions may be computed by simulation (Fig.4). The results are obtained from various simulations with the circuit simulator PACTE[1].

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It will be shown that the buck converter yields a different averaged model than the boost converter but:

\[
\begin{align*}
\delta_{\text{Buck}} & = \delta_{\text{Boost}} \\
\delta_{\text{Buck}} & = \delta_{\text{Boost}} \\
E_{\text{Pm}} & = E_{\text{Pm}} \\
E_{\text{Pd}} & = E_{\text{Pd}}
\end{align*}
\]

It will be shown that this is due to the equivalence of the associated simplified circuit in each case.

**AVERAGE MODELING OF A NON-Ideal Buck CONVERTER.**

The switching cell in figure 7 has the advantage to be easy to use in a measurement workbench, because of the simple control on \( i_F \) and \( v_R \) values.

The Buck converter yields the simulation model [5]:

\[
\begin{align*}
\langle i_d \rangle & = I_F \cdot \{1 - \rho + \frac{\delta_{\text{DD}}}{T}\} \\
\langle i_s \rangle & = \langle i_d \rangle \cdot \{1 + \rho + \frac{\delta_{\text{DD}}}{T}\} \\
\langle v_s \rangle & = (V_R - V_{\text{Ld}}) \cdot \{\rho - \frac{\delta_{\text{SS}}}{T}\} - V_{\text{Ld}} \cdot \{1 - \rho + \frac{\delta_{\text{SS}}}{T}\} \\
\langle P_{\text{Mosfet}} \rangle & = V_{\text{Ld}} I_F \cdot \{1 + \frac{E_{\text{Pm}}}{T}\} \\
\langle P_{\text{diode}} \rangle & = V_{\text{Ld}} I_F \cdot \{1 - \rho + \frac{E_{\text{Pm}}}{T}\}
\end{align*}
\]

The average value is given by:

\[
\begin{align*}
\langle i_d \rangle & = I_F \cdot \{1 - \rho + \frac{\delta_{\text{DD}}}{T}\} \\
\langle i_s \rangle & = \langle i_d \rangle \cdot \{1 + \rho + \frac{\delta_{\text{DD}}}{T}\} \\
\langle v_s \rangle & = (V_R - V_{\text{Ld}}) \cdot \{\rho - \frac{\delta_{\text{SS}}}{T}\} - V_{\text{Ld}} \cdot \{1 - \rho + \frac{\delta_{\text{SS}}}{T}\} \\
\langle P_{\text{Mosfet}} \rangle & = V_{\text{Ld}} I_F \cdot \{1 + \frac{E_{\text{Pm}}}{T}\} \\
\langle P_{\text{diode}} \rangle & = V_{\text{Ld}} I_F \cdot \{1 - \rho + \frac{E_{\text{Pm}}}{T}\}
\end{align*}
\]
\[ <i_t> = -I_F \left( 1 - \rho + \frac{\delta_{\text{Cell}}}{T} \right) \]

\[ <i_{DS}> = I_F \left[ \rho + \frac{\delta_{\text{Cell}}}{T} \right] \]

\[ <v_{DS}> = \left( V_R + V_{\text{Din}} \right) \left[ 1 - \rho - \frac{\delta_{\text{Cell}}}{T} \right] + v_{\text{DSn}} \left[ \rho + \frac{\delta_{\text{Cell}}}{T} \right] \]

The virtual energies \( E_{\text{pm}} \) and \( E_{\text{pd}} \) may be as:

\[ <P_{\text{mfront}} > = v_{\text{DSn}} I_F \rho \left( \frac{E_{\text{Cell}}}{T} \right) \]

\[ <P_{\text{pd}} > = v_{\text{DSn}} I_F \left( 1 - \rho \right) \left( \frac{E_{\text{Cell}}}{T} \right) \]

Fig. 9 shows superimposition of the virtual delays corresponding to the three circuits: Boost converter, Buck converter and Switching Cell. The superimposition shows a very good agreement, so that shows that these virtual delays do not depend on the structure of the converter so far.

![Figure 9](image)

**Figure 9.** The virtual delay \( \delta_{\text{ID}} \) and \( \delta_{\text{vD}} \) for a Boost, Buck and Cell Converters \( (V_R = 150V) \).

Using the switching cell it is possible to measure the virtual delay (Fig 10) and losses [14].

![Figure 10](image)

**Figure 10.** Experimental waveforms for a voltage \( V_R = 100V \) and a current \( I_F = 2A \) (Device BYT12PI600, MOS IRF740, \( L_d = 100nH \)).

Fig. 11 pictures the comparison between experimental measurement and simulated results of the virtual switching delay \( \delta_{\text{ID}} \) and \( \delta_{\text{vDS}} \).
Figure 11. Measurement and simulated virtual switching delay for a voltage $V_R = 100$ V and a current $I_F = 2A$.

Fig. 12 pictures the experimental measurement results of the virtual switching delay $\delta_{vD}$ (in case of a switching cell) for $V_R=100$V and $I_F=2A$, as it has been identified for the following switching cell: Mosfet=IRF740, diode=BYT12PI600, $L_d=100nH$, $r_g=5\Omega$, $l_g=10nH$, Temp=$330K$.

EQUIVALENCE OF THE SWITCHING PHASES IN ALL THE SIMPLIFIED SCHEMATIC CONVERTER

In this paragraph, we demonstrate that power device has the same behavior during cell and the DC-DC converters.

Same switching phases means the same transient currents and voltages for semiconductor devices like $i_D(t)$, $v_D(t)$, $i DS(t)$, $v DS(t)$, $i G(t)$, $v GS(t)$.

State-Space Model (1) and (2) are considered for the diode, and the MOSFET transistor [3-4]. The state variables of all the bond graphs (Buck, Boost, Switching Cell, Buck-Boost) are $X_{Ld}$, $Q_D$, $Q_j$, $Q_G$ for the Inductor $L_c$, Diode and MOSFET transistor respectively.

\[
\frac{dQ_D}{dt}=i_D-F_D(Q_D) \quad (1-a)
\]

\[
V_D=G_D(Q_D) \quad (1-b)
\]

\[
\frac{dQ_G}{dt}=i_G \quad (2-a)
\]

\[
\frac{dQ_j}{dt}=i_DS-F_{DS}(Q_G,Q_j) \quad (2-b)
\]

\[
V_{GS}=G_S(Q_G,Q_j) \quad (2-c)
\]

\[
V_{DS}=G_{DS}(Q_G,Q_j) \quad (2-d)
\]
Using the causality analysis [15] and specially the Formal Causality Analysis (FCA) [16], State Equations of the different converter bond graphs (Buck, Boost, Switching Cell, Buck-Boost) is obtained. The various simplified converter yield to the same state equations (3-4-5-6).

\[
\frac{dX_{ld}}{dt} = V_{ld} - G_D(Q_D) - G_{DS}(Q_G, Q_J) \tag{3}
\]

\[
\frac{dQ_D}{dt} = i_D - F_D(Q_D) \tag{4}
\]

\[
\frac{dQ_I}{dt} = \left(\frac{X_{ld}}{L_d} + I_F\right) - F_{DS}(Q_G, Q_J) \tag{5}
\]

\[
\frac{dQ_G}{dt} = i_G \tag{6}
\]

The state equations of the Buck-Boost converter are represented in (7-8-9-10). Defining an effective reverse voltage \( V_R = V_{R1} - V_{R2} \), the system is the same as represented in (3-4-5-6).

\[
\frac{dX_{ld}}{dt} = V_{ld} - (V_{R1} - V_{R2}) - G_D(Q_D) - G_{DS}(Q_G, Q_J) \tag{7}
\]

\[
\frac{dQ_D}{dt} = i_D - F_D(Q_D) \tag{8}
\]

\[
\frac{dQ_I}{dt} = \left(\frac{X_{ld}}{L_d} + I_F\right) - F_{DS}(Q_G, Q_J) \tag{9}
\]

\[
\frac{dQ_G}{dt} = i_G \tag{10}
\]

In the case of a Boost converter, the simplified converter is exactly the switching cell converter (Fig.3, Fig.8).

The port-variables of the MOSFET transistor and the Diode \( i_D(t) \), \( v_D(t) \), \( i_D(t) \), \( v_{DS}(t) \), \( i_G(t) \), \( v_{GS}(t) \) may be written as function of the state variables \( (X_{ld}, Q_D, Q_I, Q_G) \).

Applying causality analysis enables to obtain the state equations and the relations given all the port-variables as function of the state variables. In the case of the boost converter (Fig.3), the port-variables are written as:

\[
i_D = \frac{X_{ld}}{L_d} \tag{11}
\]

\[
v_D = G_D(Q_D) \tag{12}
\]

\[
V_{DS} = G_{DS}(Q_G, Q_D) \tag{13}
\]

\[
i_{DS} = I_F - \frac{X_{ld}}{L_d} \tag{14}
\]

\[
i_G = \frac{dQ_G}{dt} \tag{15}
\]

Finally, all the converters (Buck, Boost, Switching Cell, Buck-Boost) correspond to state equations equivalents to (3-6) and the transient signals \( i_D(t) \), \( v_D(t) \), \( i_{DS}(t) \), \( v_{DS}(t) \), \( i_G(t) \), \( v_{GS}(t) \) are always given by (11-15).

The solution of this ordinary differential equation (3-6) yields to a unique solution. Moreover Cauchy's Theorem involves the existence of the solution. Finally in all the converters the transient signals \( i_D(t) \), \( v_D(t) \), \( i_{DS}(t) \), \( v_{DS}(t) \), \( i_G(t) \), \( v_{GS}(t) \) have the same value (during switching phases) as soon as the value of \( V_R \) and \( I_F \) are equivalent in all the converters. However the simplified converters are not the same and for instance the currents in the voltage source are not the same.

We then demonstrate that power devices do have the same behavior during transit state in both circuits: the switching cell and the original converter. So the converter has the same average models.

CONCLUSION

We have already shown that the transient current and voltage for semiconductor devices in the case of “arm converter” is different to the other converter DC-DC [2]. So we can conclude it show be different in the case of the virtual delay.

The concept of switching cell in power electronics is valid. So it is possible to replace a complex circuit like buck, boost,
switching cell, and buck-boost by a simple switching cell during the switching phase but not for arm converter. It is so contradictory with traditional knowledge but corresponds largely to the concepts of ideal switch, which idealize too the switch during transient state [2].

We have shown that switching delays and switching losses are functions of the forward current \( I_F \), and the reverse voltage \( V_R \) that depend very weakly on the converter structure. So it is possible to measure these functions in the case of a switching cell. First measurements are in good agreement with simulation. Compel the experimental validation of these switching delay and switching losses will enables to use averaged model including delay and losses to design converter, specially integrated converter.

REFERENCES