

Performance assessment, in terms of ripples and power, of conventional and interleaved converter DC-DC with coupled and independent inductors dedicated to photovoltaic installations

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ABSTRACT

Our work focuses on the design and analysis of an interleaved Boost converter DC-DC with coupled and independent inductors in terms of ripples and power. An interleaving strategy is adopted to minimize the currents in the Boost components and consequently to miniaturize them. The command shift of the switch by the X.T value (X: shift coefficient $0 < X < 1$ and T: period of the command signal), minimizes the ripple of the input current and output voltage and maximizes the power extracted from the photovoltaic system. The coupling technique of inductances of interleaved Boost, furthermore reduces the ripples of the input currents and further maximizes the power extracted from the photovoltaic panels. To determine the variation of the power extracted from the PV, according to the duty cycle D and the switches command shift X.T, the duty cycle, was manually varied (Similar to a MPPT command). For this we modeled, under MATLAB/Simulink, the photovoltaic system, the power interface (DC/DC Boost interleaved). Finally, a prototype of interleaved Boost converter with coupled inductors and a shifted control of the switches was realized. Experimental results have been proposed to validate the results of simulations.

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1. INTRODUCTION

Renewable energy sources such as photovoltaic cells, fuel cells, wind energy, etc., is one of the most reliable remedies for saving electrical energy [1]-[3]. These sources require an energy conditioning system. Indeed, the voltages and currents produced by photovoltaic panels need to be improved in terms of ripples quality and efficiency [4], [5].

A conventional DC-DC Boost converter is often used as an interface converter. However, in applications requiring high-density power, such as electric vehicles, hybrid electric vehicles [8] and photovoltaic, interleaved boost converters are the most suitable solution. Several articles reported in the literature [6]-[10], have highlighted the advantages of these topologies compared to other topologies developed for photovoltaic applications.

Indeed, these topologies have many advantages in terms of power quality extracted from PV, energy efficiency, reduction of input current ripple, dynamic response, simple design, robustness and stable condition. As part of this work, and for optimization objectives in terms of maximizing the power extracted from PV, miniaturization of electronic components [11], reduction of input current ripple and output voltage, it was

chosen to focus on a two-branches interleaved DC/DC Boost converter, with and without inductance coupling compared to a conventional Boost converter [12]-[14].

In order to verify the reliability level of this converter as a function of different duty cycle values, D (duty cycle) was varied from 0 to 1, similar to an MPPT algorithm. A shift of the XT value of the switch commands, and a coupling of the inductors is shown in Figure 3 enabled us to improve the performance of the interleaved Boost converter with inductors coupling, in terms of energy efficiency and input current ripple [15], [16].

This article is divided into 5 parts: The part (I) focuses on the Boost converters, the part (II) describes the interleaving and coupling technique of the proposed Boost converter, the part (III) illustrates the results of the simulations, while the part (VI) presents the results of the measurements, in the end, part (V), we present the conclusion and the future perspectives.

2. BOOST CONVERTER (DC-DC)

2.1. Classic DC-DC Boost Converter

DC-DC Boost converters are power modulation circuits. They generate a variable DC voltage as a function of the duty cycle D and the input voltage V_e . They consist of capacitors (Cs), inductors (L) and switches (Mosfet) in blocked saturated mode as shown in Figure 1 [1], [17], [18], [19].

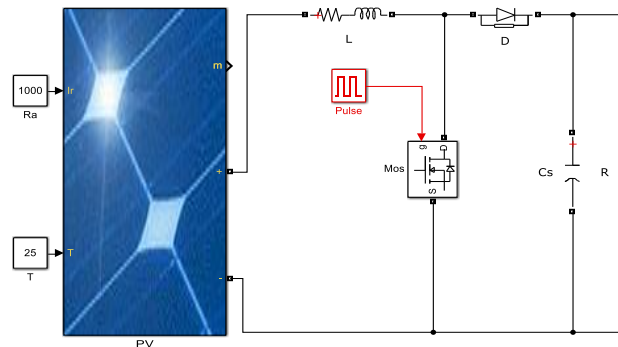


Figure 1. Classic converter boost

The ripple of the input current $\Delta i_{e_{Cl}}$ of a conventional Boost converter. It is given by (1):

$$\Delta i_{e_{Cl}} = \frac{D \cdot V_e}{L \cdot f} \tag{1}$$

The undulation of the terminal voltage of the load also depends on the duty cycle D and output capacitance C_s . It is given by the (2):

$$\Delta V_{s_{Cl}} = \frac{D \cdot I_s}{C_s \cdot f} \tag{2}$$

$\Delta V_{s_{Cl}}$: output voltage ripple of a classic Boost.

I_s : output current.

f: Frequency.

2.2. Interleaved DC-DC Boost Converter

The interleaved DC-DC Boost converter consists in connecting in parallel two or more conventional Boost converters with the same characteristics of these components ($L=L_1=L_2$) as shown in Figure 2. They are used in applications of strong currents: photovoltaic installations, power of the microprocessors of the computers, high power emergency inverters, electric car [20], [21], [22].

Each elementary Boost is controlled by the same value of the duty cycle D, while the commands are shifted between them by a value X.T (T: period, X: shift coefficient) [1], [3].

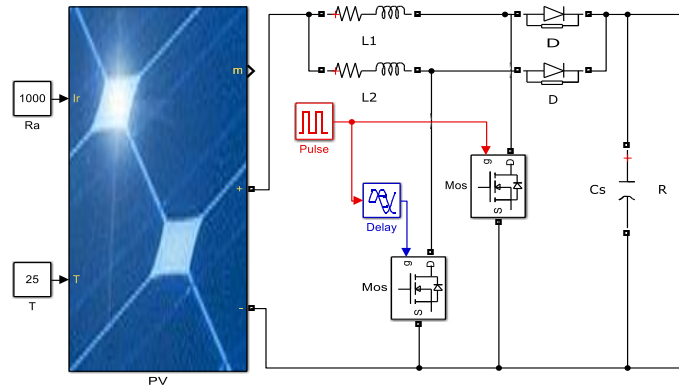


Figure 2. Interleaved converter boost with two independent branches

The input current ripple $\Delta i_{e_{Ent}}$ for an interleaved Boost converter, without coupling of the inductances, is given [1,3] :

For a duty cycle $D < 0.5$ and $X = 0.5$:

$$\begin{aligned} \Delta i_{e_{Ent}} &= \frac{D \cdot V_e}{L \cdot f} \cdot \frac{1 - 2 \cdot D}{1 - D} \\ &= \Delta i_{e_{Cl}} \cdot \frac{1 - 2 \cdot D}{1 - D} \end{aligned} \tag{3}$$

For a duty cycle $D > 0.5$ and $X = 0.5$:

$$\begin{aligned} \Delta i_{e_{Ent}} &= \frac{D \cdot V_e}{L \cdot f} \cdot \frac{2 \cdot D - 1}{D} \\ &= \Delta i_{e_{Cl}} \cdot \frac{2 \cdot D - 1}{D} \end{aligned} \tag{4}$$

From (3) and (4), we deduce that for the same inductance value of the interleaved Boost converter without coupling of the inductors, the ripple of the input current $\Delta i_{e_{Ent}}$ is small, compared to that of a classical Boost $\Delta i_{e_{Cl}}$.

The ripple of the voltage across the load, connected to the interleaved Boost without coupling of inductances, is given by (5) [1]:

$$\begin{aligned} \Delta V_{s_{Ent}} &= \frac{I_s}{C_s \cdot f} \cdot |D - 0.5| \\ &= \Delta V_{s_{Cl}} \cdot \frac{|D - 0.5|}{D} \end{aligned} \tag{5}$$

With:

$\Delta V_{s_{Cl}}$: output voltage ripple of a classic Boost.

$\Delta V_{s_{Ent}}$: output voltage ripple of interleaved Boost.

C_s : output capacitance.

According to (5), the ripple of the output voltage of the interleaved Boost without coupling of the inductors $\Delta V_{s_{Ent}}$, is low compared to that of the conventional Boost $\Delta V_{s_{Cl}}$ for the same output capacitance C_s .

2.3. Interleaved DC-DC Boost Converter with Coupled Inductance

The inductors coupling of interleaved Boost converters, consists in magnetically connecting the inductances via a magnetic coupler [23]-[25].

In this article, we have opted for a structure of the interleaved converter with two coupled branches as shown in Figure 3.

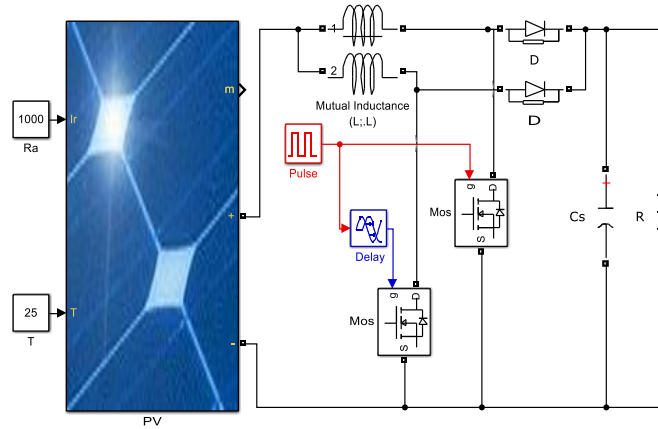


Figure 3. Interleaved converter with two coupled branches

2.3.1 Input Current Ripple Δi_{ePV}

The two branches of the converter are identical. The currents in the inductances are of the same shape. They are shifted by X.T value between them.

According to (1), the ripple of the current in each inductor are always equal (6) [2], [3]:

$$\Delta i_{L1} = \Delta i_{L2} = \frac{D \cdot V_e}{L_1 \cdot f} = \frac{D \cdot V_e}{L_2 \cdot f} = \frac{D \cdot V_e}{L \cdot f} \tag{6}$$

With:

V_e : input voltage

f : frequency

D : duty cycle

X : shift coefficient

T : period of the command signal

We choose the inductors $L_1 = L_2 = L$, the voltage across the inductors V_L . It is given by (7):

$$\begin{aligned} V_{L1} &= L \frac{di_1}{dt} + M \frac{di_2}{dt} \\ V_{L2} &= M \frac{di_1}{dt} + L \frac{di_2}{dt} \end{aligned} \tag{7}$$

With:

$$M = k \cdot L \quad \text{and} \quad -1 < K < 1$$

M : mutual between inductances

K : coefficient of coupling.

The input current ripple Δi_{eEntCo} , of interleaved Boost converter with coupled inductors, is a function of the duty cycle D , the shift of commands X and the coupling coefficient K . It is given:

For a duty cycle $D < 0.5$ and $X = 0.5$

$$\begin{aligned} \Delta i_{eEntCo} &= \frac{D \cdot V_e}{L \cdot f} \cdot \frac{1 - 2 \cdot D}{1 - D} \cdot \frac{1}{1 + K} \\ &= \Delta i_{eEnt} \cdot \frac{1}{1 + K} \end{aligned} \tag{8}$$

For a duty cycle $D > 0.5$ and $X = 0.5$

$$\begin{aligned} \Delta i_{eEntCo} &= \frac{D \cdot V_e}{L \cdot f} \cdot \frac{2 \cdot D - 1}{D} \cdot \frac{1}{1 + K} \\ &= \Delta i_{eEnt} \cdot \frac{1}{1 + K} \end{aligned} \tag{9}$$

Based on the (8) and (9), it is deduced that the coupling of the inductors of the interleaved Boost minimizes the ripple of the input current $\Delta i_{e_{EntCo}}$ by $\frac{1}{1+K}$ compared to that of interleaved Boost without coupling of the inductances $\Delta i_{e_{Ent}}$ for the same value of the inductance L.

2.3.2. Output Voltage Ripple ΔV_s

The output voltage undulation $\Delta V_{s_{EntCo}}$ of the interleaved Boost with coupling of the inductances, is a function of the duty cycle D, the command shift X and the output capacitance C_s . It is given (10):

$$\begin{aligned} \Delta V_{s_{EntCo}} &= \frac{I_s}{C_s \cdot f} |D - 0.5| \\ &= \Delta V_{s_{Ent}} \end{aligned} \tag{10}$$

With:

$\Delta V_{s_{Cl}}$: output voltage ripple of a classic Boost.

$\Delta V_{s_{Ent}}$: output voltage ripple of interleaved Boost.

According to (10), the coupling of the inductors does not allow any reduction of the output voltage ripples of the interleaved Boost for the same value of output capacitance C_s .

3. SIMULATION

Based on DC/DC converters structures, numerical simulations, both conventional and interlaced converters, were realized under the Matlab/Simulink® software is shown in Figure 1, Figure 2 and Figure 3 for different values of the duty cycle D and shift switch commands X. The parameters of the studied system are given in Table 1.

Table 1. Parameters of the Simulation System

PV System	Values)
PV Power (P)	180W
Nominal voltage of the PV (Vpv)	24.4V
Nominal current of the PV (Ipv)	7.5 A
Switching frequency (f)	13.5KHz
Load (R)	20 Ω
Output capacitance (Cs)	220 μF
Inductors (L1=L2=L)	433.47 μH
Coupling coefficient (K)	0.93

3.1. Switch Control Signal

Figure 4 illustrates the commands of the switches which are of the same frequency but they are shifted between them by a value X.T (T: period, X: shift coefficient).

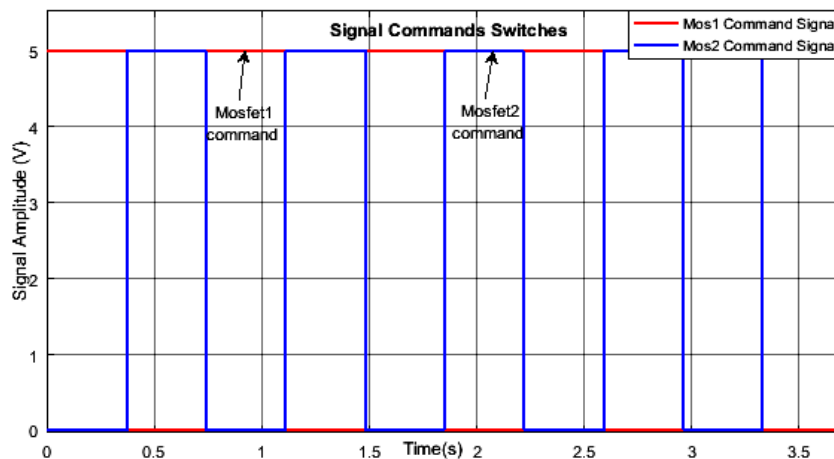


Figure 4. Switch commands with shift coefficient X = 0.5

3.2. Input Current Ripples Δi_e

In Figure 5, we simulated the input current ripple Δi_e of the photovoltaic panel, connected to a conventional and interleaved Boost, with coupled and independent inductances, for different values of the duty cycle D ($0 < D < 1$) similar to a control MPPT, with shift of switch commands $X = 0.5$.

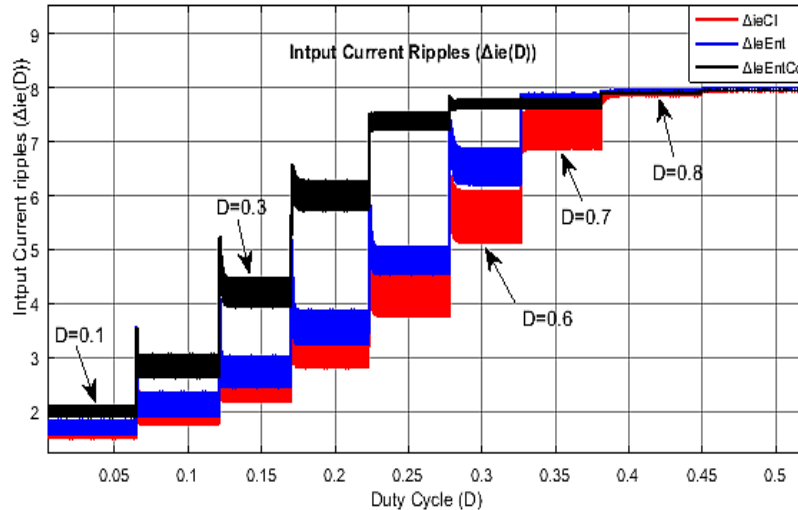


Figure 5. Input current ripple Δi_{ePV} of classical and interleaved boost with coupled and independent inductances with $0.1 < D < 0.9$ and $X = 0.5$

The input current ripple of the interleaved Boost converter, with independent inductors Δi_{eEnt} , is small compared to that of the conventional Boost Δi_{eCI} for the same value of the inductance L . Likewise, the ripple of the input currents Δi_{eEntCo} of the coupled interleaved Boost is considerably minimized compared to that of the interleaved Boost with independent inductors of $\frac{1}{1+K}$.

3.3. Ripple of the Output Voltage ΔV_s

In Figure 6, we compared by simulation, the ripple of the output voltage across the load of a conventional Boost converter compared to that of the interleaved Boost, with and without coupling of the inductors, for the same value of the output capacitance C_s for different values of the duty cycle D , similar to MPPT command, with shift commands $X = 0.5$.

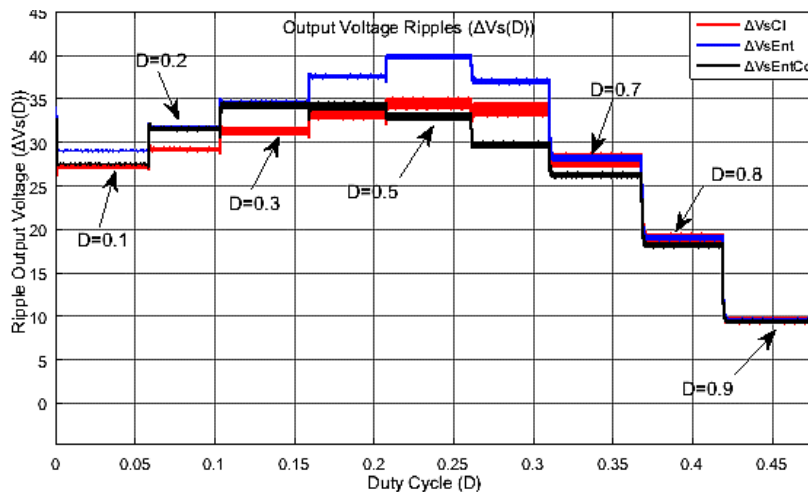


Figure 6. Output voltage ripple ΔV_s of the classical and interleaved boost with coupled and independent inductances with $0.1 < D < 0.9$ and $X = 0.5$

The interleaving of Boost converter minimizes the ripple of the output voltage $\Delta V_{S_{Ent}}$ compared to that of conventional Boost $\Delta V_{S_{Cl}}$ for the same value of the output capacitance C_s . The coupling of the inductors does not allow any gain in terms of ripple of the output voltage $\Delta V_{S_{EntCo}}$.

3.4. Maximizing the Power Extracted from the PV

In this part, we measure, by simulation, the extracted power of the PV, associated with a conventional and interleaved Boost, with coupled and independent inductances, for different values of the duty cycle D and the commands shift coefficient X [1], [3].

Then, for each value of the duty cycle D , we determine X , which corresponds to the maximum power $P_{X_{iMax}(D)}$. We then compare this power with that corresponding to the offset $X=0$ ($P_{(X=0)}$) [1], [2].

Figure 7 illustrates the comparison by simulation of the power extracted from PV panel, between the two topologies of Boost converters, conventional and interleaved with and without coupling of the inductances, for different values of the duty cycle D with $X=0.5$.

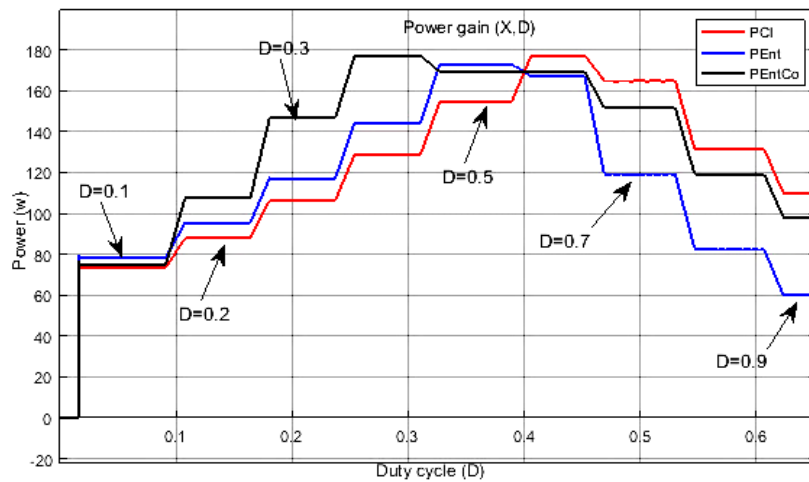


Figure 7. Power as a function of duty cycle D with $X=0.5$

The interleaving of the Boost converters with shift of the commands maximizes the power extracted from the photovoltaic panels. The inductances coupling approach maximizes more this power.

In Figure 8 we compared by simulation, the power gain $\Delta P_{X(D)}$ extracted from the PV connected to an interleaved Boost converter, with independent and coupled inductances ($\Delta P_{X(Ent/Cl)}$, $\Delta P_{X(EntCo/Cl)}$), compared to a conventional Boost, according to the duty cycle D .

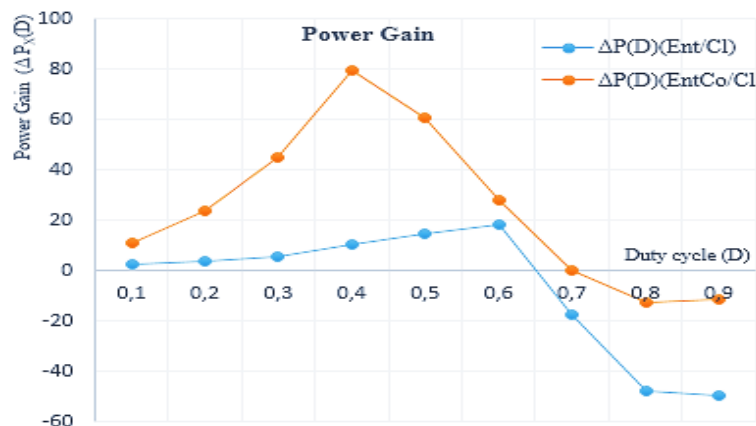


Figure 8. Power gain $\Delta P_{X(D)}$

The power, extracted from the panel connected to an interleaved Boost converter with independent inductances, is higher than that extracted from a PV connected to conventional Boost converter for $D < 0.6$. The coupling of the inductances, significantly increases this power gain $\Delta P_{(X)}$ by adopting an appropriate command shift X .

4. EXPERIMENTAL RESULTS

In order to validate the simulation results, we measured by experience, the ripple of the input currents Δi_e of the two topologies, classical and interleaved Boost converters with independent and coupled inductors. Figure 9 shows the converter circuit, connected to a DC voltage source. The measurement parameters are shown in Table 2.

Table 2. Measurement System Parameters

System Parameters	Values
Input voltage (V_e)	15V
Switching frequency (f)	13.5KHz
Load (R)	20 Ω
Output capacitance (C_s)	220 μ F
Inductors ($L_1=L_2=L$)	433.47 μ H
Coupling coefficient (K)	0.93
Shift coefficient (X)	0.5



Figure 9. Measurement setup of the classic and interleaved boost

In Figure 10, we measured the input voltage V_{eC1} , input current i_{eC1} and its ripple Δi_{eC1} , of the conventional Boost converter.

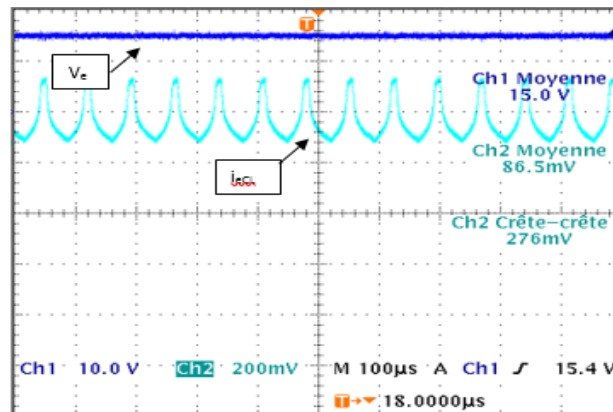


Figure 10. Input voltage V_e and current Δi_{eC1} of the classical boost, with $D=0.5$ and $X=0.5$

We have the ripple of the input current $\Delta i_{eCl} = 0.276A$.

Figure 11 illustrates by measurement the input voltage V_{eEnt} , input current i_{eEnt} and its ripples Δi_{eEnt} of the interleaved Boost without coupling.

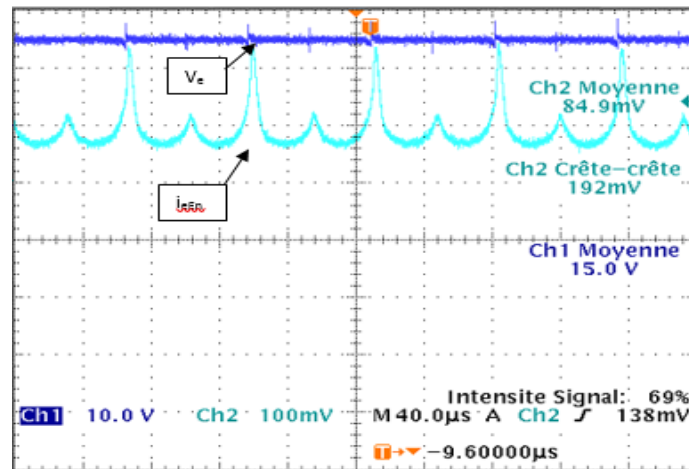


Figure 11. Input voltage V_e and current i_{eEnt} of the interleaved boost

We have the ripple of the input current $\Delta i_{eEnt} = 0.192A$. We will therefore have according to the measurements $\frac{\Delta i_{eEnt}}{\Delta i_{eCl}} = 68\%$.

The interleaving of the classic Boost converter with command shift, minimizes the ripples of the input current Δi_e . Figure 12 illustrates by measurement, the input voltage V_{eEntCo} , and input current i_{eEntCo} of the coupled interleaved Boost.

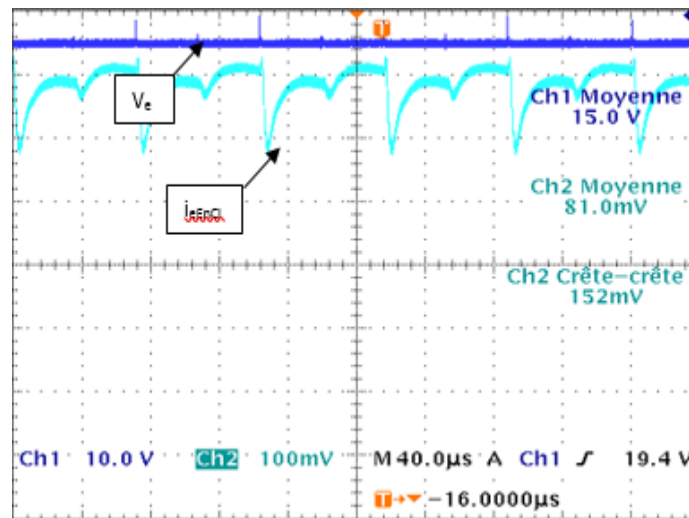


Figure 12. Input voltage V_e and input current i_{eEntCo} of the coupled interleaved boost with $D=0.5$ and $X=0.5$

We have the ripple of the input current $\Delta i_{eEntCo} = 0.152A$. We will therefore have according to the measurements $\frac{\Delta i_{eEntCo}}{\Delta i_{eEnt}} = 78\%$.

The inductances coupling approach of interleaved Boost and the shift of the command minimizes the ripple of the input current Δi_{eEntCo} compared to that of the interleaved Boost with independent inductors Δi_{eEnt} .

Figure 13 shows by measurement, the output voltage V_s and its ripples ΔV_{sCl} of the conventional Boost converter.

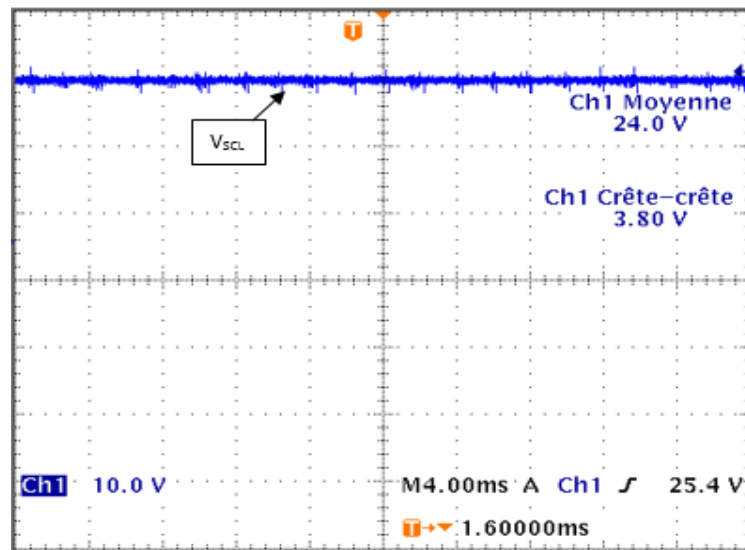


Figure 13. Output voltage V_{sCl} of the classical boost with $D=0.5$ and $X=0.5$

We have the ripple of the output voltage $\Delta V_{sCl} = 3.8V$.

Figure 14 illustrates by measurement, the output voltage V_s with its ripple ΔV_{sEnt} of the interleaved Boost converter.

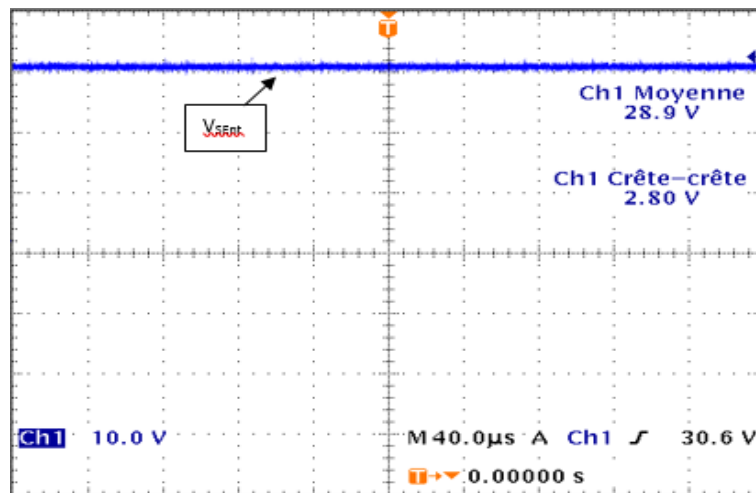


Figure 14. Output voltage V_s and, of the interleaved boost with $D=0.5$ and $X=0.5$

We have the ripple of the output voltage $\Delta V_{sEnt} = 2.8V$.

According to the measurements, we therefore have $\frac{\Delta V_{sEnt}}{\Delta V_{sCl}} = 73\%$. The interleaving of the classic Boost and the shift of the command, minimizes the ripples of the output voltage ΔV_s .

Figure 15 illustrates by measurement, the output voltage V_s and its ripples ΔV_{sEntCo} of the interleaved Boost converter with coupling of the inductors.

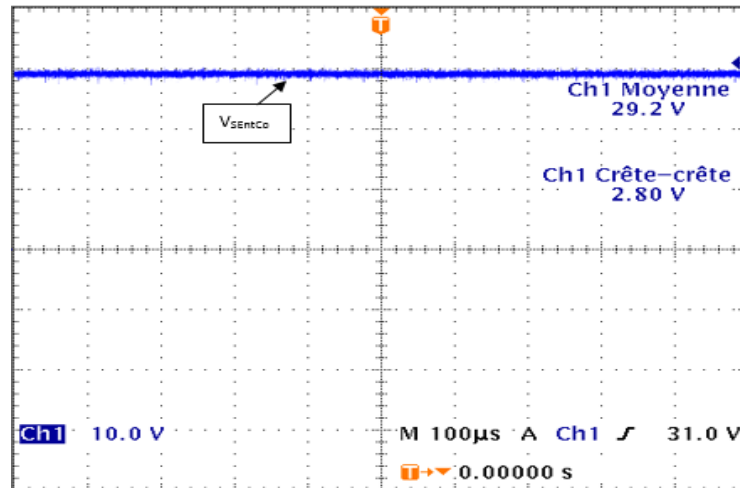


Figure 15. Output voltage V_s of the coupled interleaved boost with $D=0.5$ and $X=0.5$

We have the ripple of the output voltage $\Delta V_{sEntCo} = 2.8V$.

We therefore have, according to the measurements $\frac{\Delta V_{sEntCo}}{\Delta V_{Ent}} = 73\%$.

The interleaving approach of converters, with shift of the commands, minimizes the ripples of the output voltage. However, the coupling of the inductors does not allow any gain in terms of output voltage undulations ΔV_{sEntCo} .

5. CONCLUSION AND PERSPECTIVES

In this paper, we compare, by simulation and measurement, two topologies of conventional and interleaved Boost DC/DC converters, in terms of input currents and output voltages, the size of the converter components and the power extracted from photovoltaic panels:

- The currents in the components of the interleaved Boost converter, compared to the conventional Boost, are considerably reduced. As a result, the components (inductors, switches and capacitors of the converter) are miniaturized.
- The ripples of the input currents and the output voltage of the interleaved converters are small compared to those of the conventional Boost converter.
- The power extracted from the photovoltaic panel depends on the duty cycle D and the shift of the power switch commands.
- Interleaved Boost inductances coupling, further reduces the ripples of the input currents and maximizes more, the power extracted of the PV.
- The quality of the extracted power is improved in terms of ripples and value.

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