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Extension of the linearity range of a 3-phase Boost inverter for stand-alone photovoltaic panel-based emergency application.

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Abstract: In the context of autonomous applications isolated from electrical energy it is necessary to develop direct conversion structures giving a three-phase voltage system from a DC source. In this context, the booster inverter is an interesting solution since it limits the conversion stages. Output voltages are generally limited by the Boost conversion ratio, whose efficiency decreases rapidly. In this work we propose to extend the linearity range of the inverter function by injecting a suitable zero-sequence voltage.

Keywords: Optimization, Inverters control, Modulation, Non-linear control, Solar energy

1. INTRODUCTION

The use of electrical energy on isolated or islanded sites is increasingly being replaced by photovoltaic panel-based solutions or fuel cell system combined with direct energy converters (Videau & al. 2013). For three-phase applications (pumps, motors, etc.), converters based on three-phase inverters are distinguished by their simplicity. However, the amplitude of the usable voltages is limited by the DC-AC conversion ratio due to the increase in losses in the converter as the conversion ratio increases. To this end, we propose here to extend the linearity range of the step-up inverter by injecting a zero sequence voltage. In addition to the implementation of a non-linear control, this approach requires the resolution of an optimization problem under constraints. The results are validated in simulation in a realistic environment.

2. LIMITATION OF THE BOOSTER CONVERSION RATIO.

2.1 Case of the DC-DC Boost converter

The electrical diagram of the voltage DC-DC boost converter is shown in Figure 1.

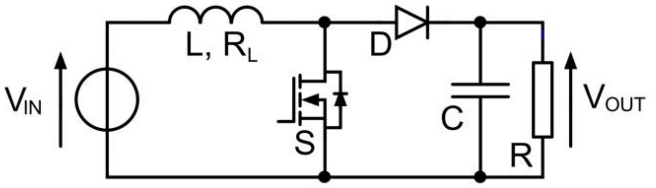

Fig.1: DC-DC Boost Converter

A modelling in the sense of average values makes it possible to determine the conversion ratio between the output voltage and the input voltage. If we consider that the inductance has a series resistance, the conversion ratio is given by the relationship (Videau & al. 2013), when the duty cycle varies.

$$\frac{V_{OUT}}{V_{INT}} = \frac{1}{(1-\alpha)+\frac{R_L}{R}\cdot\frac{1}{(1-\alpha)}} \quad \alpha\text{=duty cycle} \tag{1}$$

Thus the efficiency of the conversion function is strongly influenced by this series resistance, it is expressed by:

$$\frac{P_{OUT}}{P_{INT}} = \frac{1}{1+\frac{R_L}{R}\cdot\frac{1}{(1-\alpha)^2}} \tag{2}$$

Contrary to what the blue theoretical curve (Figure 2 (c)) may suggest, the converter conversion ratio is not infinite (Figure 2 (b)). The presence of parasitic elements in the various components limits the maximum achievable conversion ratio (red curve) [1], [2].

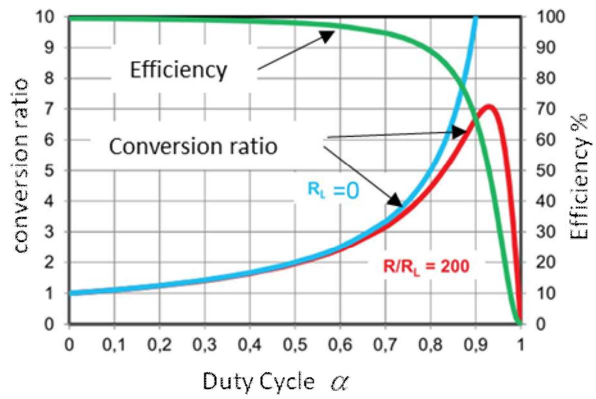

Fig. 2: Efficiency and conversion ratio as a function of the duty cycle

The efficiency (green curve) is degrades even more when the conversion ratio is high. This is 50% when the maximum value of the conversion ratio is reached. It should be noted that if we take into account the losses in the power components (switching losses, conduction losses) the situation deteriorates even further.

2.2 Single phase DC-AC Boost Inverter

By combining 2 classic structures we can build a single-phase Boost inverter, figure 3. This structure allows to generate an output voltage adjustable by action on the duty cycle (Colling & al. 2001). The output voltage is floating and is obtained by the difference between the 2 voltages across the capacitors.

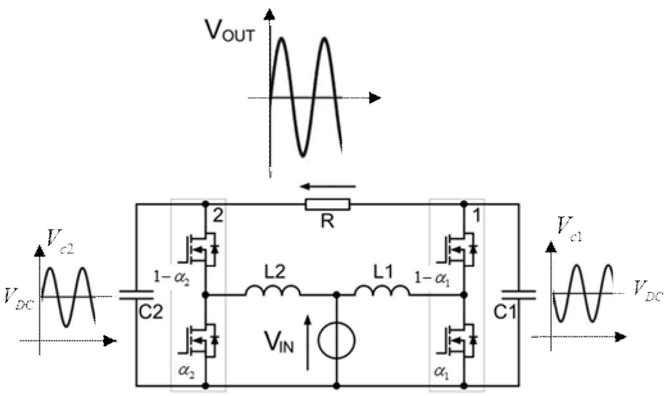

Fig.3: Single phase Boost Inverter

The principle of control consists in imposing the following voltages across the capacitors:

$$V_{c1}(t) = V_{DC} - V_m.\sin\Theta \tag{3}$$

$$V_{c2}(t) = V_{DC} + V_m.\sin\Theta \tag{4}$$

Thus the output voltage is expressed by:

$$V_{OUT}(t) = 2.V_m.\sin\Theta \tag{5}$$

If the conversion ratio for each inverter leg (cr) is limited to a value of 6 in order to guarantee an efficiency greater than 70%, the maximum conversion ratio for output voltage (cro) is limited to 5, in accordance with relationship (6):

$$cro = cr - 1 \tag{6}$$

Generally speaking, this structure does not allow very good efficiency with high conversion ratios.

3. 3-PHASE BOOST INVERTER

The extension of this structure to the three-phase case is shown in figure 4, (Sanchis & al. 2001), (Moussa & al. 2012). The output voltages are checked from the capacitor voltages. To obtain a three-phase voltage system at the output, the voltages at the capacitor terminals must comply with the following law:

$$V_{c1}(t) = V_{DC} + V_m.\sin\Theta \tag{7}$$

$$V_{c2}(t) = V_{DC} + V_m.\sin(\Theta - 2.\pi/3) \tag{8}$$

$$V_{c3}(t) = V_{DC} + V_m.\sin(\Theta + 2.\pi/3) \quad (8)$$

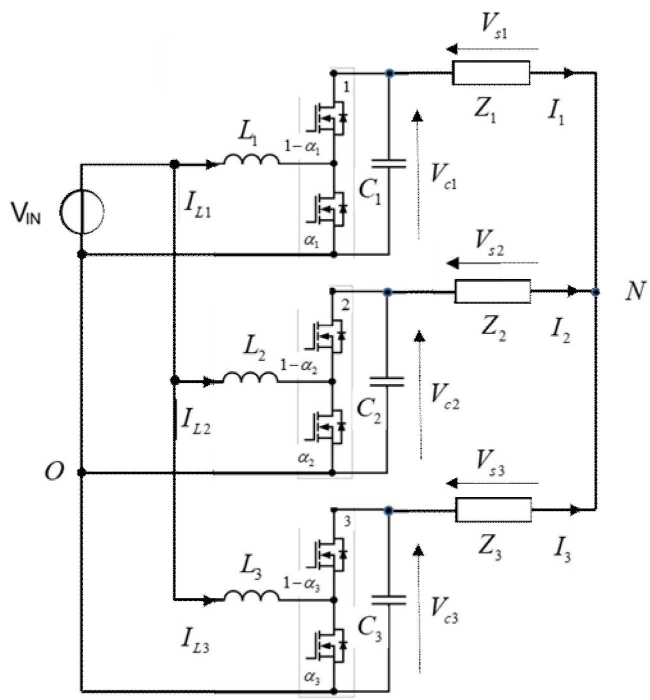

Fig. 4: 3-phased Boost Inverter

In this context, the conversion ratio of the output voltage is then equal to **2.5** according to the relationship:

$$cro = \frac{V_{s\max}}{V_{IN}} = \frac{cr-1}{2} \tag{9}$$

3.1 Modelling in average value of the converter

The behaviour of the 3 phases is similar and we can represent the evolution of the input currents by:

$$L_i.\frac{dI_i}{dt} = V_{IN} - (1-\alpha_i).V_{ci} \quad \text{for } i = 1,2,3 \tag{10}$$

$$\mathrm{C}_i.\ \frac{dV_{ci}}{dt} = (1-\alpha_i).I_i \quad \text{for } i = 1,2,3 \tag{11}$$

The coupling of the 3 elementary converters is done with the charge according to the following relationship:

$$\begin{bmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{bmatrix} = \frac{1}{3}.\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}.\begin{bmatrix} V_{c1} \\ V_{c2} \\ V_{c3} \end{bmatrix} \tag{12}$$

When the capacitor voltages are true to equations (7), (8), (9) then the output voltages become:

$$V_{s1}(t) = V_m.\sin\Theta \quad (13)$$

$$V_{s2}(t) = V_m.\sin(\Theta - 2.\pi/3) \quad (14)$$

$$V_{s3}(t) = V_m.\sin(\Theta + 2.\pi/3) \quad (15)$$

4. DEFINITION OF CONTROL LAWS

The operation of the converter represented by the model of equations (10), (11), (12) results in a non-linear system (Rachmildha & al. 2019). It is necessary to control 6 variables with 3 control variables. We propose to develop a cascade control structure with a fast loop controlling the currents in the inductances and then a voltage loop controlling the voltages across the capacitors. Operation is performed in PWM with a fixed switching frequency. Table 1 below gives the parameters of the converter.

Table 1. Parameters of 3-phase inverter

V_{IN}	200v	f_{sw}	80kHz
$L_1 = L_2 = L_3 = L$	100 µH	$Z_1 = Z_2 = Z_3 = R$	10 Ω
$C_1 = C_2 = C_3 = C$	150 µF	V_{DC}	500 v

In this example the conversion ratio is limited to 4 to limit losses in the converter. Thus the conversion output voltage will be limited to **1.5** according to the relationship (9) i. e. 300 V max output.

The control of the output voltages can be done in different ways and here the reference voltages are imposed indirectly by imposing the voltages across the capacitors. The voltages across the capacitors are themselves imposed by acting on the currents in the inductors by acting through the duty cycles. It is therefore a cascade diagram, figure 5, that is chosen and that we will develop in the following paragraph.

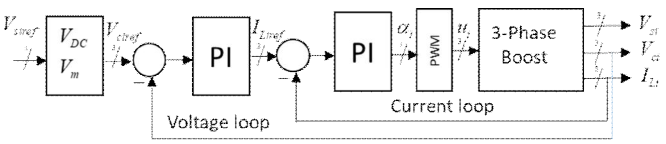

Fig. 5: General diagram of the output voltage control

4.1 Current loop

In order to linearize the behaviour, the control loop uses a compensator, figure6.

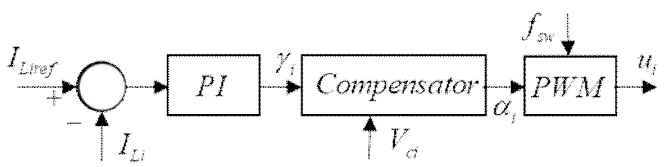

Fig. 6. Structure of the current loop

For each leg, the compensator is then expressed by:

$$\alpha_i = \frac{\gamma_i - V_{DC}}{V_{ci}} + 1 \quad (16)$$

With this compensator the system becomes linear and the regulator allowing to impose a bandwidth ω_{bpc} of value is expressed by:

$$K_p = L.\omega_{bpc} \quad \text{and} \quad \frac{1}{T_i} = \frac{\omega_{bpc}}{\sqrt{10}} \quad (17)$$

In order to maximize the performance of the current loop the bandwidth is chosen at:

$$\omega_{bpc} = \frac{2.\pi.f_{sw}}{\sqrt{10}} \quad (18)$$

4.1 Voltage loop

For the voltage loop we consider that the current loop is perfect as well:

$$I_{Li} \approx I_{Liref} \quad (19)$$

Then the tension loop can be described by the following equation:

$$\mathrm{V}_{ci}.\mathrm{C}.\frac{dV_{ci}}{dt} + \frac{V_{ci}^2}{R} = V_{IN}.I_{Liref} \quad \text{for } i = 1,2,3 \quad (20)$$

By making the following variable change: $x_i = V_{ci}^2$ (21)

The tension loop becomes linear and can be represented by the following transfer function:

$$\mathrm{T}_i(\mathrm{s}) = \frac{x_i(s)}{I_{Liref}(s)} = \frac{R}{\frac{R.C}{2}.s + 1} \quad \text{for } i = 1,2,3 \quad (22)$$

It is then simple to impose a bandwidth value ω_{bpv} by defining the parameters of the corrector by:

$$K_{pv} = \frac{C.\omega_{bpv}}{2} \quad \text{and} \quad \frac{1}{T_{iv}} = \frac{\omega_{bpv}}{\sqrt{10}} \quad (23)$$

The voltage loop is then defined by figure 7:

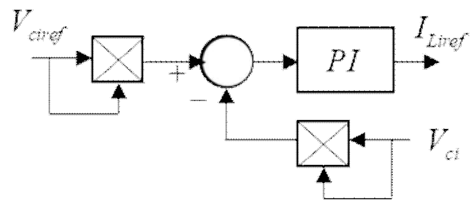

Fig.7. Structure of the voltage loop

To obtain the output voltages defined by (13), (14), (15) there are many solutions, the simplest of which is defined by:

$$V_{c1ref}(t) = V_{DC} + V_m.\sin\Theta \quad (24)$$

$$V_{c2ref}(t) = V_{DC} + V_m.\sin(\Theta - 2.\pi/3) \quad (25)$$

$$V_{c3ref}(t) = V_{DC} + V_m.\sin(\Theta + 2.\pi/3) \quad (26)$$

This solution is based on a zero-sequence voltage defined by:

$$V_{NO}(t) = \sum_{i=1,2,3} V_{ci} = V_{DC} \quad (27)$$

5. FIRST SIMULATION RESULTS

When looking for the operating limits for the amplitude of the output voltages, we observe that the voltage across the capacitors cannot fall below 200V (figure 8), this is the input voltage. Thus the amplitude limit of the output voltage is limited to 300V, which is what we see in figure 9.

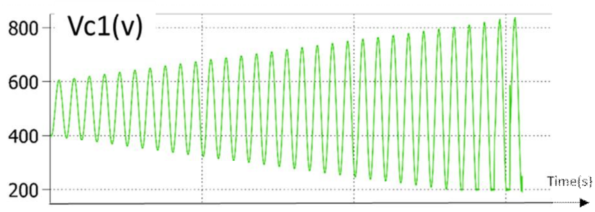

Fig.8: Voltage across capacitor Vc1(v)

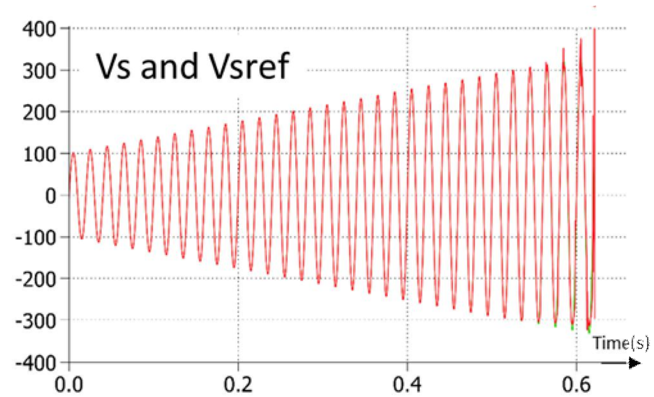

Fig. 9: Output Voltage and reference Vs1(v)

In accordance with the provisions of paragraph 4, the maximum output voltage is 300 V.

Figure 10 shows the input current of L1 inductor and confirms the non-sinusoidal shape related to the non-linear nature of the converter.

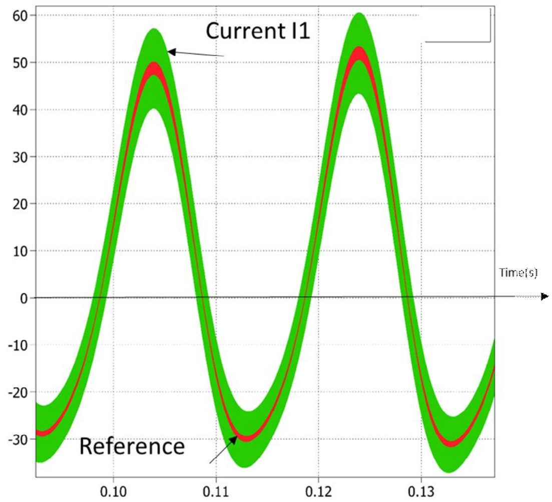

Fig. 10. Input Current and reference IL1(A)

6. EXTENSION OF THE LINEARITY RANGE BY INJECTION OF A ZERO-SEQUENCE VOLTAGE

For a given configuration (V_{DC} and V_{IN} fixes), we can ask ourselves what is the maximum voltage that can be obtained at the output? For this purpose, we must consider equation 12. This equation is of the form (28), where the matrix M is non-invertible.

$$\underline{V_s} = M.\underline{V_c} \quad (28)$$

In fact, the sum of the desired tensions is zero, which results in a degree of freedom. Thus it is possible to modify this relationship by deleting a line and replacing it with the control of a zero sequence voltage V_h. The equation becomes like this:

$$\begin{bmatrix} V_{s1} \\ V_{s2} \\ V_h \end{bmatrix} = \frac{1}{3}.\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ 1 & 1 & 1 \end{bmatrix}.\begin{bmatrix} V_{c1} \\ V_{c2} \\ V_{c3} \end{bmatrix} \quad (29)$$

$$\underline{V_s^{'}} = M^{'}.\underline{V_c} \quad (30)$$

In this case, the matrix M' is invertible and in order to obtain the reference voltages

$$\underline{V_s^{'t}} = [V_{s1r} \quad V_{s2r} \quad V_{hr}] \quad (31)$$

the solution is given by:

$$\begin{bmatrix} V_{c1} \\ V_{c2} \\ V_{c3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ -1 & -1 & 1 \end{bmatrix}.\begin{bmatrix} V_{s1r} \\ V_{s2r} \\ V_{hr} \end{bmatrix} \quad (31)$$

In order to maximize the output voltages, the half median voltage (figure 11) of the reference voltages can be chosen for the zero sequence voltage (Jacobina & al. 2001), (Holtz

1994), (Holmes & al. 2003), (Bouarfa & al. 2016), (Capitaneanu & al. 2001).

Thus the zero-sequence voltage is defined by:

$$V_h = V_{DC} + Vmedian \tag{32}$$

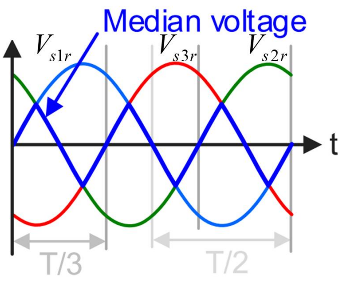

Fig.11: Median voltage

With

$$Vmedian = -0.5(\min(V_{s1r}, V_{s2r}, V_{s3r}) + \max(V_{s1r}, V_{s2r}, V_{s3r})) \tag{33}$$

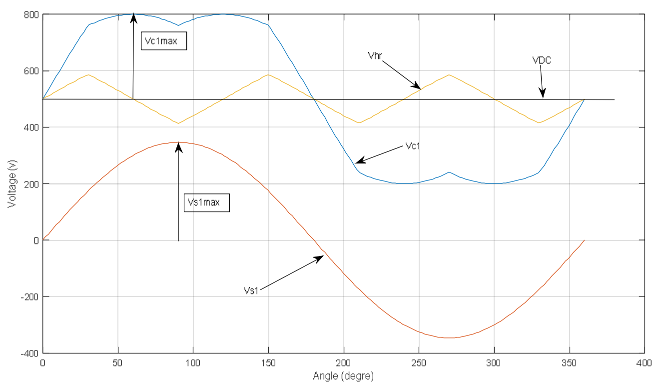

Fig.12: Reference Voltages

Theoretically, the maximum possible output voltage is expressed by:

$$V_{s1\max} = (V_{DC} - V_{IN}).\frac{2}{\sqrt{3}} \tag{34}$$

Thus the output conversion rate goes from 1.5 to $\sqrt{3}$ an increase of 15%, figure 12. This solution is equivalent to the solutions provided by a Space Vector Modulation approach (Holmes & al. 1992), (Bowes & al. 1997), (Jacobina & al. 2001).

This leads to a new control scheme to determine the reference voltages of the capacitor voltages, figure 13.

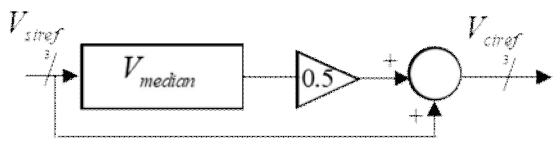

Fig. 13: New solution for reference generation

6. NEW SIMULATION RESULTS

In order to validate the results, we propose to repeat the same simulations as in paragraph 5 by modifying the reference voltages according to the relationship (31).

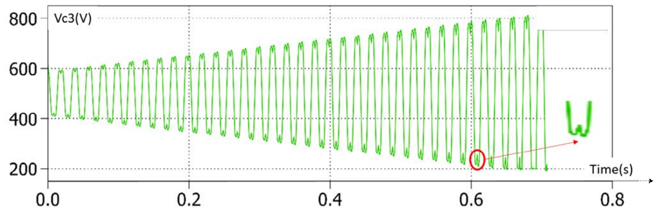

Fig. 14: Voltage across capacitor Vc3(v)

Injecting the zero sequence voltage (figure 14) on the voltage references reduces the amplitude of the reference voltages for capacitors by a factor of $2/\sqrt{3}$ .In Figure 15 we observe the good tracking of the reference voltage up to the value predicted by the theory, i. e. (34), 346,41v and even beyond, but with harmonic distortion. Beyond this limit the duty cycle reaches the stop and linearity is no longer guaranteed. This is inherent to the structure of the converter which must operate in boost mode, the output voltage must be higher than the input voltage. Figure 16 confirms this with the evolution of the duty cycle reaching the stop. Note the particular shape of the duty cycle carrying the harmonic 3 of the output frequencies.

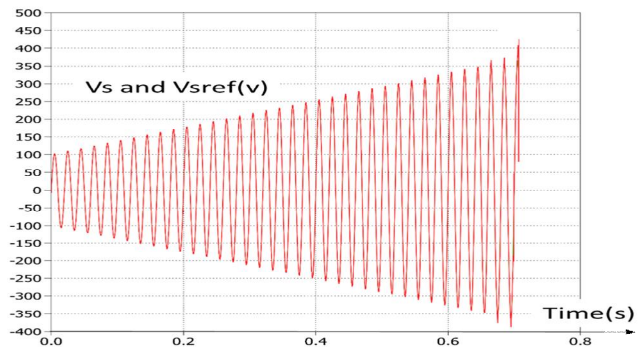

Fig. 15.: Output Voltage and reference Vs1(v)

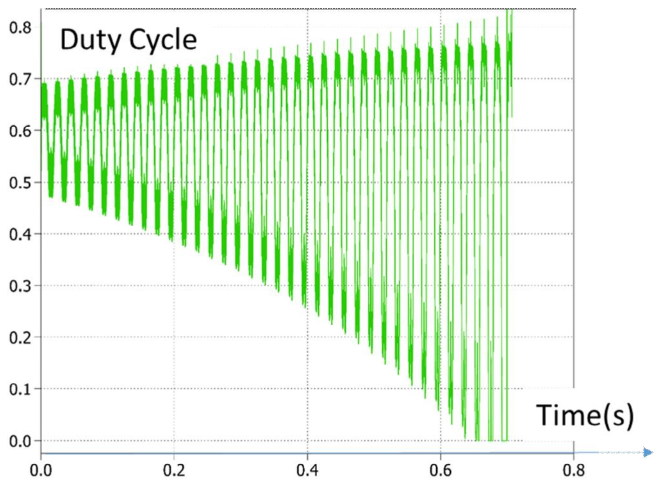

Fig16.: Duty cycle evolution in phase 1

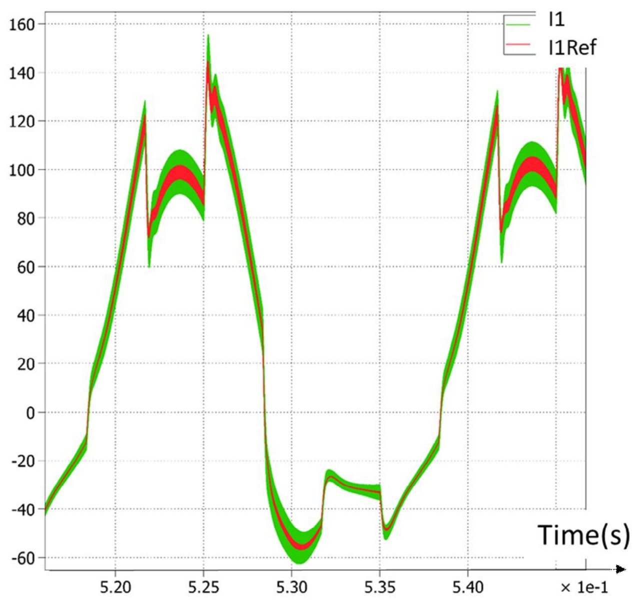

Fig. 17: Input Current and reference IL1(A)

The injection of the zero sequence voltage distorts the current drawn by each arm of the converter, Figure 17.

7. CONCLUSIONS

In this paper we have worked on an isolated energy supply system based on a continuous source, which could be a photovoltaic panel or a fuel cell supplying a three-phase charge through a single static conversion stage. In this context the Boost inverter is a good candidate and we have to try to maximize the output voltage without degrading the quality of the voltage. Thus we have shown that the injection of a zero sequence voltage increases the conversion ratio between the input voltage and the output voltage by a factor of $2/\sqrt{3}$ or 15%.

This solution is not very expensive in terms of control; it would be a shame to do without it!

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