

## The three-phase interleaved boost rectifier: Study and comparison

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### Abstract:

The three-phase interleaved boost rectifier operating in discontinuous current mode (DCM) is studied and characterized. It presents advantages compared with classical DCM boost rectifiers. Better power factor correction (PFC), reduced high frequency harmonics, lower output voltage, and greater efficiency are the main ones. Easy to control, it draws continuous current mode input currents. It is suitable for medium power switch mode power supplies.

### Introduction:

For power rectification, classical diode or thyristor converters were mainly used. However due to new high power standards IEC 1000-3-2 [1] and IEC 1000-3-4 [2], these converters do not comply anymore with specifications depending on power supply capabilities (short circuit power). As a result, a new family of converter is born, the PFC rectifiers [3]. They provide active input current shaping and output voltage control. These two essential tasks make them suitable for switch mode power supplies in a wide range of power depending on the converter topology and capabilities.

For three-phase applications, several converters are available but most of them are derived either from the single-switch boost rectifier or from the full bridge rectifier. On one hand, the single-switch boost rectifier is simple and permits high power density rectification, and it can give correct results in medium power range [4,5]. However, it generates large high frequency EMI and its power factor correction capabilities are dependent on output voltage (it is not possible to use complex control strategies). On the other hand, the full bridge rectifier is more complex involving slightly complex control strategy but it gives good results in a wider power range [6].

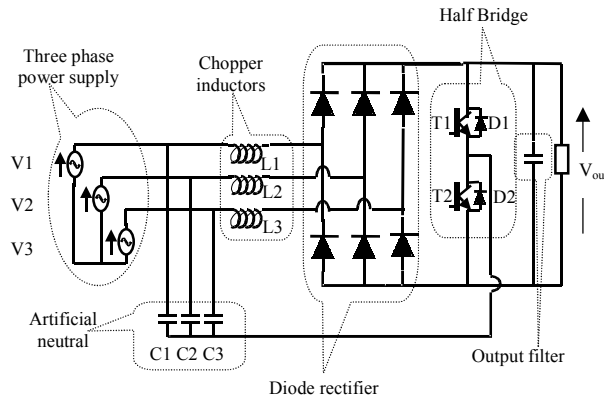
The aim of this paper is to present and to study a new converter [7] that presents advantages of both topologies. It's going to be introduced and its behavior will be described. Main characteristics and operation specifications will be underlined. Simulation and experimental results will be given to validate theoretical work. Finally a comparison with the single-switch classical PFC rectifiers will be presented in order to underline its best characteristics.

### The structure:

#### Presentation.

The structure is drawn Fig.1. It is made out of a classical three-phase diode rectifier followed by a half bridge inverter, which injects high frequency currents in an artificial capacitor neutral. Boost choppers can be seen considering a loop made out of an inductor ( $L_n$ ), a neutral capacitor ( $C_n$ ) and part of the half bridge switches. Each boost chopper is operating in discontinuous current mode as classical DCM

boost rectifiers. Both are out of phase such that the two switches never conduct at the same time (therefore, maximum duty cycle is  $\alpha=0.5$ ).

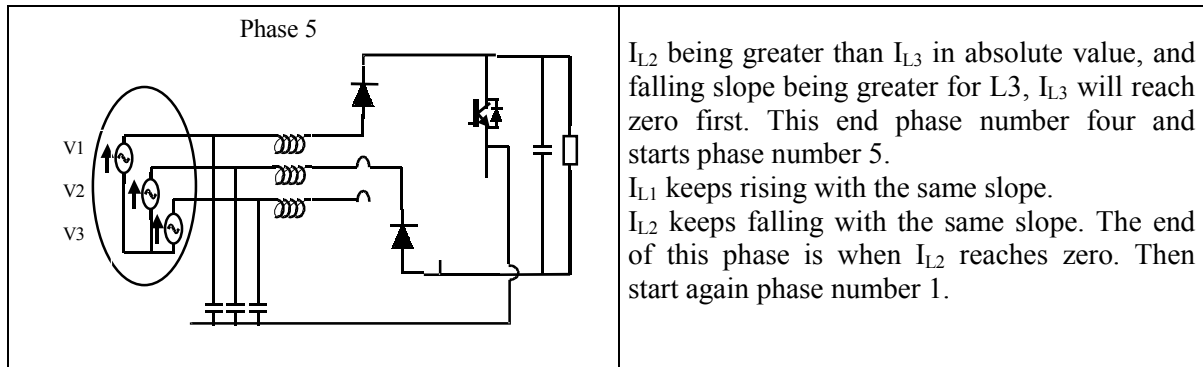


**Fig.1:** The three-phase structure.

**Operation principle:**

Operation principle of the converter can be decomposed in five sequences. They are described in the following plots and comments below (it is given for a direct three-phase power supply (origin V1) when V1 is positive and V2 and V3 are negative with V2 lower than V3). It has to be mentioned that the presence of the artificial capacitor neutral modify the behavior of the converter compared with the single-switch three-phase rectifier.

<p style="text-align: center;">Phase 1</p>	<p style="text-align: center;">Phase 2</p>
<p>Switch T1 is on. During this phase, energy is stored in L1 through the loop C1, L1 and T1 (under V1). The other inductors L2, L3 are totally discharged.</p>	<p>Switch T1 is turned off and switch T2 is turned on. Stored energy in L1 (falling slope <math>(V_{e1}-V_s)/L</math>) is fed to the load through D2 and energy is stored in L2 and L3 (rising slopes <math>V_{e2}/L</math> et <math>V_{e3}/L</math>) through T2.</p>
<p style="text-align: center;">Phase 3</p>	<p style="text-align: center;">Phase 4</p>
<p>When <math>I_{L1}</math> equal zero, phase 3 starts. Switch T2 is kept on and while energy is stored in L2, L3 (phase 3 is equivalent to phase 1 but for the two other inductors).</p>	<p>Switch T2 is turned off and switch T1 is turned on. Stored energy in L2, L3 (falling slopes <math>(V_s-V_{e2})/L</math> and <math>(V_s-V_{e3})/L</math>) is fed to the load through D1 and energy is stored in L1 (rising slopes <math>V_{e1}/L</math>) through T1.</p>



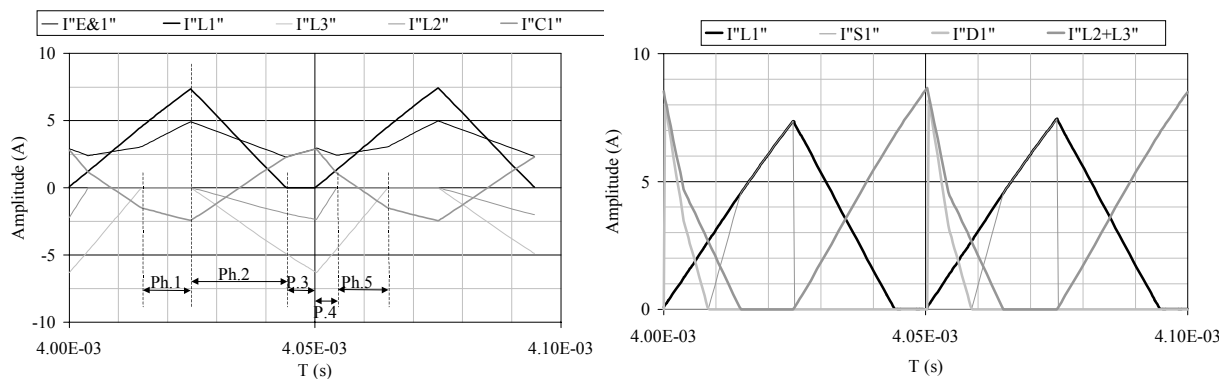
**Comments.**

The presentation of the operation principle allows to underline several aspects:

First of all, this converter can be seen as a sum of three single-phase single switch boost rectifiers operating in discontinuous current mode. Indeed, each boost chopper is always supplied by its own voltage source  $V_n$  corresponding to a neutral capacitor  $C_n$  voltage. This means that minimum output voltage can be equal to maximum composed input voltage  $U_{12}=V_1-V_2=565V$  (considering a 230:400V power supply).

$$\alpha := \frac{V_{out} - V_{max}}{V_{out}} \tag{eq.1}$$

Another interesting aspect is the natural filtering effect provided by the capacitor neutral. This is illustrated below Fig.2 with a current sharing representation during a switching period for one phase.



**Fig.2:** High frequency switching patterns.

It can be seen that part (one third in theory) of the current fed to the inductor  $L1$  comes from the corresponding neutral capacitor  $C1$  and that the other part (the two other thirds) is split on the other neutral capacitors and comes from the voltage source  $V1$ . This clearly shows the natural filtering effect of the artificial neutral. It is important to see that this filtering effect can be achieved even if line impedance is neglected. Besides, it will be shown later that the presence of line impedance improves even more the filtering capabilities of the artificial neutral.

$$I_{in1} = (2 \cdot I_{L1} - I_{L2} - I_{L3}) / 3 \tag{eq.2}$$

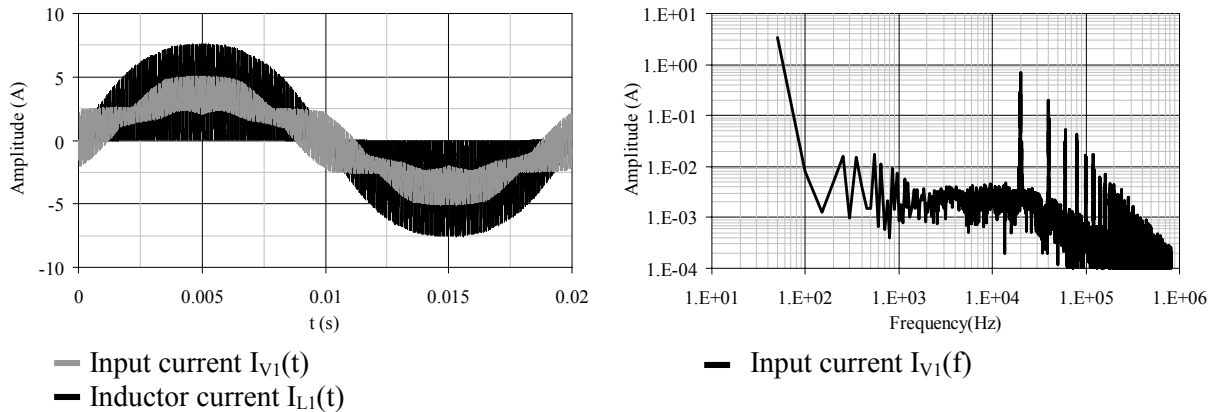
Finally, it has to be underlined that interleaved rectifier operates under reduced conduction losses. This can be seen looking at the currents flowing through a switch and its anti-parallel diode ( $D1$ ,  $T1$  for example). During phase 4 and 5, both semiconductors are supposed to be on. In fact currents are compensated as it is shown in plots below (Fig.2). This means that interleaving topologies allow to obtain lower conduction losses (whenever phases 2 and 4 occur in this case).

## Theoretical and experimental results.

Operation point is set at:  $V_{in}=127V$ ,  $V_{out}=375V$ ,  $P_{out}=1kW$ ,  $L=3*600\mu H$ ,  $C=1\mu F$ ,  $\alpha=0.45$ ,  $F_o=20kHz$

### Theoretical results.

Simulations have been run using time domain power electronic software Simplorer [8].



**Fig.3:** Theoretical results of the interleaved boost rectifier.

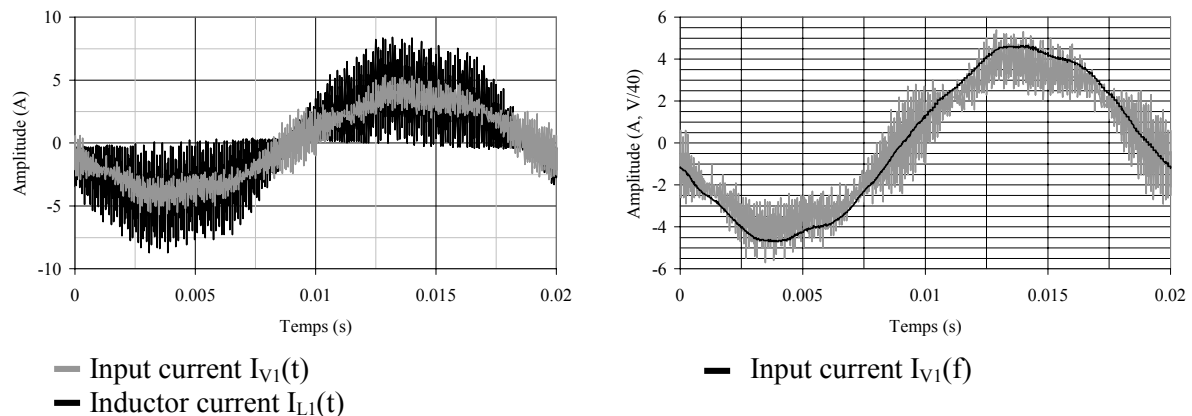
As it can be seen on the above plots, theoretical behavior corresponds quite well with resulting time and frequency domain results. It can be seen that input current is quasi-sinusoidal (almost no low frequency harmonics on the frequency representation). Besides it is in continuous current mode with a resulting high frequency ripple.

### Practical results.

Experiments have been realized in order to check the theoretical behavior and forecasted capabilities of the converter. This has been realized considering a 127/220V power supply in order to reduce output voltage under 600V and to be able to use 600V raing components (IGBT, diodes and output filter). Operation point is set identical to the above theoretical part:

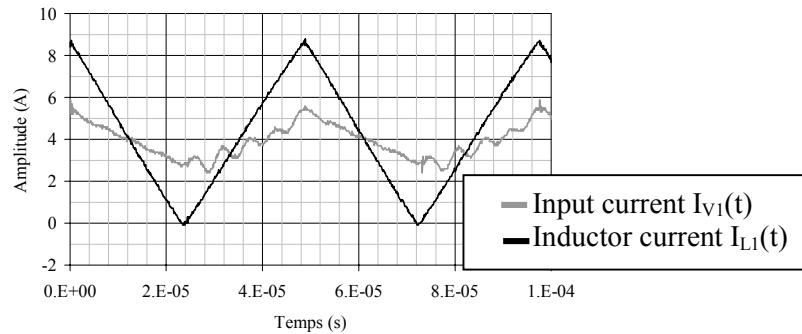
Note: effect of the line impedance has been reduced using large capacitors.

The following plots shows line current  $I_{in1}$ , the inductor current  $I_{L1}$  and the supply voltage  $V1$  for a line period.



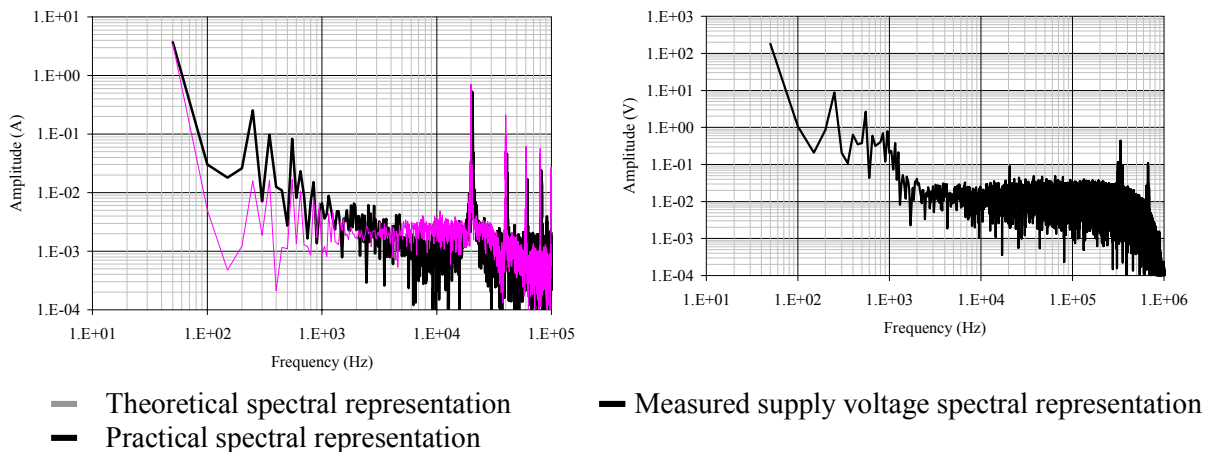
**Fig.4:** Practical results of the interleaved boost rectifier.

It can be seen that PFC is achieved correctly (input current in phase with input voltage). Besides, whereas inductor current is discontinuous, input current is continuous with a high frequency ripple. This is underlined below where are shown inductor current and line current over a switching period. It can be seen that high frequency inductor current ripple is greatly reduced due to artificial neutral effects.



**Fig.5:** Input current and inductor current over two switching periods (practical results).

A spectral representation of input current has been realized in order to quantify remaining low order harmonics. Below are shown theoretical and practical spectral representation of input current. It can be seen that low order harmonics are reduced and remain under standards specifications. However both results are different. This is due to power supply quality which is plotted below (Fig.6.right). The converter operating in open loop, it is highly dependent on power supply waveform and quality.

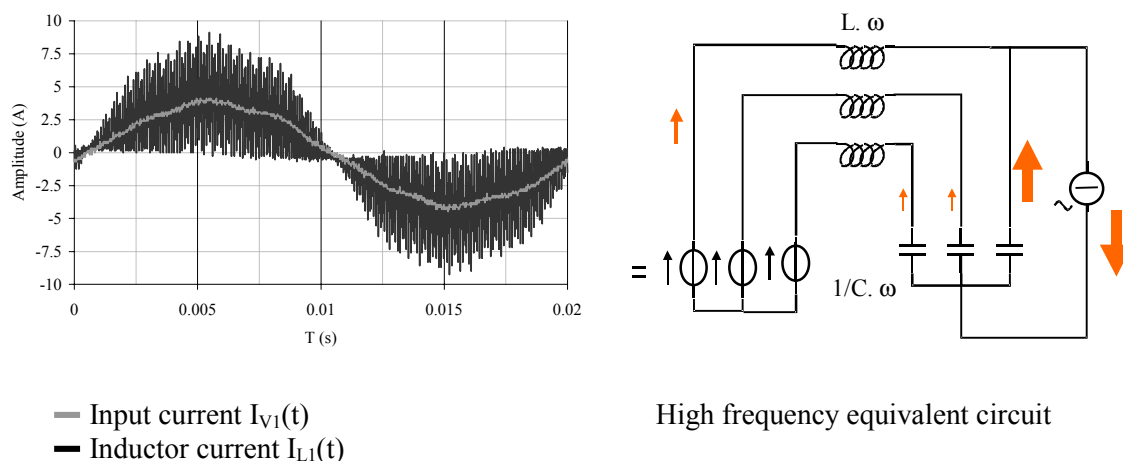


**Fig.6:** Frequency domain representations of input current and voltage.

**Effect of the line impedance:**

As it has been underlined previously, the effect of the line impedance has been neglected. In real cases, there is always a line impedance. This improves even more filtering effect as it could be supposed. The plot below (Fig.7) presents practical results where the converter has been directly connected to the main.

It clearly appears that high frequency ripple current is greatly reduced. This can easily be explained considering the plot given Fig.7.right. The greater will be the line impedance the greater will be the current coming from neutral capacitors.



**Fig.7:** Practical results considering inductive line impedance.

**Comments.**

It has to be mentioned that neutral capacitor value can be reduced without problem on the converter behavior and operation. Main consequence is that greater amount of power flows trough the converter considering identical control variable values ( $F_o$  and  $\alpha$ ). An interesting aspect is that the lower will be the capacitors the closer will be the switching frequency and the resonance frequency between  $C$  and  $L$ . This create a new operation mode that can provide additional interesting characteristics. Comparable work has been realized on the DCM single switch three-phase boost rectifier [10].

**Comparison with the three-phase single switch boost rectifier.**

This converter seems to present several interesting characteristics. However, additional components are required. Therefore, in order to really underlined its interesting aspects, this part proposes a theoretical comparison between the three-phase interleaved rectifier and the three-phase single-switch boost rectifier [4]. In order to compare them, identical operation points are considered for both converters (no inductive impedance is considered in this comparison).

Operation point is:  $V_{in}=230V$ ,  $V_{out}=1000V$ ,  $P_{out}=1kW$ ,  $F_o=20kHz$

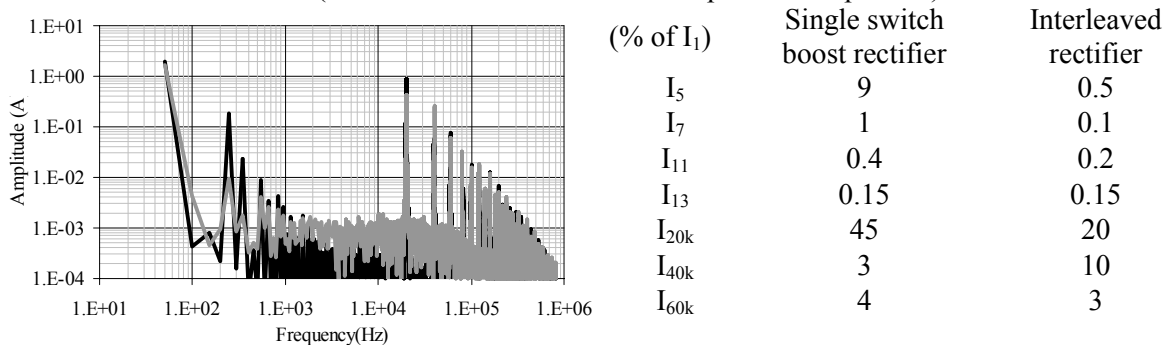
(which comply with requirement of both converters).

With such operation point, each converter has specific input inductor value and duty cycle:

For single-switch boost rectifier:  $L=3*1.65mH$ ,  $\alpha=0.437$

For interleaved rectifier:  $L=3*1.7mH$ ,  $\alpha=0.45$ ,  $C_n=1\mu F$

Below is given for this identical operation point the frequency domain representation of the input current for both converters (with a main harmonic table for specific comparison).



**Fig.8:** Theoretical frequency representation of input current for both converters (with a comparison table).

It can be seen that interleaved boost rectifier low frequency harmonics are really lower compared with the ones of the single switch boost rectifier. Besides as it can be seen, lower high frequency harmonics

are also obtained. In addition to these aspects, reduced conduction losses are obtained with the interleaved rectifier.

Coming from this comparison, the interleaved boost rectifier seems interesting. However the real interest of this structure is the fact that output voltage can be reduced a lot compared with classical boost rectifier (in a ratio of two). This allows to use lower output component ratings (capacitor switches, free wheeling diodes) which induce cost saving but also efficiency improvements due to better on state and switching characteristics of active components.

Besides, classical boost rectifiers always require input filter. It can be shown that in order to reduce the first switching frequency harmonic of the boost rectifier down to the interleaved rectifier harmonic values, 2.5 $\mu$ F filter capacitors (considering a line impedance of 100 $\mu$ H) are required compared with 1 $\mu$ F showing once more the interest of the structure.

#### Advantages

- Lower output voltage (very important in three-phase applications).
- Lower low frequency harmonics (dependent on output voltage).
- Lower switching frequency multiples harmonic levels (considering identical filters in both cases).
- Reduction of switch stress (lower conduction losses and stress repartition).
- Equivalent amount and size of passive components in both cases.

#### Drawbacks:

- Two switches and therefore two drivers.
- Additional input capacitors (although also necessary for the boost rectifier to reduce differential mode current harmonics).

### **Conclusion:**

This converter clearly appears as a possible simple converter for switch mode power supplies for medium power range. It realizes main tasks and provides advantages compared with classical DCM three phase boost rectifier. A 1kW three-phase experiment has been built and it validates the above current waveforms. Better PFC, reduced conduction losses and reduced component ratings make this converter really interesting. EMI characterization remains to be done. Besides new operation principle must be investigated (resonance) in order to improve efficiency and high frequency harmonics.

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