Is Loss free Modulator the Central Component of Switching Power Electronics? Application to Flyback Structure.

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Abstract—**To account for time variation in equivalent circuits, we introduce a macro component: the loss free modulator (lfm). In practice, it is made of a chopper inserted between two loss free smoothing filters so it behaves as an ideal transformer with a time varying voltage ratio. That way, a converter can be presented as a set of inductors and capacitors, only required to temporally store energy, associated to one or more lfm.**

As a first illustration, behavior of modulated inductors and capacitors, made of an lfm loaded respectively by an inductor or a capacitor, is derived and some surprising applications of these circuits are described.

Then, it is shown that, whatever its structure, a power factor corrected ac-dc converter must store a minimum energy to work properly. In most of practical designs, this minimum is overcome by a 10 ratio. Lowering this energy close to its minimum, offers an opportunity to use the lfm concept. Owing to two lfm, one of which being digitally controlled, the goal is reached. Simulated and measured results are presented and discussed.

Finally, the approach followed in this paper is summed up and it is suggested that it can be useful for many converter designs.

Index Terms: Time varying linear circuits, stored energy minimization, Power Factor Correction ac-dc converters.

I. INTRODUCTION

Contrary to analog filter, electronic power converters are often non linear and always time varying and the major part of their behavior is connected to the later property rather than to the former one. Converters essentially include switches and storage elements and smaller reactive components are used to remove residual switching frequency. This suggests that the representation of such circuits can be strongly clarified by grouping, in one component, every chopper with its input and output filters (Figure 1). Such a device, we call loss free modulator (lfm), looks like an ideal transformer with a time varying ratio $\eta(t)$. For the example shown in figure 1, if $\alpha(t)$ is the duty cycle of the switch, i.e. the time fraction it spends in position 1, then $\eta(t) = \alpha(t)$. That way, numerous converters appear as a set of lfm and energy storage components.

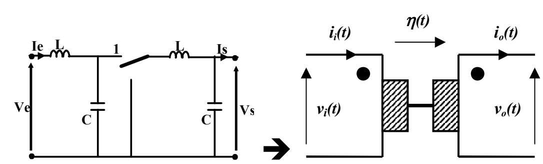


Figure 1: A Buck chopper with its HF filters behaves as a loss-free modulator

This macro component is equivalent to the modulated transformer introduced by bond graph method [1] but applications presented here are original. In practice, this component allows careful power flow investigation to be done before choosing the chopper topology and technology so these unavoidable steps are carried out when energy storage and power flow are precisely known and that simplifies the design process. Several examples will be presented to illustrate this approach.

Loading an lfm with a capacitor or with an inductor gives, at its input, a modulated capacitor or inductor. Relations linking voltage to current flowing through these two types of time varying components are established. It appears that modulated components behave very differently than constant ones. To illustrate this, we show how the voltage across a modulated capacitor can be sinusoidal when its current is constant.

After this introduction, we examine power flow in a PFC ac-dc converter. Such a converter must store, whatever its structure, a minimum energy which is easily computed. Surprisingly, most of common converters store 7 to 10 times this minimum value [2], [3]. Thus, in order to minimize stored energy, we replaced the output capacitor of a flyback converter by a modulated one. Resulting circuit have been built and tested and experimental data are supplied.

Circuits are studied owing to Simplorer and Pspice softwares [5]. Measurements have been done on a 25 W prototype in which the lfm was controlled by a digital circuit.

Finally, it is shown that the lfm concept is very useful during the preliminary study of a converter when focus is on: how to control the energy flow (in the steady state and during transient), evaluation of energy storage needs and search of ideal control laws. Simplifications this component brings free imagination so that surprising circuits can result.

II. LFM AND MODULATED REACTIVE DIPOLES

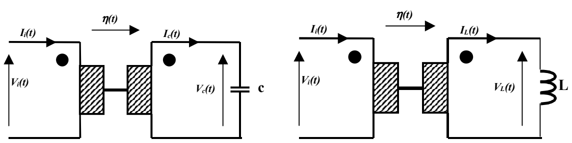
A. Loss free modulator (lfm):

As seen in figure 1, a lfm is made of one chopper with associated smoothing filters. The voltage ratio η is controlled by the switch duty cycle and its variation range depends on the chosen chopper. For the Buck chopper of figure 1, $0 < \eta < 1$, for a Boost $1 < \eta < \infty$ ...

This ratio range is a major criterion for chopper selection. Let us only remind that, for temporary accumulation choppers it can take every value of a given sign and that bridge choppers provide sign change. Combining these properties, every ratio range is reachable.

B. Electrical behavior of modulated reactive 2-port circuits.

Let us consider a circuit made of an lmf loaded by either a capacitor or an inductor (Figure 2).



a b

Figure 2: Modulated capacitor and modulated inductor.

Input impedances of these circuits are well known when η is constant. They depend on L or C and η:

$$L_i = \frac{L}{\eta_L^{\,2}} \quad \text{and} \quad C_i = C \cdot \eta_C^{\,2} \tag{1}$$

When η is time varying, the link between $i_i(t)$ and $v_i(t)$ is different. Because the input capacitance is now time varying, usual relations are not all usable. There are several consistent ways to define instantaneous capacitance $C_i(t)$. We choose that relying on the energetic relation, so stored energy in the dipole is written as:

$$W(t) = \frac{1}{2} \cdot C_i(t) \cdot V_i^2(t) = \frac{1}{2} \cdot C \cdot V_c^{\,2}(t) \tag{2}$$

From the definition of η, it comes:

$$V_c(t) = V_i(t) \cdot \eta_C(t) \text{ and } C_i(t) = C\, \eta_C^{\,2}(t) \tag{3}$$

Input current is obtained by deriving the stored energy and, finally, characteristic equation of modulated capacitor is established:

$$P(t) = V_i(t)\, I_i(t) = C_i(t) \cdot V_i(t) \cdot \frac{dV_i(t)}{dt} + \frac{1}{2} \cdot V_i^{\,2}(t) \cdot \frac{dC_i(t)}{dt}$$

so:

$$I_i(t) = C_i(t) \cdot \frac{dV_i(t)}{dt} + \frac{1}{2} \cdot \frac{dC_i(t)}{dt} \cdot V_i(t) \tag{4}$$

A very similar method supplies the characteristic relation for the modulated inductor (Figure 2-b):

$$L_i(t) = \frac{L}{\eta_L^{\,2}(t)} \tag{5}$$

and $$V_i(t) = L_i(t) \cdot \frac{dI_i(t)}{dt} + \frac{1}{2} \cdot \frac{dL_i(t)}{dt} \cdot I_i(t) \tag{6}$$

C. Special application:

Before solving a practical problem (§ III), we illustrate lfm approach benefit by solving an academic one: how to obtain a sinusoidal voltage across a modulated capacitor which is gone through by a constant current?

To answer this question, we first examine power flow in circuit shown in figure 3.

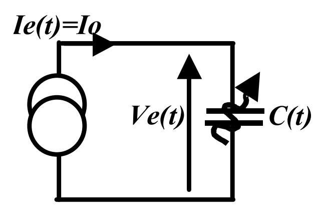


Figure 3: a modulated capacitor gone through by a constant current.

Noting *Vm* the voltage sine wave amplitude, power supplied to the modulated capacitor *P(t)* and energy stored inside *W(t)* are easily found and last one leads to the voltage ratio function of the needed modulated transformer.

$$P(t) = Vm\ Io\ \sin(\omega t)$$

$$W(t) = \frac{2\ Vm\ Io}{\omega} \sin^2\left(\frac{\omega}{2} t\right) = \frac{1}{2} C\, \eta^2(t)\ Ve^2(t)$$

$$\eta(t) = \pm \sqrt{\frac{Io}{Vm\ C\ \omega}}\, \frac{1}{\cos\left(\frac{\omega t}{2}\right)} \tag{7}$$

According to (7) chopper choice is guided. First, sign of *η(t)* changes twice a period. This leads to choose a bridge chopper. Moreover, voltage waveform across the modulated capacitor being continuous as well as that across the capacitor, the bridge must switch when the former is null. If, in addition, we choose C smaller than a value given below, the needed voltage ratio remains, for a whole half period higher than 1 so during this time, the chopper behaves as a boost. As a result we choose the circuit shown in figure 4.

$$C < \frac{Io}{Vm\ \omega} \Rightarrow \sqrt{\frac{Io}{Vm\ C\omega}} > 1 \quad (8)$$

Working of this circuit is as follows. During half a period, T2 is closed and T4 is open. In the same time, T1 and T3 provide the chopping and the involved duty cycle $\alpha(t)$ is that of T3. During the following half period, T1 is closed, T3 is open, T2 and T4 provide the chopping and the duty cycle is fixed by T4.

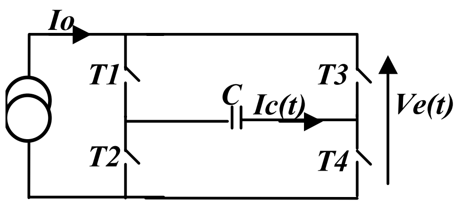


Figure 4: Modulated capacitor including

During each half period this circuit works as a boost so the voltage ratio is the inverse of the duty cycle. As a consequence, the variation law of the duty cycle is written as:

$$\alpha(t) = \frac{1}{|\eta(t)|} = \sqrt{\frac{Vm\ C\omega}{Io}}\left|cos(\frac{\omega t}{2})\right|$$

Simulation of this circuit is particular: there is no loss to damp the circuit. The only possibility to reach the steady state consists in giving initial conditions that equal that of steady state. Smoothing filters are removed to simplify these initial conditions. However, to obtain a clean curve, we apply a moving average filtering on the simulated curve with a characteristic time equal to chopping period. Result is shown in figure 5.

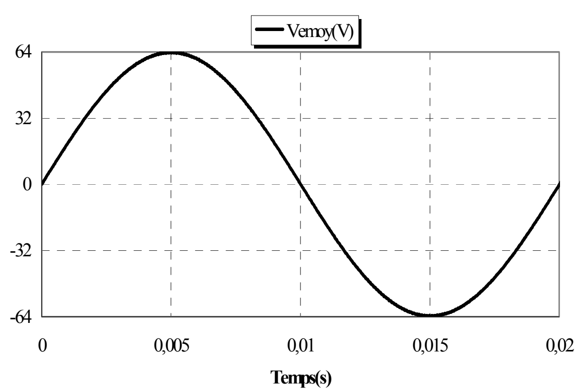


Figure 5: Simulated voltage across the modulated capacitor

Simulation has been carried out owing to Simplorer with the following parameters: Vm = 64 V, Io = 10 A, C = 450 µF. Chopping frequency is equal to 10 kHz.

III. PFC AC-DC CONVERTER: A POWER FLOW INVESTIGATION

This study concerns the two port circuit we put between the rectifying bridge and the continuous output (Figure 6). Ideally speaking, its input behaves as a pure resistance, its output voltage is perfectly constant, and its power efficiency equals 1. These few simple assumptions suffice to evaluate the minimum energy this circuit needs to store.

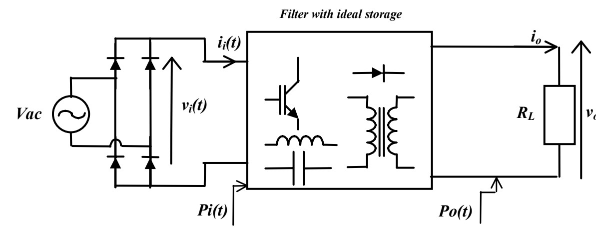


Figure 6: AC-DC circuit studied. Input voltage

With variables defined as in figure 6, the net power $P(t)$ input in this filter is:

$$P(t) = Pi(t) - Po(t) = v_i(t)i_i(t) - v_o i_o$$

Noting Ri the input resistance of the converter, input power is easily written and, after transients, average input power equals the output one $Po = v_o \cdot i_o$. Finally we can express the instantaneous power $P(t)$ as a function of Po:

$$P(t) = \frac{(Vo\ sin\omega t)^2}{Ri} - Po = -Po\ cos(2\omega t) \quad (9)$$

Integrating (9) leads to the energy stored inside the circuit:

$$W(t) = \frac{-Po}{2\ \omega} sin(2\omega t) + cst$$

To be physically realistic, this energy must remain positive. Consequently, we adjust the additive constant so that minimum energy is null:

$$W(t) = \frac{Po}{2\omega}(1 - sin(2\omega t)) \quad (10)$$

This expression shows that, in this ideal situation stored energy stay below W_{min} given by:

$$W_{min} = \frac{Po}{\omega} = \frac{Po \cdot T}{2 \cdot \pi} \quad (11)$$

Where T is the power network period

That means that, independently of chosen design and technology, no circuit works correctly if it cannot store, at least, W_{min}. An efficient control of the instantaneous energy allows the absolute minimum (11) to be closely approached.

IV. FILTERING FLYBACK OUTPUT BY A MODULATED CAPACITOR

Single-stored PFC of flyback used in ac-dc conversion adds input current control to output voltage regulation in the same converter [2], [6]. The greater disadvantage of this circuit is that the output capacitor must be dimensioned for a low frequency (twice the power network one) [4]. In this section, we examine how to lower energy storage in that converter.

A. Discontinuous mode in Flyback structure

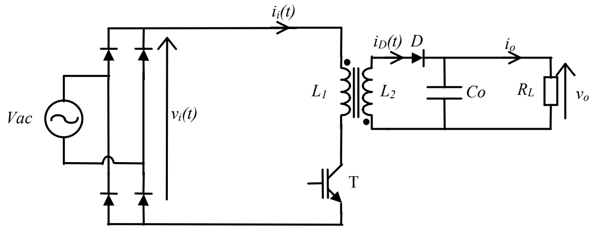


Figure 7: Flyback principal circuit

Discontinuous conduction is obtained when *L2* is completely discharged in R_L and *Co* within a switching period. This period can be subdivided in to three phases: one phase of current growth in *L1*, one phase of current decrease in *L2* and the last one during which both currents are null (Figure 8).

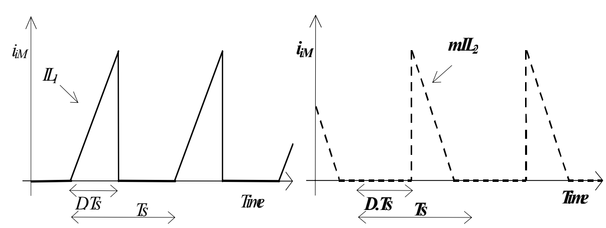


Figure 8: Waveforms in discontinuous conduction mode.

Discontinuous conduction is obtained by choosing control frequency *Fs* and duty cycle *D* accordingly to circuit time constant. Owing to these conditions, input current $i_i(t)$ is naturally sinusoidal as this appears below:

$$i_i(t) = \frac{D^2 \cdot v_i(t)}{2 \cdot L_1 \cdot Fs} \tag{12}$$

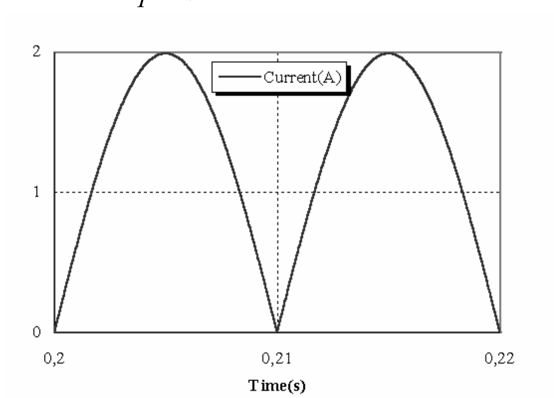


Figure 9: Simulated input current.

Figures 9 and 10 shows simulation results obtained with the following parameters:

- Input voltage : 185 V-265 V; 50 Hz,
- Output voltage 54 V,
- Output Power 324 W.
- Magnetic inductor : *Lm=70 µH*,
- Transformation ratio : *m=0.55*,
- Switching frequency : *Fs=50 kHz*,
- Output capacitor : *Co=10 mF*,
- Duty cycle : *D=0.207*.

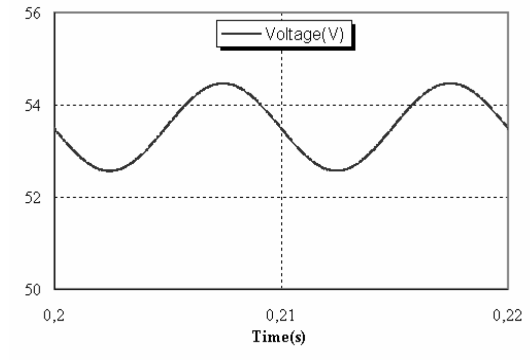


Figure 10: Simulated output voltage ripple (steady time).

Average input current is perfectly sinusoidal while, for chosen output capacitor value, output voltage waveform contains ± 2% low frequency ripple.

Energy stored in the output capacitor is evaluated to 14.6 J. To lower this value, we now introduce a modulated capacitor.

B. Replacing the storage capacitor by a modulated one

Voltage across a modulated capacitor can remain constant despite energy stored inside varies periodically. To take advantage of this property, we try to replace capacitor *Co* in figure 6 by a modulated one.

Ideally, stored energy varies according to (10) and, if it is that of a modulated capacitor, it is also given by (2) and (3). These relations gives the voltage ratio $\eta_c(t)$ of the modulated transformer:a

$$w(t) = \frac{1}{2} \cdot C \cdot \eta_C^2(t) \cdot vo^2 = \frac{Po}{2\omega} \cdot \left(1 - sin(2\omega t)\right) \tag{13}$$

$$\eta_C^2(t) = \frac{Po}{C\omega\, vo^2} \cdot \left(1 - sin(2\omega t)\right) \tag{14}$$

Now, let us examine the consequences of this variation law. First, there is no need to change the sign of the voltage ratio and, consequently, no need to use bridge chopper. Second, at first sight, with a convenient choice of *C*, variation range of η can be bound between 0 and 1 that suggest the use of a buck chopper but a fast calculation shows this choice leads to high capacitance values (sustaining very low voltage).

In order to use lower capacitance value with different technology, it is possible to keep η above one by storing a small amount of extra energy: an increase of a few % of 1 inside the parenthesis of (14) allows this possibility. We checked this possibility and, choosing a boost, we replaced the storage capacitor *Co* by the modulated capacitor shown in figure 11 which is realized with bi-directional switches. In this case, output smoothing filter is useless.

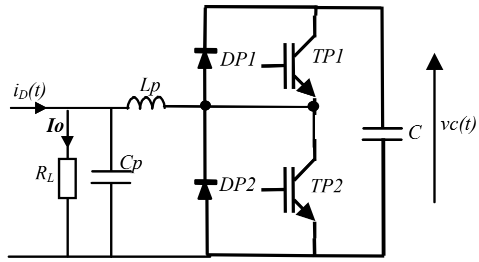


Figure 11: This modulated capacitor replaces *Co* in figure 6.
Lp=350 μH, *Cp=4 μF*, *Fc=50 kHz*, *C=100 μF*

For a boost the relation between *η(t)* and the duty cycle *Dc(t)* is:

$$\eta(t) = \frac{1}{Dc(t)} \qquad (15)$$

This gives the control law of the duty cycle $D_C(t)$

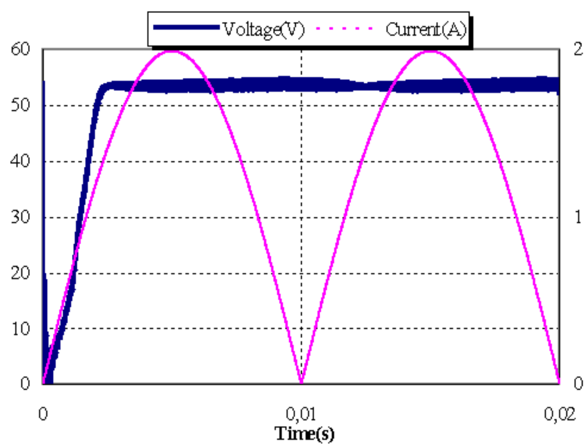


Figure 12: Simulation of output voltage and input current (with modulated capacitor)

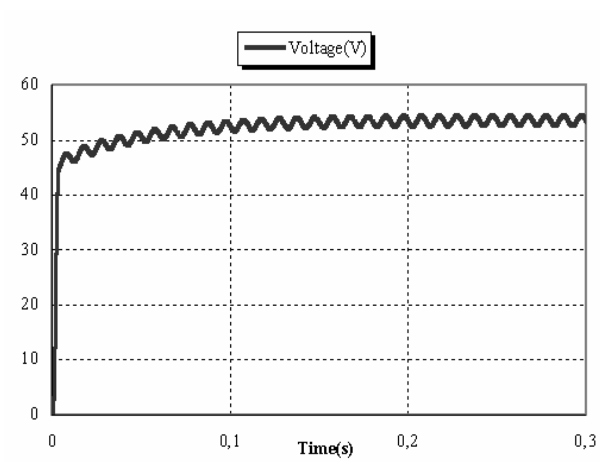


Figure 13: Transient output voltage simulation of initial circuit with Co=10 mF.

High frequency filter have been dimensioned to give the same ripple as initial structure (Figure 6). Rise time is smaller than 5 ms (Figure 12), that is 20 times less than that of initial structure (Figure 13).

The maximum energy stored in the modified circuit is calculated by adding energies stored in all reactive components including *Lp* and *Cp*. It is evaluated to 1.04 J. So, while the same voltage ripple is reached, the ratio of the two stored energies is over 10. A lighter ripple can be obtained by increasing the switching frequency *Fc* of the modulated capacitor without changing its reactive elements

V. Experimental Results

A prototype has been built to check the consistence of previous assumptions. It is a 25 W flyback which supplies 25 V at its output.

To control the modulated capacitor, the duty cycle variation law has already been obtained as (15) and (14). However, the delay introduced by the elements of the filter Lp, and Cp (Fig. 11) has a non negligible impact. To account for this, we extracted the energies stored in these elements to obtain an improved variation law of $D_C(t)$:

$$\alpha(t) = \sqrt{\frac{C}{2\cdot\left(\frac{Po}{2\cdot\omega}.(k - sin(2.\omega.t)) - W_{Lp}(t) - W_{Cfp}(t)\right)}}\cdot Vo \qquad (16)$$

With :

$$W_{Lp}(t) = \frac{1}{2} Lp\left(\frac{Vo}{Io} cos(2\omega t)\right)^2$$

$$W_{Cp}(t) = \frac{1}{2} Cp\ Vo^2$$

Control function (16) is not simple to generate using analog circuits. For this reason, we tried a numerical solution (Fig. 14). One period (10ms) of the variation law was represented by 1024 samples and then introduced in an eprom. The digital output of this eprom was input in a digital analog converter (DAC08). Then, the analog signal was introduced in a comparator (LM311) together with a triangular wave so the comparator outputs a binary signal, which exhibits the correct duty cyclic (Figure 15). This was, for our team, the first attempt to use such a complicated control law. Now, these problems are solved elegantly thanks to DSP.

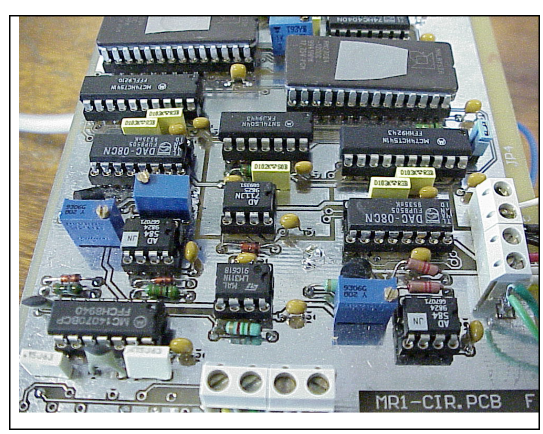


Figure 14: Digital switches control PCB

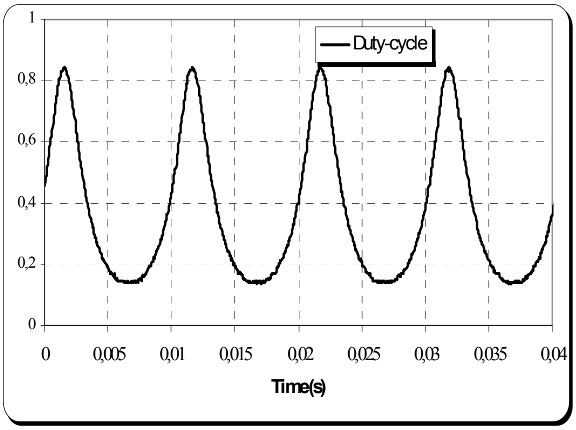


Figure 15: Measured duty cycle evolution

Measured output voltage (Figure 16), shows ± 2% ripple, that is ± .5V for 25 V output voltage.

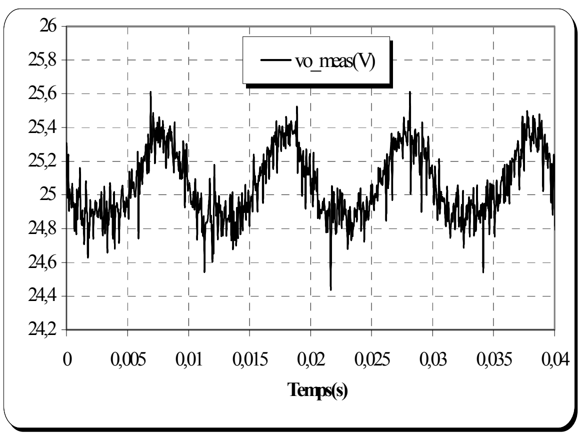


Figure 16: Measured output voltage
C=15 µF, Cp=4 µF, Lp=350 µH, Fc=50 kHz, R_L=50 Ω

VI. EXTENSION

Using the presented method, it is quite easy to investigate original solutions and some general conclusions arise.

First, storage components always store positive energies. To do the job it is always possible to choose a capacitor as well as an inductor. Moreover, keeping constant the sign of inductor current or capacitor voltage is possible too. Electrochemical capacitor area of use is thus extended.

Adjusting the minimum stored energy to zero leads to the variation law of voltage ratio and, in general, the range of values taken by this parameter guides the chopper choice. However, addition of a small amount of extra stored energy gives a freedom degree. Its impact on variation range can change the conclusion regarding chopper choice.

In view of fully integrated low power converters, all these possibilities could be interesting while DSP and additional switches do not cost a lot.

To end, let us mention another benefit. When a reactive component is linked to the circuit by a lfm, a multiplying factor close to 1 applied to $\eta(t)$ allows a different value of L or C to be chosen. This eases the use of standard values and a lower capacitance sustaining a higher voltage or reversely can replace that initially chosen.

VII. CONCLUSION

First, loss free modulator (lfm) is introduced to replace every chopper with its input and output smoothing filters. Then, electrical behavior of modulated (= time varying) capacitor and inductor, which are a direct application of lfm, are established. As illustrated by an example, these components behave very differently than constant ones.

Then, power flow through an ideal PFC ac-dc conversion is investigated in detail. It is shown that a minimum energy must be stored in that converter to obtain proper working. A look at common converter shows that this minimum value is always overcome, often by a 10 ratio. Thanks to lfm, we found a circuit that lowers the stored energy close to its absolute minimum. The new circuit is designed, simulated and even built and tested successfully. Because energy storage is about ten times less than for the standard solution, rising time is about 10 times shorter.

The design method which appears through presented examples is useful to elaborate original functions. In particular, it could be interesting to design low power converters fully integrated on silicon dies.

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