Boost PFC with 100 Hz Switching Frequency Providing Output Voltage Stabilization and Compliance with EMC Standards

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Abstract. Consumer and household applications require cheap ac/dc power supplies complying with EMC standards. Passive solutions are bulky and do not provide output voltage stabilization. Active solutions based on PFC's with high-frequency switching provide compactness and regulation capability, but are generally expensive due to the need for fast-recovery diodes and complex EMI filters.

This paper describes a boost PFC in which the switch is turned on and off only twice per line period. This results in limited di/dt and dv/dt and switch losses, allows use of slow-recovery diodes and avoids the need for heavy EMI filters. In addition, the output voltage can be stabilized in a broad load range by a simple control. The switching unit, including control and protection, can also be integrated in a simple smart-power IC for large-volume applications.

I. Introduction

Line-current harmonic standards, like IEC-1000-3-2 [1], have lead to a great effort in developing front-end AC to DC converters complying with the standard limits. Many power factor corrector (PFCs) topologies, which draw a current nearly proportional to the input voltage, have already been extensively analyzed in the literature.

However, these high-frequency switching preregulators considerably increase cost and complexity of the conversion unit and contribute to the generation of high-frequency elettromagnetic interferences, calling for suitable EMI filters in order to comply with high-frequency emission limits, like those set in EN standards 55014, 55022 and 50081-1.

Large volume applications, like household appliances and personal computers, require very cheap and reliable solutions, so that, in many cases, passive filters are still used in conjunction with diode rectifiers. For example, a classical diode bridge rectifier and filter capacitor with a series filter inductor (L-C rectifier), can achieve compliance with the standards, however, bulky and heavy reactive components are needed [2].

Different passive configurations are analyzed in [3], which are derived from the classical L-C filter by adding another capacitor inside the rectifier or even another diode [4]. The result is a substantial improvement of the harmonic content of the absorbed current and power factor. However, such solutions are useful for an input power up to 300W, even taking into account the Class A limits of IEC 1000-3-2 [1]. Moreover, being completely passive, these solutions do not provide output voltage stabilization.

This paper discusses a boost rectifier in which the switch is operated only twice per line period. This approach, which is intermediate between passive and high-frequency active solutions, allows compliance with the standards up to an output power of 700W. Moreover, the low frequency commutation results in limited di/dt and dv/dt and switch losses, allows use of slow-recovery diodes and avoids the need for heavy EMI filters. Another important feature is the possibility to regulate the rectifier output voltage in a wide load range.

Section II describes rectifier operation and its main wafeforms, section III makes a comparison with a passive solution and gives more hints on the converter operation and section IV reports experimental results taken on a 600W prototype which show a good agreement with the theoretical expectations.

II. Low-Frequency Switched PFC

The scheme of the proposed Power Factor Corrector is shown in Fig. 1. Unlike an usual boost PFC, all diodes are rated for line frequency operation. In addition, the design criteria of filter inductor L, snubber circuit and heatsink (not shown) are substantially different. The switching unit is made up of switch, diode and snubber.

Let us consider first, for reference, the case of a standard diode-capacitor rectifier with inductive filter. The scheme is the same of Fig. 1 without the switching unit. For an ac voltage of 220 V_{rms} (which is the minimum voltage

considered by IEC 1000-3-2) and a rated power of 300 W, the minimum value of inductor L which allows compliance with the standard is 19mH ($C_L = 940\mu F$). In this case, the output voltage at the rated current is 276V, due to the inductor voltage drop. The resulting line current waveform is shown in Fig. 2a and the corresponding harmonic spectrum is shown in Fig. 2b. As we can see, the waveshape of the input current waveform classifies the rectifier as a Class D equipment, whose limits are reported in Table I (these limits apply for equipment having an input power between 75 and 600W; for higher power levels the limits of Class A apply). Note that the maximum power deliverable by the equipment is limited by the third harmonic as stated also in [2]. Class D limits are given as relative values (mA_{rms}/W) and are shown in Fig. 2b for the rated output power, together with Class A limits. The latter, also listed in Table I, are given as absolute values, thus making easier compliance with the standards for low-power applications.
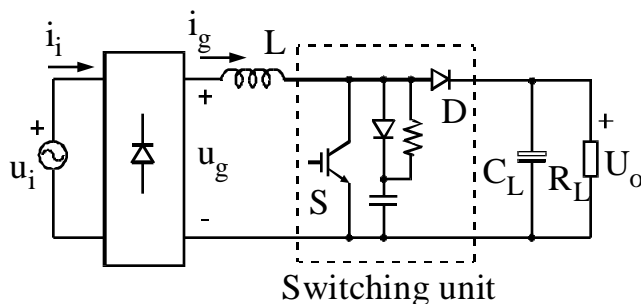

Fig. 1 - Basic scheme of low-frequency PFC

In order to enter Class A, the waveshape of the input current of the rectifier must be changed so as to stay outside the Class D template shown in Fig. 2a for at least 5ms, [1]. For this purpose, it is important to remember that the Class D template must be centered to the highest current peak and scaled accordingly.

Table I - IEC 1000-3-2 Harmonic current limits for Class A and Class D equipment

Harmonic order n	Class A A_{rms}	Class D mA_{rms}/W
3	2.30	3.4
5	1.14	1.9
7	0.77	1.0
9	0.40	0.5
11	0.33	0.35
13	0.21	0.296
$15 \le n \le 39$	2.25/n	3.85/n

The switching unit added to the standard passive L-C filter shown in Fig. 1 achieves Class A operation by operating the switch just twice per line period. The corresponding current drawn by the line is shown in Fig. 3a, together with the Class D template, for the same operating

conditions $U_i = 220V_{rms}$ and $P_o = 300W$. The switch is turned on with a constant delay after the zero crossing of the line voltage. The switch turn off is commanded by the output voltage regulator when the instantaneous switch current reaches a suitable reference value, thus allowing a simple current limiting protection to be implemented. During the on time, which is relatively short as compared to the line half-period, the inductor current increases almost linearly, with a slope determined by the instantaneous input voltage and by the inductor value. As the switch turns off, the filter inductor resonates with the output capacitor, giving rise to the current waveform shown in Fig. 3a. The resulting input current waveform stays outside the Class D template for more than 5% of the line half-period, thus the equipment is in Class A. As a consequence, the filter inductor needed to comply with the standards, at this power level, reduces to 6mH. Note that the maximum load power is now limited by the high-order harmonics.

The output voltage is now stabilized at about 300V, since the boost effect compensates for the inductor voltage drop.
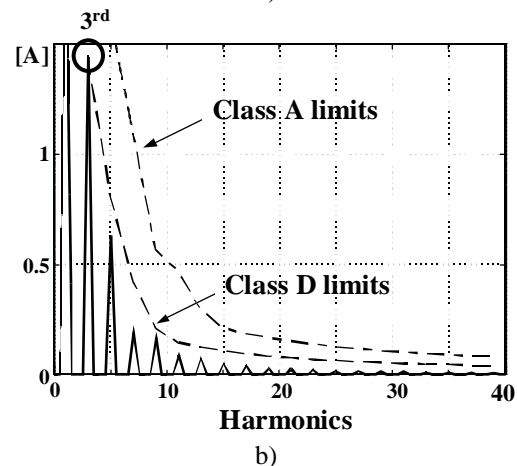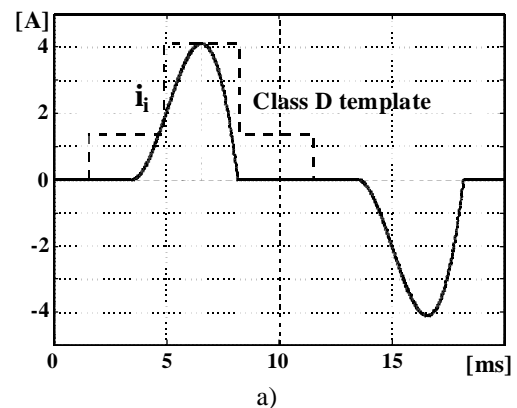

a)

b)

Fig. 2. a) Input current waveform of the passive L-C filter ($U_i = 220V_{rms}$) and Class D template; b) input current spectrum with Class D and Class A limits (fundamental component out of graphic range)
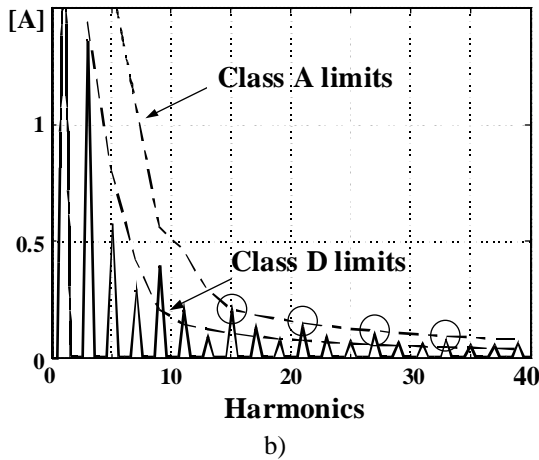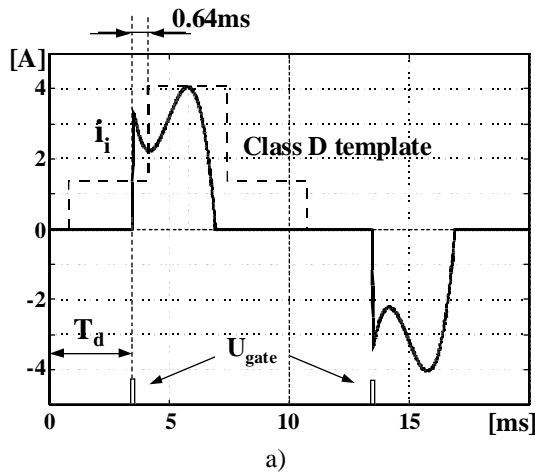
Fig. 3. a) Input current waveform of low-frequency PFC and Class D template; b) input current spectrum with Class D and Class A limits (fundamental component out of graphic range)

III. DESIGN CONSIDERATIONS

A. Selection of reactive element values

For the purpose to develop a full-compliant rectifier, the first step is the selection of the L and C reactive element values. As far as the output capacitor value is concerned, a good guess is the value obtained by the approximate analysis of the classical diode-bridge+capacitive filter rectifier, i.e.:

$$C_L = \frac{P_o}{2 f_{LINE} U_o \Delta U_{opp}} \tag{1}$$

where ΔU_{opp} is the maximum allowed output voltage ripple (peak-to-peak). Note that, due to the extended diode conduction angle, caused by the filter inductor, and the switching unit operation, the effective output voltage ripple will be lower than the theoretical one. Later we will quantify this output voltage ripple reduction.

The choice of the filter inductor is more difficult and the design guidelines we given here shall be verified by simulation. Nevertheless, we can make the following considerations:

- for power levels below 600W the main goal is to modify the waveshape of the input current so as to take advantage of the less restrictive Class A limits. This single condition, in most cases, allows compliance with the standard. Thus, a good starting point should be an inductor value which, without the help of the switching unit, achieves at least 60° of conduction angle, which is the width of the Class D template. Only in this case, in fact, the switching unit can increase the conduction angle so as the current waveform stays outside the Class D template for at least 5% of the line half-period.
- for power levels above 600W no difference exist between Class D and Class A limits, thus the inductor value should be progressively increased as the power increases. In fact, the extension of the conduction angle and the reduction of the current rate of change during the switch on-time are mandatory in order to keep the current harmonics below the limits.

B. Selection of switching unit parameters

The actual harmonic content of the current drawn by the line, besides the inductor value, depends on many other factors, like the turn-on delay time T_d and the switch on-time T_{ON} (see Fig. 3a), which, in turn, affect also the output voltage value. As an example, we consider a converter which must deliver an output power of 300W with an output voltage of 300V, which is also the situation described in the previous section. Following the guidelines given in subsection A, the output capacitor value turns out to be 2x470μF for 10V output voltage ripple (peak-to-peak) and the inductor value results 6mH (3.4ms of conduction interval without the switching unit).

The dependence on T_d and T_{ON} was analyzed by simulation for an input voltage of 220V$_{rms}$. Fig. 4 shows the effect of changing the turn-on delay time T_d with a constant switch current reference (the natural diode turn-on instant is about 4ms). The effect of lower T_d values is to increase the diode conduction angle, which has a beneficial effect on low-frequency harmonics, and, at the same time increases the sharpness of the first current peak, which, instead has a detrimental effect on high-frequency harmonics. As a result, the input current THD changed moderately (some harmonics increase and other decrease), while stabilization of the output voltage is affected, as reported in Table II.

In conclusion, it is better to choose a turn-on time T_d not too far from the natural diode turn-on instant.

The effect of the on-time T_{ON} is analyzed in Figs. 5 and 6. The first shows the input current waveforms for different T_{ON} values with T_d constant at 3.4ms. Waveforms a), b), and c) are still in Class D, while curves d) and e) belong to Class A. Their harmonic content (up the 19th harmonic) is reported in Fig. 6: as we can see, up to the 7th harmonic, the increase of T_{ON} causes a reduction of the harmonic peak value, while higher order harmonics rapidly increase (see 11th, 15th, and 17th). Curve e) is actually at the limit in the 15th and 17th

harmonics. The output voltage variation as function of T_{ON} is reported in Table III: as expected, higher T_{ON} values enhance the boost action, causing an increase of the output voltage, which is a beneficial effect.

From the above analysis, we can also observe that in general it is not possible to increase the initial current peak to make it the highest peak, in order to exit Class D template more easily, because high order harmonics become rapidly dominant.

In conclusion, the highest T_{ON} value should be chosen which still complies with the standards.
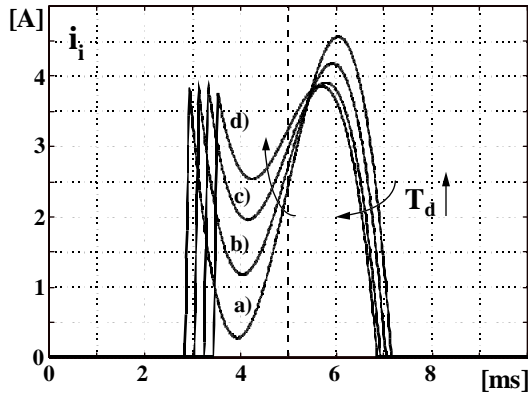
Fig. 4 - Input current waveform at increasing T_d values. a) T_d = 2.8ms; b) T_d = 3ms; c) T_d = 3.2ms; d) T_d = 3.4ms; Curves a), b) and c) belong to Class D, while curves d) and e) belong to Class A ($T_{ON} \approx 80\mu s$, U_i = 220V_{rms}, P_o = 300W)

C. Output voltage regulation

The output voltage can be regulated against load variation by simply modulating the switch on-time T_{ON}, while keeping the turn-on delay time T_d constant. This is accomplished by using a standard PI regulator with a low bandwidth (below the line frequency) like any other PFC regulator. Clearly, the output voltage regulation cannot be maintained below a minimum power level. In fact, this type of control can only produce a boost action, thus it can work only for power levels for which the passive L-C rectifier (without the switching unit) achieves an output voltage value below the reference value. For this reason, a high output voltage reference is preferable, since it can be maintained for a broader load variation. Just to clarify, the converters whose parameters are listed in Table IV (Active rectifiers) can maintain the output voltage regulation approximately down to 30% of the nominal power.

As far as the input voltage variation is concerned, we can make similar considerations, i.e at lower input voltage values, the control is able to maintain a constant output voltage by increasing the switch turn-on interval, while at higher input voltage values it becomes a simple L-C rectifier.
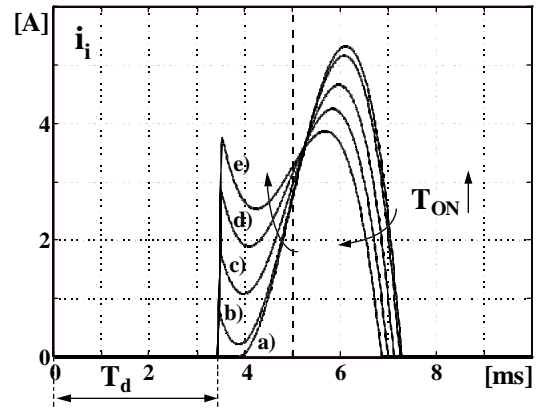
Fig. 5 - Input current waveform at increasing T_{ON} values. a): passive L-C filter; b) T_{ON} = 20μs; c) T_{ON} = 40μs; d) T_{ON} = 60μs; e) T_{ON} = 80μs. Curves a), b) and c) belong to Class D, while curves d) and e) belong to Class A (T_d = 3.4ms, U_i = 220V_{rms}, P_o = 300W)
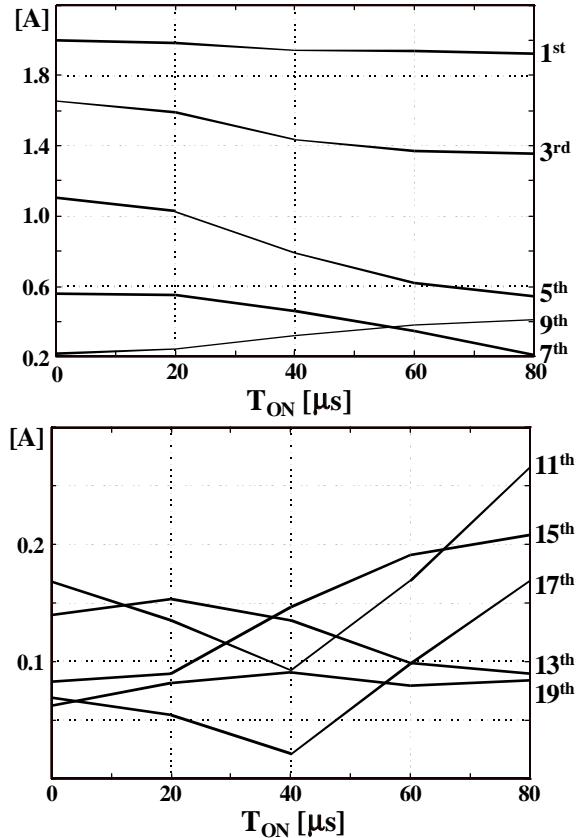
Fig. 6 - Input current harmonics corresponding to the cases depicted in Fig. 5 (T_d = 3.4ms, U_i = 220V_{rms}, P_o = 300W)

Table II - Output voltage variation as a function of the turn-on delay T_d

T_d [ms]	2.8	3.0	3.2	3.4
U_o [V]	295	298	301	304

Table III - Output voltage variation as a function of the switch on-time T_{ON}

T_{ON} [μs]	0	20	40	60	80
U_o [V]	293	294	297	300	304

D. Snubber

One of the major advantage of passive rectifiers compared to active ones, is their inherent lack of high-frequency noise emission, due to the absence of fast commutations. In addition, the big reactive elements L and C act as differential EMI input filters for the noise generated by the switching post regulator.

The proposed converter, having two commutations per line period, can produce a certain amount of high-frequency noise. In fact, the common mode noise current generated by the dv/dt across the switch through parasitic capacitive coupling to ground has a high-frequency roll-off dependent on the voltage rate of change. Thus, the purpose of the RCD snubber is simply that of limiting the switch dv/dt at turn off. The power dissipated in the snubber resistance is very small due to operation at line frequency. On the other hand, the switch turn on commutation can be simply slowed down by increasing the series gate resistance of the switch.

E. Fault conditions

A switch current limitation can be easily implemented to face overcurrent conditions. However, also in case of fault of the unit, the power supplies behaves regularly as an uncontrolled rectifier with passive filter.

IV. COMPARISON WITH PASSIVE FILTER

As we have seen in the previous section, the advantage of reducing the filter inductor value comes from the change from Class D into Class A, thus allowing more harmonic distortion. This advantage vanishes at higher power levels: at the limit power of 600W, for which the difference between the two classes disappears, the required inductor value for the passive solution results lower actually than that needed for the active one. However, other aspects must be taken into account for a correct comparison between the passive and the active solution; these are summarized in Table IV. Here, for different power levels ranging from 300 up to 700W, an active rectifier design was carried out, following the criteria outlined in the previous section, and it was refined by simulation. For each power level listed in the Table the following data were collected: average output voltage U_o, inductor current value ensuring compliance with standards (Class D for passive solutions and Class A for active ones), peak inductor current, peak energy E_L in the inductor ($E_L = 0.5\ L\ I^2_{gpeak}$), input current RMS value I_{grms}, distortion factor $DF = I_{g1rms}/I_{grms}$, displacement factor $\cos(\phi_1)$, power factor $PF = DF \cdot \cos(\phi_1)$, peak-to-peak output voltage ripple ΔU_o, normalized output voltage ripple ΔU_{oN} (ratio between the theoretical ripple value obtained by (1) and ΔU_o), natural conducting angle α_{nat}, i.e. without operation of the switching unit, normalized switch turn-on

delay time T_{dN} (ratio between actual T_d value and natural diode turn-on instant, i.e without switching unit). From these data we can make the following considerations:

- the active solution reduces both rms and peak current in the filter inductor. This fact, together with the reduction of the inductor value, reduces volume and cost of the rectifier compared to the passive solution. Even for output power levels higher than 600W, the reduction of the peak input current compensates for the increase of the inductor value so that the energy stored in the inductor (which ultimately determines its volume) remains lower than the corresponding passive solution;

- distortion factor, displacement factor and consequently the power factor increase in the active solution, and the improvement is more consistent at higher power levels;

- the inductor voltage drop can be compensated by the boost action thus allowing higher output voltage levels. Moreover, by changing the switch turn-on interval, output voltage regulation can be achieved down to about 30% of the nominal power. For lower power levels, the switch remains open and the output voltage tends to the peak input voltage, as for a standard rectifier;

- the actual output voltage ripple is reduced by a factor ranging from 1.5, at lower power levels, up to 1.9. This means that the filter capacitor value can be accordingly reduced for the same voltage ripple, as compared to the standard rectifier;

- the last two columns of Table IV were added in order to verify the design guidelines given in the previous section. In particular, the natural conducting angle α_{nat} confirms that at low power levels values close to 60° are enough to achieve compliance, while as the power increases, higher inductor values must be used in order to increase the conduction angle (at 600W the natural conducting angle is 92°). As far as the switch turn-on delay time T_d is concerned the last column shows that a good value ranges from 70% to 90% of the natural diode conduction instant, depending on the power;

- even if the proposed solution can be used at higher power levels than those reported in Table IV, clearly the required inductor value makes it progressively less interesting.

Table IV. Comparison between passive and active rectifiers at different power levels

P_o [W]	U_o [V]	L [mH]	I_{gpeak} [A]	E_L [mJ]	I_{grms} [A]	DF	$\cos(\phi_1)$	PF	Δu_o [V]	ΔU_{oN}	α_{Nat}	T_{dN}
300 - P	*276*	*19*	*4.11*	*321*	*1.85*	*0.792*	*0.926*	*0.733*	*7.02*	*1.65*	*84.5°*	
300 - A	301.5	6	4.08	100	1.78	0.766	0.998	0.764	7.13	1.48	60.8°	0.87
400 - P	*277*	*14*	*5.51*	*425*	*2.47*	*0.789*	*0.929*	*0.733*	*9.34*	*1.64*	*82.7°*	
400 - A	298	10	4.38	192	2.18	0.836	0.996	0.833	8.97	1.59	74.5°	0.82
500 - P	*276.5*	*12*	*6.78*	*552*	*3.07*	*0.794*	*0.928*	*0.74*	*11.6*	*1.66*	*83.6°*	
500 - A	296	12	4.99	299	2.62	0.866	0.998	0.864	10.4	1.73	84.1°	0.80
600 - P	*284*	*7*	*8.9*	*554*	*3.806*	*0.757*	*0.946*	*0.716*	*14.46*	*1.55*	*74.5°*	
600 - A	288.5	14	5.92	491	3.12	0.891	0.984	0.877	13.6	1.63	92.2°	0.78
700 - P	*275*	*10*	*9.23*	*852*	*4.25*	*0.806*	*0.925*	*0.745*	*16.05*	*1.69*	*87.7°*	
700 - A	286	20	5.92	701	3.46	0.93	0.99	0.92	13.5	1.93	106.7°	0.71

P = passive; A = active; DF = Distortion Factor; $\cos(\phi_1)$ = displacement factor; PF = Power Factor

V. EXPERIMENTAL MEASUREMENTS

In order to verify the results obtained by simulation a prototype was built having the following specifications:

$U_g = 220V_{rms}$ $U_o = 284V$ $P_o = 600W$
$L = 14mH$ $C = 2 \times 470\mu F$

The turn-on delay T_d of the gate signal was set to 2.2ms. Fig. 7 shows the main converter waveforms at nominal conditions: as we can see the input current waveform well agree with the simulation results. The input current spectrum is shown in the same figure and the first 25 harmonics are listed in Table V: harmonics 19th and 23th are the closest to the corresponding limits, thus confirming the simulation results.

Conducted noise measurements were also carried out on the prototype in order to quantify the high-frequency noise generation. A Line Impedance Stabilization Network (50Ω/50μH) and a receiver were utilized as prescribed by the standards. The results are shown in Fig. 8 which compares quasi-peak measurement with the corresponding limits (EN50081-1): in order to slightly filter the low-frequency differential noise due to the sharp rise edge of the absorbed line current a DM capacitor (0.47+0.68μF) was used at the converter front end. The snubber capacitor was 470nF and the snubber resistance 110Ω.

Fig. 7 - Rectified input voltage (100V/div), input current (2A/div) and its spectrum (0.4A$_{rms}$/div) at $U_i = 225V_{rms}$, $U_o = 284V$ and $P_o = 600W$

Table V - Measured input current harmonics at nominal conditions

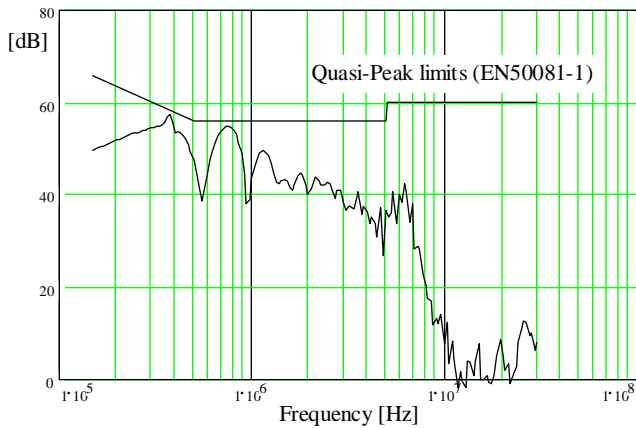| I_n	Harmonics [A$_{rms}$]	Class A limits [A$_{rms}$]
I_1	2.75	
I_3	0.856	2.30
I_5	0.612	1.14
I_7	0.134	0.77
I_9	0.320	0.40
I_{11}	0.112	0.33
I_{13}	0.182	0.21
I_{15}	0.114	0.15
I_{17}	0.106	0.132
I_{19}	0.105	0.118
I_{21}	0.0606	0.107
I_{23}	0.0804	0.098
I_{25}	0.0488	0.09

Fig. 8 - Conducted measurements (quasi-peak)

VI. CONCLUSIONS

The proposed low-frequency switched PFC is a simple and cheap solution to achieve compliance with EMC regulations together with output voltage stabilization in ac/dc power supplies for household and general-purpose applications.

As compared to a passive rectifier, it allows substantial reduction of the filter inductor size at the expense of a limited increase of circuit complexity.

The added switch allows regulation of the output voltage against load variations, without affecting the converter efficiency.

The switching unit, including control and protection, can also be integrated in a simple smart-power IC for large-volume applications.

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