Design Trade-Offs To Meet Class A IEC 61000-3-2 Regulations with Passive Circuits In Low Power Applications

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Abstract. The last amendment to IEC 61000-3-2 regulations significantly modified the regulation. In fact, Class A limits are now much softer. As a consequence, many of the solutions presented in the last years are now more or less useless for low power applications. This is due to the fact that simpler solutions as a passive LC filter can meet the regulations if the power level is below 500 W. This paper presents a study of trade-off passive solutions to meet IEC 61000-3-2 regulations for power levels below 300 W, even for universal line voltage. As it is demonstrated in the paper, designing the filter in such a way that the series resistance is higher can reduce the size of the inductor although the efficiency is penalized. A trade-off between size and efficiency can be established and, in some cases, using just the resistor can reduce the input current harmonic content sufficiently to comply with the abovementioned regulation and with an acceptable efficiency penalty.

I. INTRODUCTION

In order to limit the harmonic content of the line current of mains-connected equipment, different agency regulations have been in force since 1975. These regulations are different in Europe (EN 61000-3-2 [1][2]) and in America (IEEE 519)[3]. Much effort has gone into finding cost-effective solutions to comply with these standards. These circuits can be roughly classified as active or passive circuits.

Active Power Factor Correction (PFC) circuits are complex, more expensive, and generate electromagnetic interference (EMI). For power levels higher than 600 W-700 W, the classical two-stage solution (Unity PFC circuit + DC/DC converter) is probably the best approach, especially for universal line voltage applications. However, for lower power levels, the best solution is not so obvious.

A possible option are Single Stage circuits. Many different topologies have been recently proposed [4-12] with the common objective of complying with the low frequency harmonic content regulations at low cost. Most of them have nearly the same operation principle, which basically consists in adding a voltage value between the input rectifier and the bulk capacitor in order to enlarge the conduction angle of the input current. The obtained waveform is not completely sinusoidal but is good enough to have a low harmonic content, at least lower than the limits that IEC 61000-3-2 regulations impose.

Passive PFC solutions, which mean mains-frequency reactive devices (inductor, capacitors and transformers) plus uncontrolled rectifiers, offer an attractive trade-off between cost and performance, because they are simple, reliable and robust, and do not generate EMI. Some simple passive circuits (e.g., basic single-phase rectifier with an LC filter [13,14] and an LCD filter [15]) have been proposed. These circuits are quite economical and, therefore, they can be used in many low-cost applications. In addition, the new version of the IEC-61000-3-2 [2] establishes essential differences compared with the old edition [1], and this has an important impact on the passive solutions. The impact is so important that for low power levels (100 W- 200 W), the solution to meet the regulations can be the simplest one: a resistor. In between, there is a broad range of trade off solutions combining the effect of the inductor and the series resistance. This paper presents a study of all those solutions trying to get some practical design rules.

II. PASSIVE SOLUTIONS BASED ON AN INDUCTOR

In the new version of IEC 61000-3-2, the Class D template disappeared and the classification changed. Now, only TV sets, monitors and computers belong to Class D. Hence, most of conventional electronic equipment belong to Class A independently of the power level. Thus, for low power levels it is very easy to be below Class A limits with the new version and hence, much simpler solutions can be used as will be shown now.

The simplest passive solution to comply with the first IEC-61000-3-2 edition is the LC filter (Fig. 1) [14]. As Class D template disappeared under the new edition of the regulation, the calculations carried out in [14] are only valid for equipment that belongs to this class due to their application. However, for Class A equipment the harmonic limit is higher, especially for low power levels. Therefore the inductance needed to comply with IEC-61000-3-2 will be lower. Analysis and design of the LC filter for compliance with this new edition of the standard are presented in [16]. Fig. 2 shows the value of the inductance needed to comply with the harmonic limitation in Class A, which also depends on the output power level.

The conclusion to be drawn from these calculations is that for Class A compliance, the size of the inductor needed to

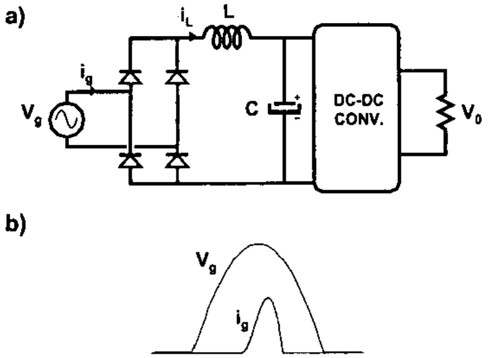

Fig. 1: a) PFC solution based on an LC filter; b) Typical input current waveform

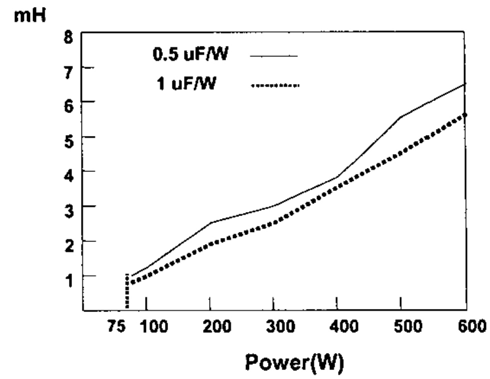

Fig. 2: Minimum inductance needed to comply with IEC 61000-3-2 regulations (Class A)

comply with the regulation is very small, which makes this solution very competitive in comparison with active circuits, especially for the low input power level. The size and the cost of two different active approaches to meet the IEC 61000-3-2 in a power range between 100W and 1000W have been calculated in [17]. The first approach compared is a two-stage solution, while the second is a single-stage one. Both solutions add passive and active devices to comply with the standard, and by comparing these circuits with the LC sizes and losses, the LC filter can be seen to be a very attractive solution for Class A requirement compliance. For Class D equipment, this inductor is too big at lower input power levels. However, the solution is more interesting for the highest ones.

III. Effect of the Series Resistance

In all the studies performed, the inductor was supposed to be ideal and the experimental results were obtained with low series resistance inductors. However, a resistor placed between the input rectifier and the bulk capacitor can have an important influence on the input current waveforms and hence, on the harmonic content. Fig. 3a shows the equivalent circuit of the LC filter including the series resistance.

As the circuit is non-linear, the approach will be to study a range of series resistance values with the minimum inductance needed for each case. Then, the size and the losses will be calculated in order to evaluate the performance of the circuit. The input power will range from 100 to 300 W to consider only the best application range of this type of solutions. As the circuit is non-linear, it is not possible to obtain a closed-form expression that describes the input current waveform. Then, the input current waveforms and the harmonic content will be obtained by simulation.

When the resistor is included in the circuit, the impedance is higher and the main effect is that the input current harmonic content is reduced. A possible idea could be to design the inductor in such a way that the resistor is integrated in the magnetic component. However, the values needed range from 1Ω to 3Ω and the associated power losses range from 1.5 W to 20 W. Hence, the core size needed to deal with the generated heat will be excessively increased. Thus, it is much interesting to use a separate resistor than to integrate it completely in the same component. However, the series resistor associated to the inductor should be taken into account in the study process.

When the resistor is included, the input current is softer and, as a consequence, a smaller inductance can obtain the same input current harmonic content. However, the resistor is a dissipative component and the losses are increased. The higher the resistance value, the smaller the inductance. On the other hand, as the resistance value increases, the efficiency decreases. Table I shows the inductor values needed for different series resistance values. Moreover, the inductor has been calculated for two different bulk capacitor values. It should be noted that, depending on the hold-up time specifications and on the voltage regulation capability of the converter, the capacitor can take different values. Typical practical design values are 0.5 μF/W and 1μF/W. As can be seen in Table I, if a 47 μF capacitor is used in a 100 W application, the harmonic content is low enough to meet the

Table I. Inductance values needed to comply with IEC 61000-3-2 as a function of the series resistance

Power	R = 0Ω	R = 1Ω	R = 1.25Ω	R = 1.5Ω	R = 2Ω	R = 3Ω
100 W (0.5μF/W)	-	-	-	-	-	-
100 W (1μF/W)	1.5 mH	1.5mH	1.15 mH	1 mH	-	-
200 W (0.5μF/W)	2.7 mH	2.7 mH	-	-	2.3 mH	1 mH
200 W (1μF/W)	2.1 mH	1.9 mH	-	-	1.4 mH	300 μH
300 W (0.5μF/W)	3.4 mH	3.2 mH	-	-	2.6 mH	2 mH
300 W (1μF/W)	2.7 mH	2.4 mH	-	-	1.8 mH	1 mH

TABLE II. LOSSES ASSOCIATED TO THE PASSIVE COMPONENTS WHEN THE INPUT POWER IS 200 W

R	R_{EXT}	R_L	L	I_{rms}	I_{peak}	Core size	L Losses	R_{EXT} Losses	Total Losses
0 Ω	0 Ω	0.75 Ω	2.1 mH	1.84 A	5.81 A	E34	2.6 W	-	2.6 W (1.3%)
1 Ω	0.4 Ω	0.6 Ω	1.9 mH	1.85 A	5.77 A	E34	2.1 W	1.4 W	3.5 W (1.75 %)
2 Ω	1.4 Ω	0.6 Ω	1.4 mH	1.87 A	5.79 A	E30	2 W	5 W	7 W (3.5 %)
3 Ω	2.85 Ω	0.15 Ω	300 μH	1.85 A	5.40 A	E20	0.5 W	9.75 W	10.25 W (5.1%)

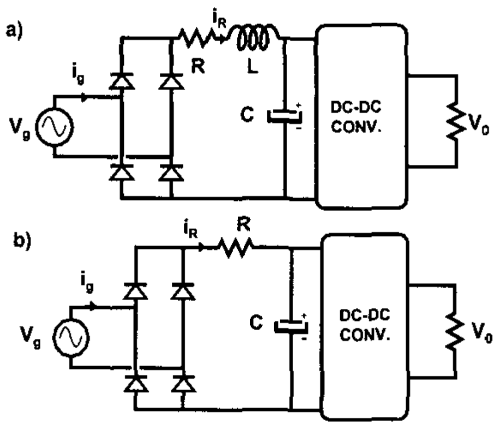

Fig. 3: a) Inductor with series resistance, b) circuit based on an RC filter.

regulations. Hence, if the converter can deal with the input voltage variation due to this capacitor, nothing at all is needed to meet IEC 61000-3-2 regulations.

To design the components, the worse operating conditions are considered. Hence, the input current is also measured at low line conditions (190 Vrms) to calculate the peak value and the rms value of the input current. Once both of them are known, the inductor and the resistor losses can be calculated. Table II shows the obtained results as well as the associated losses to each component for a 200 W application. The capacitor used in this case is a 220μF one.

As can be seen in Table II, as the series resistor increases, the inductance needed is smaller. It should be noted that R is total series resistance of the circuit, R_{EXT} is the external resistor added and R_L is the series resistance of the inductor. As the rms and peak value of the input current are more or less the same for every case ($I_{rms} \approx 1.85$ A, $I_{peak} \approx 5.8$ A), the core size needed is also smaller. In the 200 W example, an E34 silicon steel laminated core is needed if no resistor is used and only an E20 core is needed if a 3 Ω resistor is placed in series. The drawback is obviously the power losses increase. However, the losses could be assumed in a low cost converter due to the savings in the core size. It should be noted that losses rise up to 5.35 % in the worst case, which is not too much if the benefits are taken into account: a very simple and non-expensive solution to meet IEC 61000-3-2 regulations. If a better efficiency is desired, the solution based just on the inductor can be used. The drawback in this case is the core size.

This solution is only useful for low power and low cost applications with either the European or the American voltage range. If the application needs universal input voltage range, this solution is not interesting because the losses at low line will be unacceptable. Only if a mechanical switch and a voltage doubler configuration are used, this solution can be used with both input voltage ranges.
Another interesting conclusion that can be obtained from Table II is that the inductor could be completely removed from the circuit if a higher resistance value is used (see Fig. 3b). In this case, the power losses will increase but the cost would be the minimum possible. Then, it seems interesting to explore this possibility.

IV. COMPLYING IEC 61000-3-2 WITH A RESISTOR

If low cost is the main concern and performance is not critical, this solution could be considered. It should be noted that this is the simplest possible solution. Obviously, performance is the worst but in low power levels, the efficiency penalty could be assumed. Fig. 3b shows the proposed circuit and as can be seen, the solution is really simple because a standard power resistor can be used. The cost and the size are also the smallest possible. However, the drawback is evident: the efficiency will be the worst. As usual, this is a trade-off between cost and performance. A study has been done in order to calculate the resistor needed for different power levels and a 230 V input voltage. The results are shown in Table III. As can be seen, as the power increases the resistor needed is larger and the power losses are also higher. For power levels above 300 W, the efficiency penalty is very high and the solution is clearly useless. However, for power levels below 300 W, the losses

TABLE III: RESISTOR NEEDED FOR DIFFERENT POWER LEVELS (V_{IN}=230V, 1MF/W)

Power	100 W		200 W		300 W		400 W		500 W		600 W	
Resistor needed	1.6 Ω		3.6 Ω		3.6Ω		4 Ω		5.5 Ω		6 Ω	
Power Losses 230 V / 190 V	1.3 W	1.6 W	8.5 W	11.5 W	18 W	24W	32 W	44W	63 W	89 W	96 W	140 W
Power Losses %	1.3 %	1.6%	4.3 %	5.75 %	5.8%	8%	8%	11%	13%	18%	16%	24 %

TABLE IV. LOSSES ON THE RESISTOR AT LOW INPUT VOLTAGE LEVELS

Power	R	C	Rms Curr. (85 V)	Losses (85 V)	Rms Curr. (110V)	Losses (110 V)
100 W	1.6 Ω	2 x 220uF	1.83 A	5 W (5%)	1.6 A	3.8 W (3.8%)
200 W	3.6 Ω	2 x 440 uF	3.75 A	50 W (25%)	2.84 A	29 W (14 %)

are assumable and the solution can be considered. In fact, power losses are around 1% for 100W. It should be noted that any other previously proposed solution has similar losses at this power level [4-17]. Power losses have also been calculated for low line operation (190 V) in order to correctly design the resistor.

As has been mentioned, this losses have been calculated when the input voltage is 230 V and 190 V and it would be interesting to see what happens at a lower line voltage in order to evaluate the performance for universal input voltage applications. Fig. 4a shows a circuit that can be used with a voltage doubler and hence, can operate at two different input voltage ranges: European (190 V – 265 V) and American (85 V-130 V). The resistance value needed is exactly the same because the regulations should only be met at the European input voltage range and only at the nominal value (230V). However, the input current rms value will be much higher at the lower input voltage range and hence, the losses will be higher. Table IV shows the rms value of the input current at 85 V and 110 V as well as the power losses on the resistor. As can be seen, at low input voltage (85 V) the losses on the resistor are much higher. Thus, for 100 W the solution is still interesting for low cost applications because losses are about 5% of the total power.

For 200 W this value grows up to 25%, which is excessive. However, there is still a simple solution to improve the performance of this circuit. If the total resistance is split in two resistors as shown in Fig. 4b, losses are almost halved as is shown in Table V. The reason for this can be seen in Fig. 4c. When the voltage doubler setup is used and the input voltage is in the lower part of the range, the current passing through each resistor is half the total current (either the positive or the negative part of the waveform). Losses are not exactly halved because the input current of the circuit shown in Fig. 4a is obtained with R and C. However, the input current of the circuit shown in Fig. 4b is obtained with R/2 and C. For the European voltage range, the behaviour of the circuit is similar to the behaviour of the circuit shown in Fig. 3a. It should be noted that the resistance value should be calculated in such a way that IEC 61000-3-2 regulations are met at 230 V.

As can be seen, at low power levels, losses with this scheme are more assumable, especially if the extremely low cost of the solution is taken into account. However, at 200 W and 85 V losses are too high.

A final consideration should be made regarding the design of this circuit. The value of the resistance is slightly dependent on the bulk capacitor value. The calculi made above are based on a 1μF/W ratio, which is the value needed to meet the conventional hold-up time specifications of AC/DC converters. If another capacitor value is needed, the resistor needed may be different. However, the variation is not very significant. Fig. 5 shows the resistor values needed to comply with the regulations for three different capacitor values: 0.5 μF/W, 1 μF/W and 2μF/W.

Then, the solution presented based on a simple RC filter appears to be really competitive for low power levels, especially below 200 W. In these cases, it is even interesting for universal line voltage applications based on a voltage doubler. As has already been mentioned, the primary concern of the proposed circuit is cost. In fact, this is probably the cheapest solution that can be used. As a consequence, the

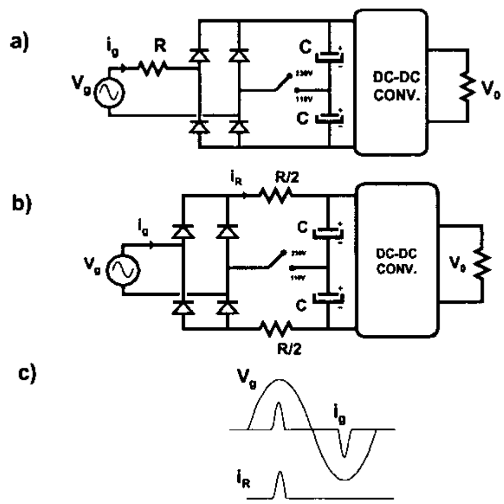

Fig. 4: a) RC solution proposed for a rectifier based on a voltage doubler, b) Optimum solution based on two resistors; c) Main waveforms of the solution shown in b)

TABLE V. POWER LOSSES ON THE RESISTORS WITH THE PROPOSED TWO RESISTOR SCHEME

Power	R	C	I_{Rrms} (85 V)	Losses (85 V)	I_{Rrms} (110 V)	Losses (110 V)	Losses (230V)
100 W	2 x 0.75 Ω	2 x 220 μF	1.45 A	3.1 W (3.1%)	1.19 A	2.1 W (2.1 %)	1.3 W (1.3%)
200 W	2 x 1.8 Ω	2 x 440 μF	2.67 A	25 W (12.5%)	2.11 A	16 W (8 %)	8.5 W (4.3%)

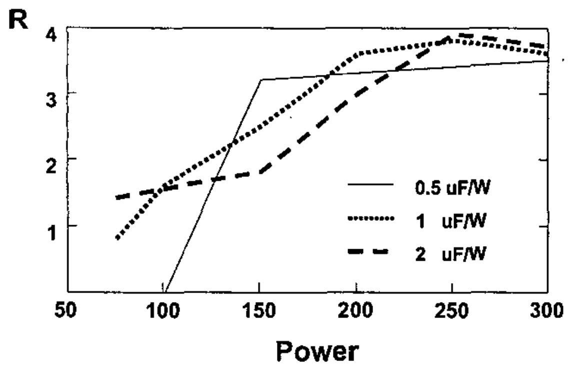

Fig. 5: Resistor values needed to comply with IEC 61000-3-2 regulations for different power values

performance is worse than the performance of other solutions, although the efficiency penalty for 100 W is really competitive and quite interesting for 200 W.

Finally, Table VI and VII show the results of the different trade-off designs for 100 and 300 W. As can be seen, for a 100 W application, the efficiency difference between using an inductor or a resistor is only 1%. Thus, for such low power levels, the best option is the resistor as far as it is much cheaper than the inductor. For higher power levels (i.e. 300 W as shown in Table VII), the difference is much more important. If an inductor is used, losses are only around 2%. However, if a resistor is used, losses are around 8%. In this case, although the resistor is cheaper, the solution based on an inductor is probably more interesting. In between, there are several trade-off solutions with intermediate losses. Nevertheless, due to the commercial core sizes, it is difficult to reduce the size of the inductor. It should be noted that only a few finite core sizes are commercially available. Hence, in most of the cases the exact core needed does not exist and the most similar one should be used. In this case, the size will not be completely optimised.

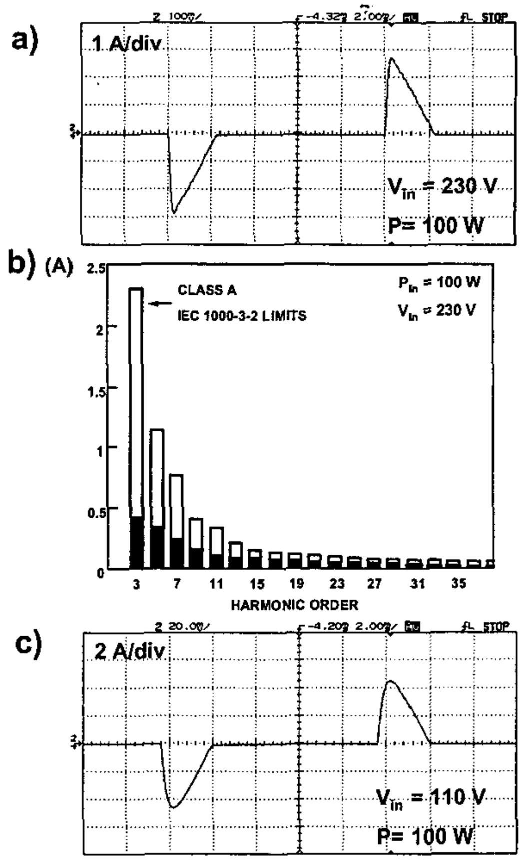

Fig. 6: a) input current waveform (100 W, 230 V); b) harmonic content at nominal conditions; c) input current waveform (100 W, 110 V)

V. Experimental results

A experimental setup has been built in order to verify the theoretical results. The configuration chosen is the one shown in Fig. 4b, with the voltage doubler rectifier. Both 100 W and 200 W cases were tested. Fig. 6a shows the input current of

Table VI. Losses associated to the passive components when the input power is 100 W

R	R_{EXT}	R_L	L	I_{rms}	I_{peak}	Core size	L Losses	R_{EXR} Losses	Total Losses
0 Ω	0 Ω	0.5 Ω	1.5 mH	1.09 A	4.07 A	E25	0.7 W	-	0.7 W (0.7%)
1 Ω	0.6 Ω	0.4 Ω	1.25 mH	1.1 A	4.13 A	E25	0.5 W	0.73 W	1.23 W (1.2 %)
1.25 Ω	0.15 Ω	1.1 Ω	1.15mH	1.1 A	4.14 A	E20	1.3 W	0.2 W	1.5 W (1.5%)
1.5 Ω	0.7 Ω	0.8 Ω	1 mH	1.1 A	4.18 A	E20	0.9 W	0.85 W	1.75 W (2.7%)
1.6 Ω	1.6 Ω	0 Ω	0	1.02 A	3.45 A	-	-	1.7 W	1.7 W (1.7%)

Table VII. Losses associated to the passive components when the input power is 300 W

R	R_{EXT}	R_L	L	I_{rms}	I_{peak}	Core size	L Losses	R_{EXT} Losses	Total Losses
0 Ω	0 Ω	0.3 Ω	2.7 mH	2.54 A	7.26 A	E42	2 W	-	2 W (0.6%)
1 Ω	0.75 Ω	0.25 Ω	2.4 mH	2.57 A	7.29 A	E42	1.7 W	4.9 W	6.6 W (2.2 %)
2 Ω	1.85 Ω	0.15 Ω	1.8 mH	2.61 A	7.38 A	E42	1 W	12.6 W	13.6 W (4.5%)
3 Ω	2.75 Ω	0.25 Ω	1 mH	2.64 A	7.29 A	E34	1.7 W	19 W	20.7W (6.9%)
3.6 Ω	3.6 Ω	0 Ω	0	2.58 A	7.3 A	-	-	23.96 W	23.96 W (8%)

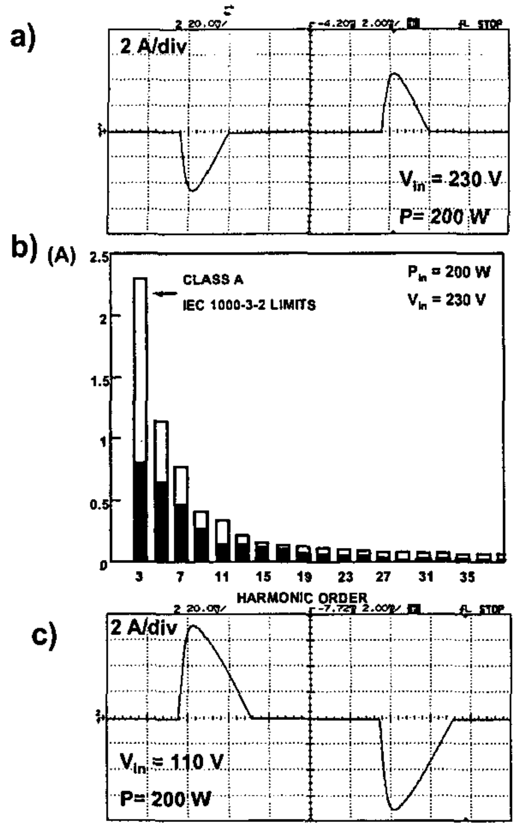

Fig. 7: a) input current waveform (200 W, 230 V); b) harmonic content at nominal conditions; c) input current waveform (200 W, 110 V)

the converter at 230 V and 100 W. As can be seen in Fig. 6b, the harmonic content of this current is below Class A limits. Fig. 6c shows the input current of the converter at 110 V input voltage. Two 0.82 Ω - 1 W resistors were used in this case. Fig. 7a shows the input current of the converter at 230 V and 200 W. In this case, two 1.8 Ω–4 W resistors were used. Fig. 7b shows the harmonic content of the input current and again in this case it is below Class A limits. Finally, Fig. 7c shows the input current at 110 V input voltage. Both experiments agree with the theoretical results.

It should be noted that for low power levels, the high order harmonics are the most restrictive ones. However, for higher power levels the most restrictive harmonics are the low order ones. For the 200 W experiment, a commercial converter (Fig. 8) with EMI filter was used in order to see the compliance of the regulations in a real product. The influence of the filter was not significant and the converter complied with the regulations as well.

VI. Conclusions

This paper presents a study of trade off passive solutions based on the influence of a series resistance placed between the input rectifier and the bulk capacitor. The most efficient solution is the one based on a conventional LC filter. However, the size of the core can be reduced increasing the series resistance of the inductor (using an external resistor). The drawback is the loss increase due to this resistor. In the opposite side of the trade-off range it is a solution based on removing the inductor and using only the resistor as a filter. This is probably the cheapest solution to meet IEC 61000-3-2 regulations for power levels below 200 W. In this power level, losses are acceptable and the solution is very competitive. In order to use this method with universal line applications, a variation based on splitting the resistor in two in a voltage doubler scheme has also been presented. In this case, losses are almost halved in relation with the single resistor scheme. For 100 W, losses are only 1.3 % for nominal input voltage (230V) and 2.1% for low line voltage conditions (110V). In the 200 W case, losses are 4.3 % of the total power at nominal conditions and 8 % at low line conditions. Thus, the cost is really small due to the simplicity of the circuit and the performance is quite interesting, especially taking into account that IEC 61000-3-2 regulation is complied.

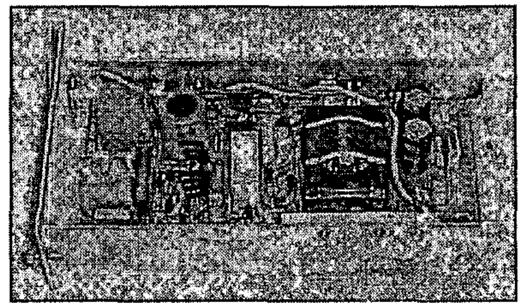

Fig. 8: Commercial converter used for the 200 W experiments

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