Single Phase Power Factor Correction: A Survey

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***Abstract*—New recommendations and future standards have increased the interest in power factor correction circuits. There are multiple solutions in which line current is sinusoidal. In addition, in the recent years, a great number of circuits have been proposed with nonsinusoidal line current.**

In this paper, a review of the most interesting solutions for single phase and low power applications is carried out. They are classified attending to the line current waveform, energy processing, number of switches, control loops, etc. The major advantages and disadvantages are highlighted and the field of application is found.

***Index Terms*—ac/dc converters, EN61000-3-2, power conditioning, power factor correction, reactive power, sinusoidal line current.**

I. Introduction

POWER supplies connected to ac mains introduce harmonic currents in the utility. It is very well known that these harmonic currents cause several problems such as voltage distortion, heating, noise and reduce the capability of the line to provide energy. This fact and the need to comply with "standards" or "recommendations" have forced to use power factor correction in power supplies.

Unity power factor and tight output voltage regulation are achieved with the very well known two stage approach, shown in Fig. 1. Since the power stage is composed by two converters, size, cost and efficiency are penalized, mainly in low power applications. However, this is probably the best option for ac-dc converters due to the following reasons.

1) Sinusoidal line current guarantees the compliance of any Regulation.
2) It gives good performance under universal line voltage.
3) It offers many possibilities to implement both the isolation between line and load, and the hold-up time.
4) The penalty on the efficiency due to the double energy processing is partially compensated by the fact that the voltage on the storage capacitor is controlled. The fact of having a constant input voltage allows a good design of the second stage.

Although unity power factor is the ideal objective, it is not necessary for meeting the Regulations. For example, both IEEE 519 and IEC 1000-3-2, allow the presence of harmonics in the line current [1], [2]. This fact has lead to the publication of a great number of papers in the last years, proposing solutions that obtain some advantages over the two stage approach. Some

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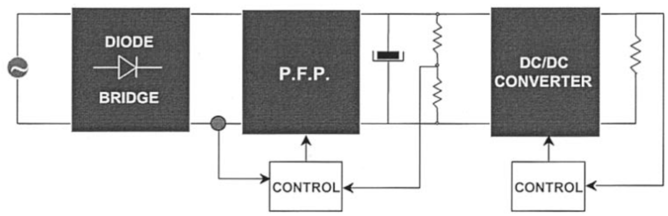

Fig. 1. Two stage ac-dc PFC converter.

of these circuits are practical but others are too complex to be worth changing.

The purpose of this paper is to classify and compare several converters proposed for the ac–dc conversion with power factor correction, having the two stage approach as a reference and focusing the study in the low power range. Other revisions have been published with different objectives [3]–[6].

II. Tradeoff Quality-Cost

Several dc-dc converters are suitable to work as a "power factor preregulator (pfp)" or "resistor emulator" in ac–dc applications [7]. In general, these converters require two control loops (input current and output voltage) to achieve this goal (see Fig. 1).

When the input current is sinusoidal (at $50 \div 60$ Hz), the input power is pulsating (at $100 \div 120$ Hz) and, since the power demanded by the load is constant, it is necessary to include an element to store the energy.

This element is usually a capacitor, but it should be dimensioned for twice the line frequency (100 or 120 Hz). Therefore it is a large component. Finally, a second dc–dc converter is required to regulate the output voltage.

Therefore, the penalty for the highest quality waveform (sinusoidal) and tight output voltage regulation is

1) two control loops in the preregulator;
2) a big storage capacitor;
3) an additional dc–dc converter with its own control circuit.

However, in general terms, the "two stage approach" is probably the best option for power factor correction taking into account the advantages of this scheme. Fig. 2 shows the power stage of the combination *boost* plus *flyback* converters. It is one of the simplest, and very interesting for low power applications (i.e., less than 300 W).

Regarding the power factor correction stage, the *boost* converter is widely used because of its advantages: grounded transistor, small input inductor, simplicity and high efficiency (around 95%). The main drawback is that the output voltage is higher than the peak input voltage, causing switching losses in the transistor and in the diode, due to its reverse recovery.

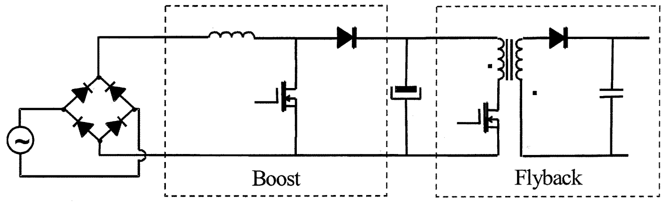

Fig. 2. Power stage of boost plus flyback converters.

These inconveniences may be overcome using a multi-level converter [8], where a double number of devices is used, but with lower voltage stress.

Regarding the quality of the current waveform, it is possible to consider three types (see Fig. 3). On top, the sinusoidal waveform usually involves a high-cost circuit. An intermediate quality level is composed by those solutions that comply with the regulations without achieving unity power factor. Among them, there are the so called "single stage converters" that offer some advantages, but its field of application is limited to low power (up to 300 W, approximately). Finally, if there is not any requirement about the line current, the simplest solution composed by a diode bridge and a filter capacitor can be used as a first stage.

III. Classification of the Solutions

The solutions will be classified in two groups, according to the input current shape: sinusoidal or nonsinusoidal.

A. Sinusoidal Line Current

For comparison, we have selected as a reference the aforementioned cascade association of converters [Figs. 1 and 10(a)]. Fig. 4 shows some possible alternatives to this traditional scheme. All of them, except passive filters, involve the use of two converters (PFP plus dc-dc) with their respective control loops.

1) Voltage Follower Approach: Some converters designed to work in discontinuous conduction mode are natural voltage followers and the inner current loop can be removed [9]–[14]. This means a simplification of the control circuit. Sinusoidal line current is maintained in converters such as *buck-boost* and *flyback, SEPIC, Cuk,* and *Zeta*. *Boost* converter may be designed for sinusoidal line current but forcing a high output voltage. In general terms, this is a good option for medium and low power applications (100 W–1 kW) because RMS currents cause a penalty in the conduction losses. Other advantages may be obtained such as the absence of losses due to the reverse recovery of the *boost* diode. This fact allows the use of this circuit in higher power applications.

2) Using Passive Filters: Just using reactive elements, it is possible to obtain an almost sinusoidal current [15], without the power factor preregulator (first stage). The advantages of this solution are the reliability and the absence of EMI. However, the reactive elements are heavy and bulky. Furthermore, this solution is not valid for universal line voltage ($85 \div 264\ V_{AC}$), unless a typical switch to change the rectifier were included.

3) Processing Less Energy: Many attempts have been done to improve the energy processing in ac/dc converters compared with the two-stage approach, where the output power is processed twice. The objective is to increase the efficiency by changing the way the power is processed (see Fig. 5, where it is assumed that both input voltage and current are sinusoidal) as explained below. Anyway it should be noted that this parameter does not define exactly the efficiency of the power conversion, and it will be useful to complete this analysis with the device exploitation factor. However many authors use the power processing to give an idea of the efficiency. Four solutions are highlighted in this section.

a) Using a bidirectional converter: Reference [16] describes a bi-directional converter in shunt connection at the output of the PFP [see Fig. 10(b)] to absorb the excess of the power (P2 in Fig. 5) and store it. This 32% of the power is released to the load to complete area P3. Averaging, the output power is processed **1.64** times instead of 2. The problem is that there are still two converters and one of them is bi-directional, what forces the use MOSFET's instead of diodes.

b) Parallel processing of the energy: In these solutions [17], [18] there are two paths for the power [see Fig. 10(c)]. P1 is delivered through one of them straight to the load. The rest 32% (P2) is stored after the first processing and then delivered to the load as P3. Therefore, the output power is managed **1.32** times. The problem is that the power stage is very complex (requires at least three switches) plus a specific control scheme.

c) Repositioning the power blocks: Circuits described in [19] split the power waveform in two equal parts, delivering one of them to the load. This is achieved by changing the position of the converters of the two stage approach [see Fig. 10(d)]. Therefore, 50% of the output power is processed once. The rest half is managed twice. So, output power is managed **1.50** times without increasing the complexity of the circuit. The problem is that the field of application is limited due to the restrictions in the connection of the converters.

d) Using a series dc/dc converter: The low frequency ripple at the output of the PFP may be eliminated using a series post-regulator [see Fig. 10(e)] [20]. The output voltage is mainly fixed by the PFP to maintain low power ratings in the dc–dc converter, processing a fraction of the output power ($\approx$**15%**) twice. This may reduce the size of the post-regulator. However, the post-regulator is designed for low output voltage and nominal current, and the implementation penalizes the stress on the components.

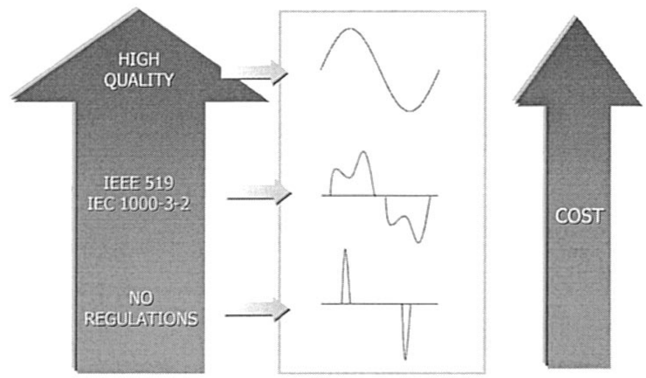

Fig. 3. Tradeoff between cost and quality of the line current waveform.

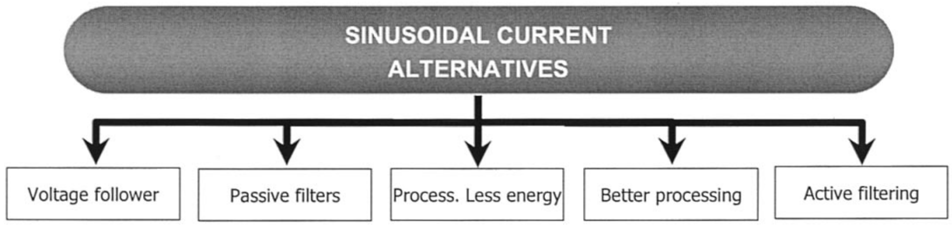

Fig. 4. Alternatives to the two stage approach.

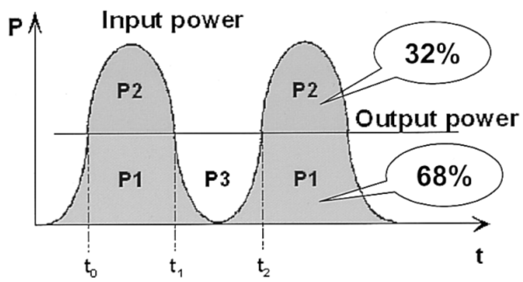

Fig. 5. Power waveform in a PFC converter with sinusoidal line current.

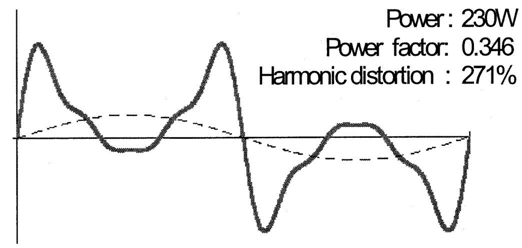

Fig. 6. Example of a line current with big distortion that meets IEC 61 000-3-2 requirements.

As a summary, in this group of solutions, since two converters and their control circuits are required, no great advantage is found from the point of view of cost compared with the two-stage approach.

4) Better Processing of the Energy: It should be noted that it is not only important how much power is processed (previous group 1.3) but also how efficiently it is processed. In this section, some ideas are highlighted to reduce the power losses and to improve the efficiency of one of the stages. Therefore, the whole conversion is improved from the efficiency viewpoint.

It is inherent to PFP's to manage high voltage (hundreds of volts) and, therefore, it penalizes the efficiency of the PFP and the dc–dc converter, especially in low power applications. For this reason, soft-switching is desirable if it is feasible to be implemented.

a) Power factor preregulator:

— *Auxiliary networks to reduce switching losses*: many techniques have been described to reduce the switching losses in PFC converters. Probably the most interesting is applied to the *boost* converter [21] due to its high output voltage and the losses due to the reverse recovery of the diode. In general terms, all these solutions require an additional switch and some but small reactive elements. These networks do not affect the line current evolution. The size of the control stage is also increased.

— *Resonant and quasiresonant converters*: due to the soft-switching nature of these converters, they have been used in PFC applications [22], [23]. An advantage is that a good line current waveform is obtained without input current loop. The main drawback is the circulating energy that penalizes the efficiency.

b) Second stage (dc–dc converter):

— *Soft-switching converters*: especially important are those topologies suitable for high input voltage, because in many cases the first stage is a *boost* converter. Halffonverters may operate with ZVS taking advantage of the leakage inductance, without introducing many additional elements [24], [25].

— *Using a high efficiency post-regulator*: the overall efficiency is improved by means of a very optimized converter used as second stage. Reference [26] describes a post-regulator with two inputs that uses low voltage devices independently of the output voltage [see Fig. 10(f)]. This leads to a very high efficiency, especially in high output voltage applications. The drawback is that it forces to modify the power factor preregulator by adding a second output.

5) Active filtering: The use of active filters is very common in high power installations (from tens of kW). Fig. 10(g) shows the parallel configuration. The four quadrant active filter is in charge to obtain a sinusoidal line current even when the load is nonlinear. Usually, the control stage is made using a DSP. In a low power application, this solution is not cost-effective. However, a more simple implementation can be found in [27] if the filter is placed at the rectified side [see Fig. 10(h)], being a two quadrant converter. The power stage has two switches and the control circuit is implemented using a common PFC controller. This solution is interesting because it can be used in existing systems to convert a distorted line current into sinusoidal, without any change in the system. Therefore, it can be considered as optional equipment used only in those cases where Regulations need to be complied.

B. Nonsinusoidal Line Current

Since Regulations allow harmonic currents, designers may take advantage of that, simplifying the circuitry and using new topologies, mainly in low power applications. For example, Fig. 6 shows an example of line current with a high harmonic content but meeting the normative IEC 61 000-3-2 in Class A up to 230 W (third, fifth, seventh and ninth harmonic currents are close to the limit). The fundamental harmonic is also drawn.

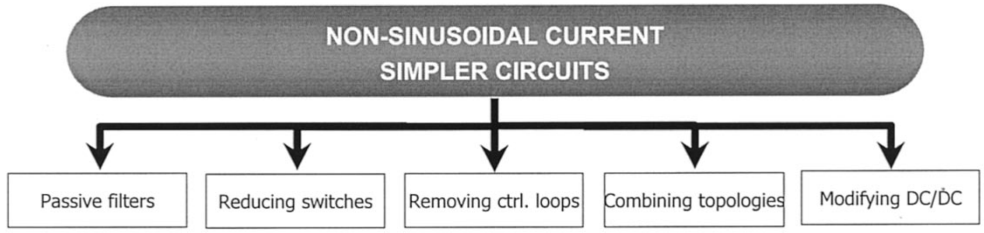

Fig. 7. Alternatives to the two stage approach for nonsinusoidal line current.

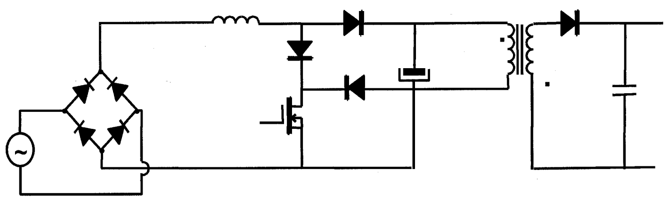

Fig. 8. Combination of boost PFC and flyback dc-dc converter with a single switch.

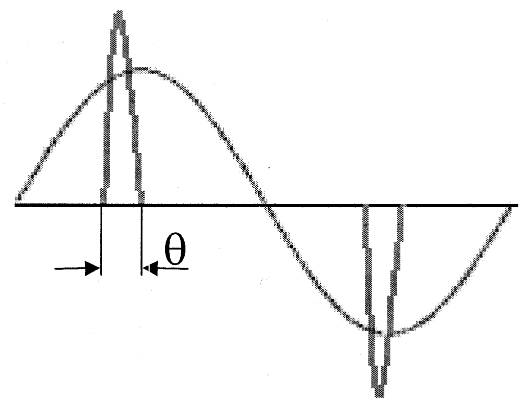

Fig. 9. Line current of a diode rectifier and conduction angle.

For example, *buck* converter is not an ideal power factor corrector because its line current has crossover distortion (zero current when input voltage is smaller than output voltage). However, depending on the power level, it can be used in the two stage approach to comply with the Regulation IEC 61 000-3-2 [28].

Other type of solutions has been proposed to simplify the two stage approach. The main alternatives are shown in Fig. 7. Most of them have a single control loop for the whole converter. The key element is the storage capacitor. Its position and its voltage determine the goodness of the proposals. A general representation of these solutions is shown in Fig. 10(i).

1) Using Passive Filters: If the objective is not to obtain unity power factor, passive filters are a very interesting option to replace the PFP as the first stage, in low power applications [29]–[32]. High efficiency and reliability are the major advantages, while the problem is its design for universal line voltage.

2) Reducing the Number of Switches: Reference [33] shows a general procedure to reduce the number of switches of the two stage approach. This means reduction in cost due to the removed switch and its control circuit. This interesting procedure has been the base to develop further solutions. An example using the boost and the flyback converters is shown in Fig. 8.

In this circuit, there is only one controlled switch. It is controlled to obtain a tightly regulated output voltage in the load. Thus, line current only depends on the voltage follower capabilities of the first converter (*boost*). A high power factor is obtained, but the problem is that the efficiency is penalized because of the high voltage on the storage capacitor and because both converters should be designed in discontinuous conduction mode (DCM), limiting this solution to low power applications (100–200 W).

3) Removing Control Loops: This is similar to the previous one but without combining the switches. The two stages share the duty cycle. With a proper selection of the converters, the line current can be almost sinusoidal. For instance, a continuous conduction mode (CCM) dc–dc converter gives a constant duty cycle not very sensitive to load variations; this converter combined with a DCM PFP converter such as *flyback*, produces an almost sinusoidal line current. Reference [34] shows an example where part of the output power is processed once.

4) Combining Topologies: Many of the proposals in the recent years combine two known topologies into one and use a single control loop. The selection of the topologies and conduction modes determines the line current and the voltage on the storage capacitor.

a) BIFRED converter: One of the very first proposals was a *boost* plus a *flyback* converter with a topological transformation [35]. The advantage is the simplicity (single switch and single control loop plus isolation) and that a small part of the output power is processed once. The big problem is that the voltage on the storage capacitor is very high and it is load dependent due to the combination DCM *boost* and CCM *flyback*. At light load this converter is not feasible. Adding some complexity in the control loop, this last drawback can be eliminated [36]. In particular, using a variable frequency control scheme, the voltage on the storage capacitor is limited to reasonable limits.

b) Charge pump converters: Although they are derived from other type of solution, they can be considered as the combination of a resonant converter and a PWM dc-dc converter [37]. The power stage is again very simple because there is a single switch and a single control loop. Voltage on the storage capacitor is line and load dependent but the variation is smaller than in other solutions. Therefore, this is a good alternative for universal line voltage ac-dc converters. The main drawback is that the resonant stage makes difficult the design.

c) Multiwinding transformer: In this circuit [38], a *boost* converter is combined with a *flyback* or *forward* converter. By means of a power transformer with several additional windings,

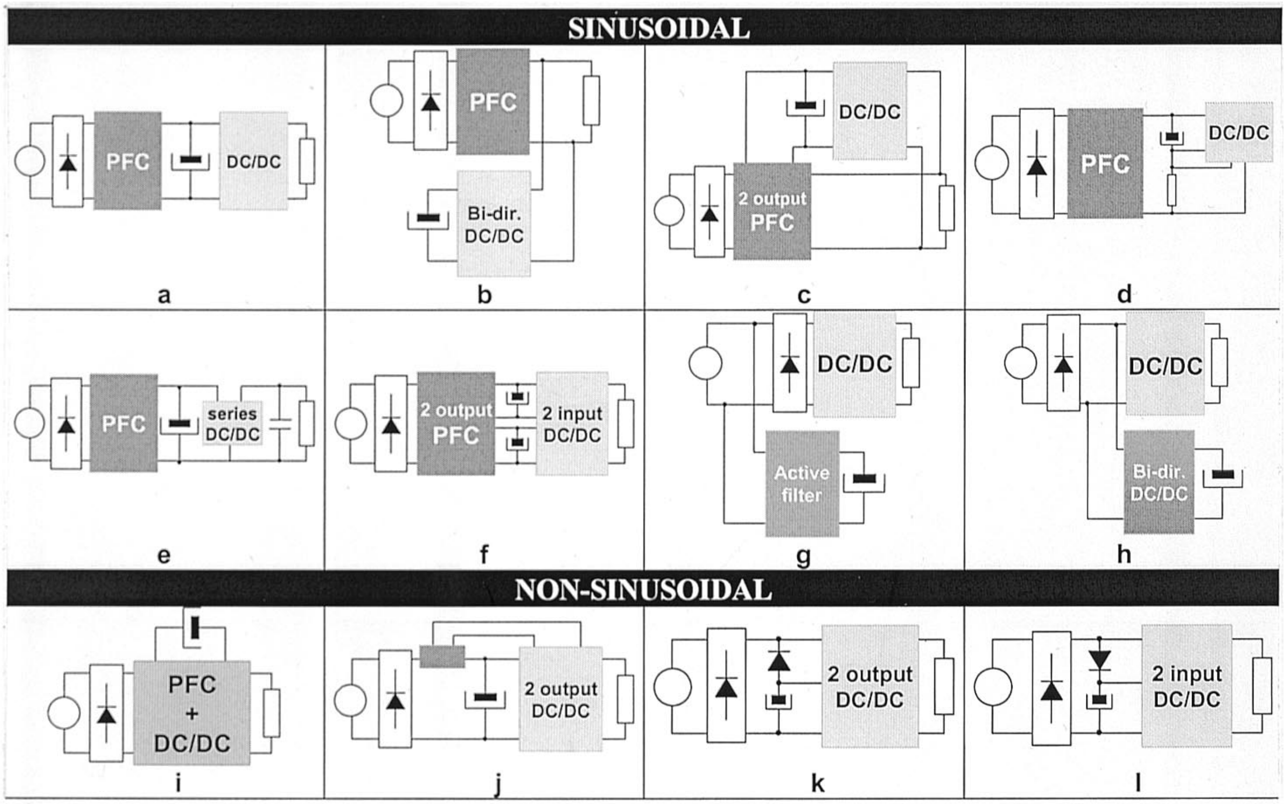

Fig. 10. Some approaches proposed for power factor correction.

the voltage on the storage capacitor is reduced to reasonable levels, allowing the performance under universal line voltage. The performance of this solution is very similar to the ones proposed in Section III-B-5-b.

5) Modifying a DC–DC Converter: Some of the most simple circuits belong to this option. They are obtained by adding some elements to a dc-dc converter, to work in ac-dc applications meeting the Regulations, as explained below. All of them except the first one have a single switch and a single control loop, being an interesting option in terms of size and cost.

a) Additional resonant output: In solution [39], an auxiliary output is included in a full bridge topology and its output voltage is added to the rectified ac to compose the actual input to the converter [see Fig. 10(j)]. Whereas the main output is controlled in the classical way, the auxiliary output is controlled by frequency variation, to obtain a constant voltage in the storage capacitor. The line has a relatively small harmonic content. The problem is the energy recirculation through the auxiliary input and the control complexity.

b) Input current shapers: Several circuits have been presented with a similar approach [40]–[42]. The objective is to enlarge the conduction angle of a diode bridge reducing the harmonic content of the line current (see Fig. 9) to comply with the Regulations. This is achieved by means of the addition of an auxiliary output connected in series with the input [also the same Fig. 10(j) applies]. In these circuits there is a tradeoff between the conduction angle and the power delivered through the auxiliary output. This is a very interesting solution since only few elements are added to a dc–dc converter (in some cases an inductor, an auxiliary winding and a couple of diodes). The only problem is that the storage capacitor is placed in an intermediate position and its voltage is higher than the line voltage, penalizing its use in universal line voltage applications.

c) Additional forward output: In this interesting solution, an auxiliary *forward* output is included and is connected to the input through a diode [see Fig. 10(k)] [43]. This arrangement acts as the valley fill technique where the conduction angle is controllable by design. Moreover, the storage capacitor holds a voltage smaller than the input. However, a nonnegligible part of the output power is flowing again to the input and the efficiency is penalized.

d) Additional input: This solution is based on the inclusion of an additional input to the circuit [44]. The storage capacitor is placed at this input and it is fed directly from the rectified ac through a diode [see Fig. 10(l)]. Thus, the converter has two inputs and it is possible to select the amount of power taken from each input by design. The advantages are that the output power is processed once and the voltage on the storage capacitor is clamped to the line voltage. This solution is valid only for low power (up to 300 W approx.) due to the harmonic content of the line current.

IV. CONCLUSION

Many proposed solutions for ac-dc power factor correction have been analyzed. They have been classified according to the line current waveform and their performance.

If the purpose is to obtain a sinusoidal line current, the classical two-stage approach is the best option, mainly if universal line voltage operation is required. It is desirable to include ZVS if it is feasible to implement it in any or both PFP and dc-dc converter. In general terms, the solutions based on a better energy management (either processing less energy or process it with higher efficiency) do not offer great advantages, unless the efficiency were the unique parameter to consider. Passive solutions are adequate in the low power range for simplicity.

Single stage solutions are a good option to meet the low frequency harmonic Regulations in low power applications with low cost. Depending on each particular specification, one of the topologies that belong to the group 2.5 could be the best solution. These topologies are based on a dc/dc converter with few additional elements [Fig. 10(j)–10(l)] to operate as ac/dc converter. The solutions derived from the two-stage approach with slight modifications usually have a higher number of components and, therefore, a higher cost.

As a final comment, solutions with sinusoidal line current are valid considering any standard or recommendation. However, the feasibility of the second group of converters (nonsinusoidal current) depends on each particular Regulation and its evolution along the years. Therefore, some converters useful today might not be used tomorrow and viceversa.

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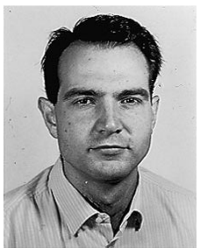

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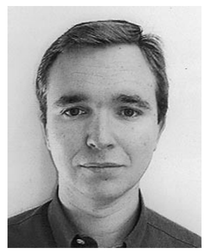

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