Article

PFC Single-Phase AC/DC Boost Converters: Bridge, Semi-Bridgeless, and Bridgeless Topologies

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Abstract: Power Factor Correction (PFC) single-phase AC/DC converters are used in several power electronics applications as full wave control rectifiers improving power quality and providing high standards of efficiency. Many papers dealing with the description or use of such topologies have been published in recent years; however, a review that describes and organizes their specific details has not been reported in the technical literature. Therefore, this paper presents an extensive review of PFC single-phase AC/DC converters operating with the Boost converter topology for low and medium voltage as well as and power appliances. A categorization of bridge, semi-bridgeless, and bridgeless, in accordance with the construction characteristics, was carried out in order to unify the technical terminology. Benefits and disadvantages are described and analyzed in detail. Furthermore, a comparison performance in terms of PFC, Total Harmonic Distortion (THD), power capacity, electromagnetic compatibility (EMC), number of elements, and efficiency is included.

Keywords: single phase AC/DC converter; bridge; semi-bridgeless; bridgeless; boost converter; power factor correction; review

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1. Introduction

Conventional diode rectifiers convert an AC supply into a DC voltage draw pulsed current from the supply network, which increases electromagnetic interference (EMI), reduces energy efficiency, and decreases the capacity of the network to carry electrical power [1,2]. An alternative for overcoming these issues in power systems is the use of Controlled Boost Power (CBP) converters instead of conventional diode rectifiers [3–6]. CBP converters implement the Power Factor Correction (PFC) technique that consists of controlling the AC current demanded from the network in such a way that AC current is sinusoidal and in phase with the voltage of the supply network and, at the same time, they perform DC voltage regulation in their output. Basically, CBP converters behave as a resistive load for the electrical network, improving the power quality and overall efficiency and also by helping comply with the harmonic regulation IEC 1000-3-2 [7–11]. Another important aspect is that CBP converters may also avoid the use of active power filters between the power network and loads, which yields a more economic and suitable solution in these kinds of applications [12,13]. The implementation of CBP converters contributes to the better use of power networks avoiding reactive and harmonic components of power flow through the power system; consequently, energy losses are reduced in transmission and distribution lines, and the energy quality is improved. In general terms, the improvement of power quality by means of CBP converters not only for PF correction but also for EMI and THD_i reduction are issues that concern the users, distributors, and generators [14–16].

The implementation of CBP converters is still a research topic. Most of the research in this area focuses on control strategies and new topologies [2,17,18]. However, an organized document that permits to consult advantages and drawbacks of CBP converter topologies and their control strategies have not yet been reported in the technical literature. This review includes organized information useful in selection, design, and implementation stages of CBP converters.

As regards their applications, CBP converters are widely used in modern power converter suppliers for computers, data centers, servers, telecommunication equipment, and on-board electrical vehicle chargers [19–21]. High efficiency, high power density, low harmonic distortion, and high power factor are attributes that drive the innovation and evolution of this technology [1,17]. These attributes largely depend on the implemented circuit topology. Based on this feature, CBP converters can be classified into: Bridge Boost converter (BBC), Semi-Bridgeless Boost Converter (SBBC), and Bridgeless Boost converter (BLBC) whose main features are described below, while the main modifications of topologies reported in the scientific literature are explained in detail in the body of the work.

BBC topologies have been incorporated in recent years for powering DC loads due to their general simplicity. BBC allows for reaching low levels of THD_i and high PF. However, this topology exhibits the following comparative disadvantages when used in medium-high power applications: (1) BBC has at least three semiconductor devices in the path of currents from source to load which increases conduction losses; (2) BBC requires a switching frequency greater than 30 kHz to lower the THD_i below the IEC 1000-3-2 standard; (3) the inductor is located on the DC side requiring design considerations to avoid saturation of its core. BBC topology, in its conventional form, is only recommended for applications up to 1 kW [8,22,23]. The power consumed by the line bridge rectifier takes up to 30~60% of the total losses in a large range in a BBC rectifier [23]. Some advances have been presented in the technical literature trying to solve these disadvantages. In [24], a control structure for the operation of BBC converters under variable switching frequency was proposed. Switching frequency is modified for two reasons: (1) to reduce switching losses; in this case, frequency around the peak of the current signal is decreased; (2) to reduce THD_i during the current zero crossing; in this case, frequency is increased. It was found that THD_i is reduced; however, the current waveform is not fully sinusoidal causing THD_i to not meet IEC/EN 61000-3-2 (or IEC 1000-3-2) and IEEE Std. 519 [25]. In [26], EMI produced by BBC functioning was mitigated using a filter, being adequate for low power converters. BBC operation requires a closed-loop controller with a power filtering stage to simultaneously ensure EMI and THD_i reduction while keeping high PFC and regulating of DC voltage [27–31]. For these factors, a number of hardware changes for the BBC topology have been proposed by the scientific community which are explained in detail in this paper [4,32–37].

SBBC topologies allow for reducing conduction losses; basically, SBBC has less semiconductor devices in the path of the current from the source to the load compared to BBC topologies. However, this converter exhibits a significant amount of common mode noise in the input current, requiring additional components that increase the complexity of the circuit. The common mode problem is induced by the floating output ground, which is pulsating according to the switching frequency. In addition, this topology requires an additional inductor that increases the weight, size, and cost of the power converter. In this topology, EMI problems at the common coupling point can be reduced by adding diodes, capacitors, inductors, and also appropriate location of symmetrical switches for phase and neutral lines [38–40].

BLBC converters have an asymmetrical arrangement of their elements in the converter branches which mitigates reverse-recovery currents from diodes. It has no common mode interference problem because the output voltage is clamped to the input by diodes during each half-line cycle. Additionally, this topology has the potential capacity for bidirectional

power conversion. Nevertheless, its inherent asymmetry increases the complexity of the controller and requires isolation in each driver of the branches [41–43].

For CBP converters, performance measures such as efficiency, number of components, PFC, THD_i , maximum operating power, and other features are highly dependent on the circuit topology. In recent years, researchers have reported a large number of CBP topologies that have received increased attention from the scientific community [17,27,28,35,37]. Some bibliographic reviews that have gathered information on the BBC, SBBC, and BLBC have recently been published [16,44]. However, these reviews neglect the analysis of interleaved converters and do not include any analysis regarding electromagnetic compatibility and power factor. In addition, review [16] was published in 2005, while review [44] was published in 2010; nonetheless, in the last decade, the scientific community has presented important advances in terms of new topologies, control systems, input filters, and power switches. This paper presents the CBP topologies and their modifications reported in the last fifteen years. In addition, according to the literature search, we found that CBP converters are called by different names by different authors; however, according to their topological structure, we categorized the converters into BBC, SBBC, and BLBC converters. Finally, this paper provides a comparative analysis that can be useful for researchers and developers to select the appropriate topology according to their application, showing their corresponding advantages and disadvantages and also giving recommendations.

This paper is structured as follows: Sections 2–4 are respectively focused on the categorization of BBC, SBBC, and BLBC converters. Section 5 corresponds to the summary of the topologies included in the paper, and a comparative study is made in terms of: control type, voltage level, power level, number of semiconductors, and number of inductors and capacitors that compose each topology; in this section, recommendations are given to assist designers and developers in the topology selection process according to their particular requirements. Finally, Section 6 concludes and highlights the most relevant aspects of the paper.

2. Categorization of Bridge Boost Converter Topologies

BBC topologies with PFC based on Boost converter are presented in this section. BBC converters are mainly composed of a full rectifier bridge; however, all BBC topologies presented in this section need a line EMI filter between the feeding source and the bridge to comply with international normatives regarding THD_i (lower than 6%), regardless of the control system [25]. Nevertheless, sizing of the EMI filter depends on the number of switches, control strategy, voltage level, power level, and paths to handle the converter currents.

2.1. BBC Topologies

Figure 1 shows the conventional BBC topology where (v_{ac}) is the electrical grid or feeding source. The rectification is performed by means of the diode bridge (D_1 , D_2 , D_3 and D_4) [16,30,32,33,45]. Inductor (L) and capacitor (C) interchange energy while diode (D) prevents reverse currents. Resistor (R) is the load that is feeding through a regulated voltage from the DC bus. Control structure is usually implemented by using a cascade PI structure for regulating the DC bus and also performing PFC.

The conventional BBC is the most common topology used in low voltage and power applications due to its reduced number of components. However, when medium and high voltage converters are required, power losses must be taken into account in the design process for obtaining a more accurate estimation of efficiency and gains of the system [28,46].

In [16,47], the authors showed the importance of soft switching for medium and high voltage and power applications of BBC. In [16], a review concerning soft switching techniques with snubber circuits to reduce power switching losses in BBCs was presented. This work analyzes four main aspects: (1) application for low voltage; (2) behavior in Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM); (3) contrast

between Zero Voltage Switching (ZVS), Zero Voltage Transition (ZVT), and Zero Current Switching (ZCS) techniques; and (4) comparison between MOSFET and IGBT switching technologies. It should be noted that there are switch technologies with better performance than conventional IGBTs and MOSFETs. These technologies include Gallium Nitride (GaN) switches and Silicon Carbide (SiC) MOSFET switches. GaN and SiC technologies can be used (recommended) in frequencies between 100 KHz and 200 KHz, so that GaN and SiC switches present better efficiency (lower losses) than conventional IGBTs and MOSFETs. More information concerning these switch technologies is available in [48–50]). In general terms, switching with ZVS or ZCS increases the switch useful life. Resonant BBC topology that operates with ZVS or ZCS can be implemented by adding an LC circuit to BBC conventional topology. Further details can be consulted in [51–63]. The aforementioned resonant LC circuit requires an additional switch (a second one) to introduce an inductor to the converter circuit for providing an additional path with zero impedance where the current and voltage do not strongly change their values.

Figure 1. Conventional BBC topology with PFC.

The BBC converter is directly connected to the AC supply, so its diodes and power switches inject harmonics and produce noise; then, an EMI filter is required. The authors in [26] present a design of an EMI filter for a medium power BBC, where results show a reduction of the Common Mode (CM) and Differential Mode (DM) noise when high switching frequency is needed. The EMI filter with classical linear PID control can reduce THD_i to normative ranges; nevertheless, limitations of PID control (slow and tuning around of an operation point) can reduce its efficiency, increasing THD_i and causing poor dynamic performance when the converter operates out of its design range [64]; this can be solved with nonlinear controllers or PID hybrid control techniques [3,22,24,29,30,45,65–68]. For example, a modulation technique for the BBC that can operate in DCM or CCM, exhibiting a high PF and low THD_i over a wide range of input voltage and load is presented in [3,69].

The conventional BBC topology can be modified as it was proposed in [70]. Figure 2 shows the BBC with pseudo-continuous conduction mode where diode D_5 and switch Q_1 were added in parallel with L . This modification increases dynamic behavior in transients and reduces stress in L by current circulation. Nevertheless, the addition of two semiconductors introduces two issues: (1) the increasing of losses because of the addition of more elements and (2) a complex control strategy to control Q_1 . This converter modification presents low ripple in DCM and CCM operation for low power application. Another modification to this topology was presented in [71], where two capacitors and inductors were added between the feeding source and the rectifier bridge. This converter presents low THD_i and high efficiency with cascade PID control for low voltage and power application. Nevertheless, the additional components increase its implementation cost.

Figure 2. Conventional PFC topology with pseudo-continuous conduction.

In conclusion, a BBC of conventional topology requires an intermediate filtering equipment for EMI mitigation together with a robust control strategy—this is in order to ensure a correct behavior in low and medium power applications [27,34,50,69,72–75]. In addition, SBBC of conventional topology are recommended instead of BBC in applications for medium and high power due to their low EMI [16].

2.2. Conventional Interleaved BBC

An interleaved BBC converter has several boost converters connected between the rectifier bridge and DC link capacitor for providing current levels, which improves power quality; consequently, ripple current in input is reduced. In addition, the levels make it possible to reduce the size of inductors, diodes, and circuit switches since thermal stress is reduced. An interleaved BBC converter is recommended for regulating the DC voltage in medium voltage applications since it provides voltage levels in the DC link bus; however, it is not recommended for high voltage applications since power losses and EMI issues are high due to the rectifier bridge. In medium voltage, a robust filter is necessary (EMI filter with several stages) between the AC power supply and the converter; in addition, the use of resonant circuits is recommended for each level for providing soft switching which reduce losses [32,76–78]. Figure 3 corresponds to the interleaved BBC converter that is composed of two stages which is commonly implemented in industrial applications [10,28,79,80]. In [28,81,82], and it presented a methodology for the design of inductors, capacitors, diodes, and power switches. The authors also included the design of the EMI filter. Simulation and experimental results presented an efficiency of around 97% and a power factor up to 0.995.

Figure 3. Interleaved PFC topology.

The conventional Interleaved BBC with two states can be modified as it was presented in [7]. The authors proposed to move switches and inductors before the rectifier bridge. Simulation results presented THD_i into a normative range with classical PI control for applications in low voltage and power. In addition, operation in DCM and CCM was considered, obtaining an efficiency greater than 96%.

2.3. Conventional Hybrid Interleaved PFC Topology Based on a Boost Converter

An interleaved hybrid BBC topology with three levels was proposed in [31]; please see Figure 4. This converter may feature an efficiency around 97% when using a PI controller. The authors reported that THD_i normative is reached when an EMI filter is used. Basically, currents flow between the branches of the converter, allowing not only the reduction of the ripple current and but also the losses when compared with the interleaved converter of two levels; nonetheless, the addition of a third branch increases its cost. In general terms, this converter is suggested for medium voltage applications because of its low ripple and THD_i compared to the conventional BBC converter. In addition, this three-level topology is also recommended in low-voltage applications—this together with independent soft switching circuits considering an independent design control for each switch. The interleaved hybrid BBC topology complies with approximately the same function as the interleaved topology (with three states) presented in Section 2.2; then, the interleaved topology is recommended instead of the hybrid one considering that the hybrid is limited by three states.

Figure 4. Hybrid Interleaved PFC topology.

2.4. Conventional PFC Topology with Bidirectional Switch

Figure 5 shows the BBC Conventional PFC Topology with Bidirectional Switch [37,83]. In this topology, inductors L_1 and L_2 ($L_1 = L_2$) are used as coupling inductors, while the bidirectional switch composed of Q_1 and Q_2 is on the AC side of the converter. For an appropriate operation, D_1 and D_4 must be fast-recovery diodes. This topology permits the reduction of the common mode noise; however, an EMI filter in the input of the converter is still necessary. One advantage is that the same control signal can be used for controlling Q_1 and Q_2 . It is important to mention that Q_1 and Q_2 must be installed in inverted order to avoid reverse currents in the operation when both switches are open. In addition, stages of control and power should be isolated as recommended in [36]. In this topology, a resonant circuit for soft switching in order to reduce switching power losses is recommended [84–86].

Figure 5. Conventional PFC topology with a bidirectional switch.

Different configurations were proposed to enhance the performance of the bidirectional BBC topology [83,87]. The PFC Topology with Bidirectional and flexible switches is depicted in Figure 6a. This converter includes (Q_3 and Q_4) as auxiliary switches and also a split DC link bus configuration (C_1 and C_2). Q_3 and Q_4 allow supplying the converter with two levels of input voltage, and both auxiliary switches are open or closed at the same time facilitating the control strategy. This converter is only recommended for low voltage and power applications since the bidirectional switches increase power losses and need a robust soft switch circuit for the management of high currents. The BBC PFC Interleaved Topology with Bidirectional switch is depicted in Figure 6b. This converter is only suggested for low voltage and low power applications since it requires a great quantity of semiconductors that need independent soft switching, isolation, and drivers—so that conventional interleaved (Section 2.2) BBC complies with the same function with less components and control complexity.

Figure 6. BBC converter with bidirectional switch: (a) bidirectional and flexible switches; (b) bidirectional and interleaved.

Bidirectional switch topologies are only suggested for low voltage and low power applications since they require additional switches which increase the cost of implementation and operation. For medium and high power applications, bidirectional topologies have a low efficiency because the converter currents have only one path of flow, not splitting in each half-cycle as in the previous converters. Consequently, thermal stress and power losses increase, which yields the increasing of differential noise [36,37,83,88]. Additionally, it is important to reduce switching losses in bidirectional topologies for two reasons: (1) bidirectional converters have more switches than other topologies for the same function, (2) bidirectional switches are in the converter input (before the rectifier bridge), where the voltage is low and the input current is high; then, bidirectional switches must be more robust than those located after the rectifier bridge.

3. Categorization of Semi-Bridgeless Boost Converter Topologies

SBBC topologies are also based on the BBC topology; however, they use a half bridge composed of Q_1 and Q_2 as can be seen in Figure 1. In this topology, the inductor L is between the AC power supply and the half-bridge; basically, each switch operates independently for each semi-cycle using the same inductor for controlling the AC current.

3.1. Conventional Semi-Bridgeless Boost Converter Topology

Conventional or symmetrical SBBC topology is depicted in Figure 7 [39,40]. SBBC conventional topology can reduce conduction power losses since less semiconductors are required in the current path (current through of two semiconductors per cycle) if compared with BBC topologies [72,89].

Figure 7. Semi-bridgeless boost converter topology.

The conventional SBBC topology has low Common-Mode (CM) and Differential-Mode (DM) noises in comparison with the conventional PFC BBC topology [34]. The DM noise and thermal stress in L can be reduced when it is added an inductor in the path of the neutral conductor [4,38]. The inductors work in series in each semicycle; in this case, the CM noise can also be reduced if both inductors are coupled [90,91].

3.2. Conventional Semi-Bridgeless Boost Converter with Soft Switching

Soft switching is performed by adding a snubber circuit composed of a switch Q_3 , an inductor L_3 , and a capacitor C_1 as shown in Figure 8. Basically, the snubber circuit allows for reducing switching losses from SBBC [92]. In addition, resonant circuits can be coupled for SBBC topologies as suggested in [93,94].

Figure 8. Semi-bridgeless boost converter with soft switching.

3.3. Semi-Bridgeless Boost Converter with Isolation

Figure 9 shows a modification of the SBBC conventional topology [95]. Such modification consists of adding a switch (Q_3) between the half bridge and the capacitor to isolate the AC power supply and DC link bus. This topology presents a reduction of leakage

current to the ground line from the grid. However, power losses can increase due to the addition of Q_3 that operates when the converter is discharging; in addition, this converter has a disadvantage that requires an additional control action for Q_3 and a greater filter in comparison with the SBBC conventional topology.

Figure 9. Semi-bridgeless boost converter with isolation.

3.4. Semi-Bridgeless Boost Converter with Clamped Diodes

The topology of SBBC with clamped diodes or pseudo totem-pole SBBC topology is depicted in Figure 10. This configuration includes two additional diodes (D_3 and D_4) to the symmetrical topology. As a result, this topology is built by two boost converters, each one operating in each semi-cycle of the AC sinusoidal wave [13,38,72,89,96–100]. For this reason, this topology is also known as dual boost PFC rectifier.

Figure 10. Semi-bridgeless boost converter with clamped diodes.

An advantage of this converter is that switches Q_1 and Q_2 can be driven with the same control signal. This topology reduces CM noise since D_3 and D_4 avoid the coupling between ground and the power supply. However, DM noise and current ripple can increase since only one inductor operates in each semi-cycle. In comparison with conventional topology with a rectifier bridge, this converter has less current ripple and also produces less DM and CM noises; consequently, a smaller filter could be used for this topology which makes it less expensive [32]. The authors in [89] designed a cascade PI controller, and they obtained a PF of 0.99 and a THD_i around 3.9%. This implies a significant energy quality improvement if the SBBC control system is also designed for harmonic mitigation. Additionally, the CM noise can also be reduced if coupling inductors are used [101] while switching losses can be reduced if a snubber circuit is implemented [63,102–104]. In addition, THD_i can be improved if any nonlinear control technique is implemented [11]; the authors in [11] developed a sliding mode control together with PI and an adaptive hysteresis band were proposed to reduce THD_i and, at the same time, to improve the dynamic converter response.

A modification of this topology is presented in [12]. The authors replace Q_2 by two diodes making a hybrid converter between conventional BBC and SBBC with clamped diodes. This converter can operate in low voltage and power with a classical cascade PI control.

3.5. Semi-Bridgeless Boost Converter with Clamped Switches

SBBC hybrid clamped topology or SBBC with active virtual ground is depicted in Figure 11 [105]. The capacitor C_1 and two clamped switches (Q_3 and Q_4) are added while diodes are removed. As an advantage, it is possible to implement an LCL filter (with L_1 , L_2 and C_1) between the SBBC and the AC power supply; then, this filter can reduce the DM noise. In addition, this topology requires less robust EMI filters compared to the SBBC with clamp diodes' topology. CM noise can be reduced using C_1 ; however, the conduction losses are increased. In [106], this converter is controlled by cascade PI control for Q_1 and Q_2 , operating as conventional SBBC while switches Q_3 and Q_4 have an independent control. This paper presents an application in low voltage and power with THD_i into a normative range for powers greater than 200 W. The active filter allows for reducing or eliminating (depending on the application) the passive EMI filter between the grid and converter; additionally, the switches increase conduction losses, control requirements, and implementation cost. In contrast, the SBBC topology with clamped diodes and passive EMI filter presents a similar behavior with lower design and implementation requirements.

Figure 11. Semi-bridgeless boost converter with clamped switches.

3.6. Semi-Bridgeless Boost Converter with Clamped Diodes and Switches

SBBC based on a clamped topology with diodes and switches is depicted in Figure 12. The authors in [107] reported that this topology presents high efficiency. This topology considers two additional switches (Q_3 and Q_4); consequently, each boost converter works by using two switches per semi-cycle. The main advantage corresponds to the reduction of conduction losses due to the current return path being shortened; in addition, Q_3 and Q_4 contribute to the reduction of CM noise. Please note that power losses do not increase for this topology when compared with a topology with only clamped switches; basically, clamped diodes (D_3 and D_4) only operate for the pre-charge of the DC bus, being excluded from the current path in normal operation conditions or in steady state.

Figure 12. Semi-bridgeless topology with clamped diodes and switches.

3.7. Semi-Bridgeless Boost Converter with Clamped Capacitors

This converter (Figure 13a) incorporates two clamped capacitors (C_1 and C_2) [5]. The capacitors work as a filter with low impedance when the converter needs to operate in high frequency, which is used for CM noise mitigation. The current ripple may increase up to two times in comparison with a converter with clamped diodes; in addition, this converter presents a lower efficiency than the SBBC with clamped diodes and switches in similar applications. In this topology, the clamped capacitors must have the same values; otherwise, the converter has imbalances, increasing CM noise. In this case, the converter could need a different controller for each switch. Figure 13b presents a modification for this converter [6]; the modification includes two coupled inductors (L_3) in series with L_1 and L_2 for mitigating CM noise. In this case, the capacitors are also used to reduce the magnetization current from L_3 (they present low impedance); additionally, the choke inductors present high impedance in their terminals. Then, this topology has a wide frequency range for CM noise mitigation.

Figure 13. Semi-bridgeless boost topology with clamped capacitors: (a) conventional; (b) coupling inductors.

3.8. Semi-Bridgeless Topology with Internal Snubber Circuit

Figure 14 depicts the SBBC with an internal snubber circuit [108]. This converter has an additional switch (Q_3) in comparison with the topology with clamped diodes in order to switch the converter with zero voltage transition. The main function of Q_3 is to control the snubber circuit made of diodes D_5 , D_6 , D_7 , D_8 , inductor L_3 , and capacitor C_1 . The snubber circuit provides a soft switching for Q_1 , Q_2 , and Q_3 in order to reduce switching losses and reverse recovery losses from D_1 and D_2 . Other topologies with a snubber circuit for SBBC soft switching can be consulted in [109–111].

Figure 14. Semi-bridgeless topology with an internal snubber circuit.

In conclusion, SBBC topologies present better behavior than BBC topologies in terms of efficiency, THD_i , and losses. Therefore, SBBC topologies are suggested in applications of low voltage and medium power instead of BBC topologies [32,36,37,112].

4. Categorization of Bridgeless Boost Converters

This section categorizes the BLBC based on boost topology that basically replaces the rectifier bridge by switches or asymmetrically situating not only the switches but also the diodes of the converter branches.

4.1. Totem Pole Topology

Figure 15 depicts the conventional or asymmetrical topology based on boost converter [33,41–43,113,114]. Figure 15a illustrates the conventional BBC totem-pole with line rectification done by diodes; this topology has switches (Q_1 and Q_2) in the first branch of the converter and diodes (D_1 and D_2) in the second branch. This converter can operate in the limit of CCM and DCM, including techniques for sampling (as explained in [115]). This allows for reducing reverse-recovery of diodes and THD_i . Nonetheless, this operation mode produces a random ripple to consider in control designing. In addition, power losses can be mitigated with snubber circuits [92,116–122]. This topology has commonly been used in low voltage and power applications; nevertheless, in medium power applications, it is suggested to build the converter with switches (Q_1 and Q_2) using GaN technology [123]. GaN switches allow for converter operation using higher switching frequencies (greater than 100KHz) with low power losses in comparison with IGBT power switches. It should be noted that the maximum switching frequency of power switches is a function of multiple factors such as structure dimensions, duty cycle, control, technology, etc. In this way, an IGBT switch can also operate at frequencies up to 100 KHz [124]; nevertheless, IGBTs are limited by their constructive features and working at high frequencies reduces their efficiency and operating current.

Figure 15. Conventional BBC or totem-pole converter: (a) line rectification with diodes; (b) line rectification with switches.

A modification to the totem-pole topology is shown in Figure 15b where diodes are removed and the line rectification is carried out by means of switches (Q_3 and Q_4); additionally, it is suggested that Q_1 and Q_2 be GaN, so that it is possible to reach high power factor and efficiency with PI control outside the design operation point [125]. In [126], a BBC with GaN switches was implemented for low voltage and medium power applications. The experimental results show efficiency of 99% considering copper losses from the converter inductor and EMI filter. In the same way, in [127], a BBC totem-pole with GaN switching was implemented for low voltage and medium power applications. The authors showed that THD_i complies with the normative range with classical cascade PI control, improving the PWM modulation technique. This topology can reach a great reduction of switching power losses when used with a resonant circuit [76,128–132].

4.2. Bridgeless Boost Converter, Interleaved Totem-Pole

Totem-pole and GaN totem-pole topologies can be improved according to Figure 16. Figure 16a presents a BBC totem-pole with additional diodes (D_3 and D_4) and inductors (L_1 , L_2 and L_3) [133]. In this case, L , L_1 , and L_2 are coupling inductors and their function consists of reducing reverse recovery currents from diodes D_1 and D_2 . Diodes D_3 and D_4 contribute to ZCS of Q_1 and Q_2 . This converter is used in low voltage and power applications, and its efficiency is lower than the one of the totem-pole and GaN totem-pole (between 94% and 97%) topologies due to the additional components in the converter. In the same way, the GaN totem-pole can be modified by adding diodes D_1 and D_2 and inductors L_2 and L_3 according to Figure 16b [8,23,134]. Diodes and inductors comply with the same function as the converter in Figure 16a (reducing reverse recovery issues and contribute with ZCS); additionally, efficiency is also reduced requiring a robust control strategy and filtering to comply with THD_i limits given by the normative.

Figure 16. Interleaved boost converter: (a) totem pole topology; (b) GaN totem-pole.

4.3. Pseudo Totem-Pole

Figure 17 depicts the pseudo totem-pole converter. This converter has two AC/DC boost rectifiers (one for each grid semi-cycle) [9,135,136]. In the positive semi-cycle, the first boost converter (formed by L_1 , Q_1 , and D_1) operates due to the polarization of D_4 . In the negative semi-cycle, the second boost converter (formed by L_2 , Q_2 , and D_2) operates due to the polarization of D_3 . This topology needs independent signals for controlling both switches [36]. Additionally, it also requires coupling inductors for EMI mitigation and snubber circuits for switching losses' reduction [137,138]; therefore, this topology is not commonly used since a similar performance can be obtained with other BLBC topologies (with less number of components or control complexity).

Figure 17. Bridgeless boost converter pseudo totem-pole topology.

5. Summary of PFC Single-Phase AC-DC Based on Topologies of a Boost Converter

This section summarizes the BBC, SBBC, and BLBC converters categorized in this paper. It was found that most of the PFC Single-Phase AC-DC Boost converter topologies are used for applications in low (L) and medium (M) voltage and power; a classification concerning these aspects is included in this section. This section also includes recommendations to help designers and developers in the process of topology selection according to their specific requirements. Table 1 includes the summary in terms of control, voltage level, power level, number of semiconductors (SM), and number of inductors and capacitors (IC) that compose each topology.

Table 1. Summary and comparison among BBC, SBBC, and BLBC topologies categorized in this paper.

Converter	Category			Control		Voltage		Power		Semi-Conductors	Inductors+Capacitors
	BBC	SBBC	BLBC	Linear	Non-Linear	L	M	L	M		
Conventional	X			X	X	X		X		6	2
Pseudo continuous	X				X	X		X		8	2
Interleaved	X			X	X		X	X		8	3
Hybrid interleaved	X			X	X	Not recommended				10	4
Bidirectional	X				X	X		X		6	3
Bidirectional flexible switches	X				X	Not recommended				8	3
Bidirectional interleaved	X				X	Not recommended				8	3
Conventional		X		X	X	X		X		4	2
Soft switching		X		X	X	X			X	6	5
Isolation		X		X	X	X		X		5	3
Clamped Diodes		X		X	X	X		X	X	6	3
Clamped switches		X		X	X	X		X		6	4
Clamped diodes and switches		X			X	X		X		8	3
Clamped capacitors		X		X	X	X		X		4	5
Clamped capacitors coupling inductors		X		X	X	X		X	X	4	7
Zero voltage transition		X			X	Not recommended				11	5
Conventional			X	X	X	X		X		4	2
Conventional GaN			X		X	X		X	X	4	2
Interleaved			X	X	X		X	X		6	5
Interleaved GaN			X		X		X		X	6	4
Pseudo totem-pole			X		X	Not recommended				6	3

Concerning control techniques, it was found that most topologies can reach a high power factor when a linear control technique is used; however, high values of THD_i and efficiency are difficult to obtain. Basically, to reach high standards of power quality, a robust EMI filter is required, which increases the cost. It was also found that, when nonlinear control techniques are implemented, all topologies present low THD_i (lower than 6%), high power factor (greater than 0.99) and high efficiency (greater than 97%). Then, it is concluded that, by using nonlinear control techniques, it is possible to obtain a high standard of power quality and at the same time reduce the cost of the converter; however, the implementation of a nonlinear control represents a greater effort in the development stage.

BBC topologies with bidirectional switch are not recommended due to the fact that these topologies increase the number of switches; consequently, the converter cost is higher and the control technique is more difficult to develop. Moreover, a better performance in terms of dynamic response can be obtained by means of other BBC or SBBC topologies. SBBC with zero voltage transition is not recommended due to its large number of components, which make it expensive; BLBC pseudo totem-pole is not recommended since similar dynamic performance can be obtained with the conventional totem-pole topology.

The topologies presented in this paper require an input filtering process; however, SBBC converters need a less robust filter than BBC or BLBC under the same operative conditions, due to the reduction of CM noise obtained by their symmetry in construction. It was also found that a better efficiency can be obtained by using several current paths by means interleaved circuits, and reducing losses by means of snubber or resonant circuits. BLBC topologies (not symmetrical) need a conditioning circuit for isolation of control signals.

6. Conclusions

In this paper, a review and categorization regarding BBC, SBBC and BLBC topologies for PFC based on boost converter was presented; the basic operation, advantages, and disadvantages of these topologies were analyzed, including criteria for categorization which allows for unifying the technical language that is used in these types of devices. All consulted topologies need an input EMI filter and may reach high power factor (complying with IEEE Std. 519 and IEC/EN 61000-3-2) when PID controls are used; however, to reach high standards of power quality, the use of nonlinear control techniques is recommended. Basically, challenges are focused on improving energy quality concerning electromagnetic compatibility. An adequate PI tuning that includes any optimization technique can reduce the filter size; nevertheless, it could present a slow response in the face of disturbances or load changes in comparison with nonlinear control techniques. In general terms, nonlinear control can significantly reduce the filter size improving the converter behavior.

BBC is widely used in low voltage applications due to its simplicity (low components and control requirements). Nevertheless, in medium voltage and power, a robust EMI filter is required, increasing power losses, implementation cost, and control requirements. BBC topologies based on bidirectional switches are not recommended due to the fact that other topologies can carry out the same function with better electromagnetic compatibility performance and less demanding requirements not only in control but also in implementation. In conclusion, BBC topologies present an appropriate dynamic performance for low voltage and power applications. As regards medium voltage applications, the use of interleaved BBC is recommended; nevertheless, it must be considered that its rectifier bridge may produce higher EMI.

In general, topologies based on the symmetric distribution of components (SBBC) have better behavior than other topologies (BBC and BLBC) regarding efficiency and EMI when similar control strategies are implemented. In some topologies (as the clamped one), the same control signal can be used to operate all converter switches. SBBC topologies are symmetric with respect to the ground and several paths for current circulation. This reduces thermal stress in their components such as inductors and power switches. In addition, SBBC topologies can easily comply with IEEE Std. 519 and IEC/EN 61000-3-2 when PID controls

are implemented while using less robust filters than BBC topologies. For these reasons, SBBC topologies are recommended for low voltage and medium power applications.

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