

The Versatile Buck-Boost Converter as Power Electronics Building Block (PE-BB)

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Abstract

The versatile buck-boost (VBB) converter has been extensively studied because of its advantageous features such as step-up/step-down voltage conversion ratio, high efficiency, low-ripple continuous input/output currents easy to regulate, and the possibility of controlling any converter variable. These interesting features make it an excellent candidate to be a power electronics building block (PE-BB). This article summarizes the state-of-the-art PE-BBs and briefly describes the topological changes, control techniques implemented, and applications for which the VBB converter has been used so far. Finally, the experimental tests show that the proposed PE-BB can perform exceptionally well in dc-dc, ac-dc, dc-ac, and ac-ac applications.

I. THE SEARCH FOR A POWER ELECTRONICS BUILDING BLOCK

The collected working papers produced by Ćuk and Middlebrook (C&M) [1] are some of the most inspiring power electronics documents. The first volume deals with the modeling and analysis of switched converters. The second volume is dedicated to the *optimal topology converter* or Ćuk converter, a tremendously versatile dc-dc switching converter structure (see Figure 1).

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Topologically, it is a structure that Ćuk derived from the conventional buck-boost topology and which allows the voltage to be stepped up or down.

The nonisolated polarity inverting Ćuk topology has continuous input and output currents as the VBB converter. Unlike most non-switched capacitor converters, the Ćuk topology's intermediate capacitor stores all the energy that flows between input and output. This converter also presents high stress in the switches, which as in the conventional buck-boost converter, strongly penalizes the efficiency.

The basic Ćuk converter can be modified by including a damping network for the intermediate capacitor or magnetically coupling its inductors. In the discontinuous conduction mode (DCM), Ćuk proposed, among many other modifications, an isolated version. And before reporting his converter, Ćuk presented the boost converter's cascade connection with the buck converter called Split-Pi. Figure 1 shows Split-Pi's structure with ideal bidirectional switches [2]. But it has a dynamic limitation when used to step-up the voltage.

The C&M articles studied the magnetic coupling between the "cascaded boost-buck" inductors. However, they focused mainly on 1:1 and $n = k$ magnetic coupling conditions. They ignored other essential alternatives, such as using an intermediate capacitor damping network simultaneously with magnetic coupling or different magnetic coupling values' dynamic effects. This is strange because C&M proposed damping the capacitor in the input filter to improve the converter's stability. They also overlooked the enormous advantage for the stability of moving the transfer function zeros from the right half-plane (RHP) to the left half-plane, selecting the appropriate coupling coefficient. The absence of zero current ripple magnetic coupling in the "boost-buck" converter and the fact that more elements were required to implement the Split-Pi converter than the Ćuk converter must have made C&M focus mainly on the research and patent of the Ćuk converter.

Naturally, the search for versatile structures did not end with the work by C&M. Nowadays, many authors have focused on changes in the Ćuk converter. But perhaps the most interesting work is done on the standard multiple application regulator topology (SMART) used by the European Space Agency. This topology was obtained from a buck stage's cascade connection with a push-pull, or its variant with continuous input current shown in Figure 1 [3].

Other studies focused on searching for a converter with an easily scalable topology for many applications. One example is the simplified five-level diode-clamped topology presented in [4] (see Figure 1), the multilevel technique uses lower-voltage rated devices to improve the converter's efficiency. However, its main disadvantages are the number of switches required and the greater control complexity.

Figure 1 shows the current-fed boost-buck push-pull converter with independent charge mode control on each leg of the push-pull converter, which allows to operate in buck and boost modes [5]. In buck mode, the input current is discontinuous, while in boost mode, it is the output current.

A tapped-inductor buck-boost with perfect magnetic coupling to implement a power factor (PF) correction rectifier is proposed in [6]. This topology (see Figure 1) allows step-up and step-down conversion and uses a technique for generating the control's signals, similar to the one used in [7]. However, the converter does not solve non-minimum phase behavior's drawbacks due to RHP zeros or discontinuity in the input and output currents.

One of the most widely employed concepts of the power electronics building block (PE-BB) is to integrate several technological aspects of an innovative power converter [8]–[10]. These blocks have a defined set of characteristics [11]–[13], and structured hardware and control interfaces for multiple applications [14], [15], resulting in reductions of cost [16], the effort for maintenance [17], and the losses of power processing systems [18]–[20]. Currently, none of those mentioned above converters have met all the requirements of Figure 2 to be a PE-BB as summarized in Table 1. Nowadays, they are met by the VBB converter shown in Figure 1 proposed in [7]. This converter's most important feature is the improvement in its dynamic response since boost mode can be achieved without non-minimum phase behavior. It also offers step-up/step-down voltage conversion with high efficiency, and wide bandwidth [7].

The discovery of the VBB converter, shown in Figure 1, resulted from a single converter design that would meet all the desired characteristics of a PE-BB. This design was highly influenced by the C&M collection of studies [1] and resulted in a converter with magnetically coupled inductors and an RC-type intermediate capacitor damping network. The section below reviews the various control techniques, proposed applications, and topological changes for the VBB converter.

Power Electronics Building Block

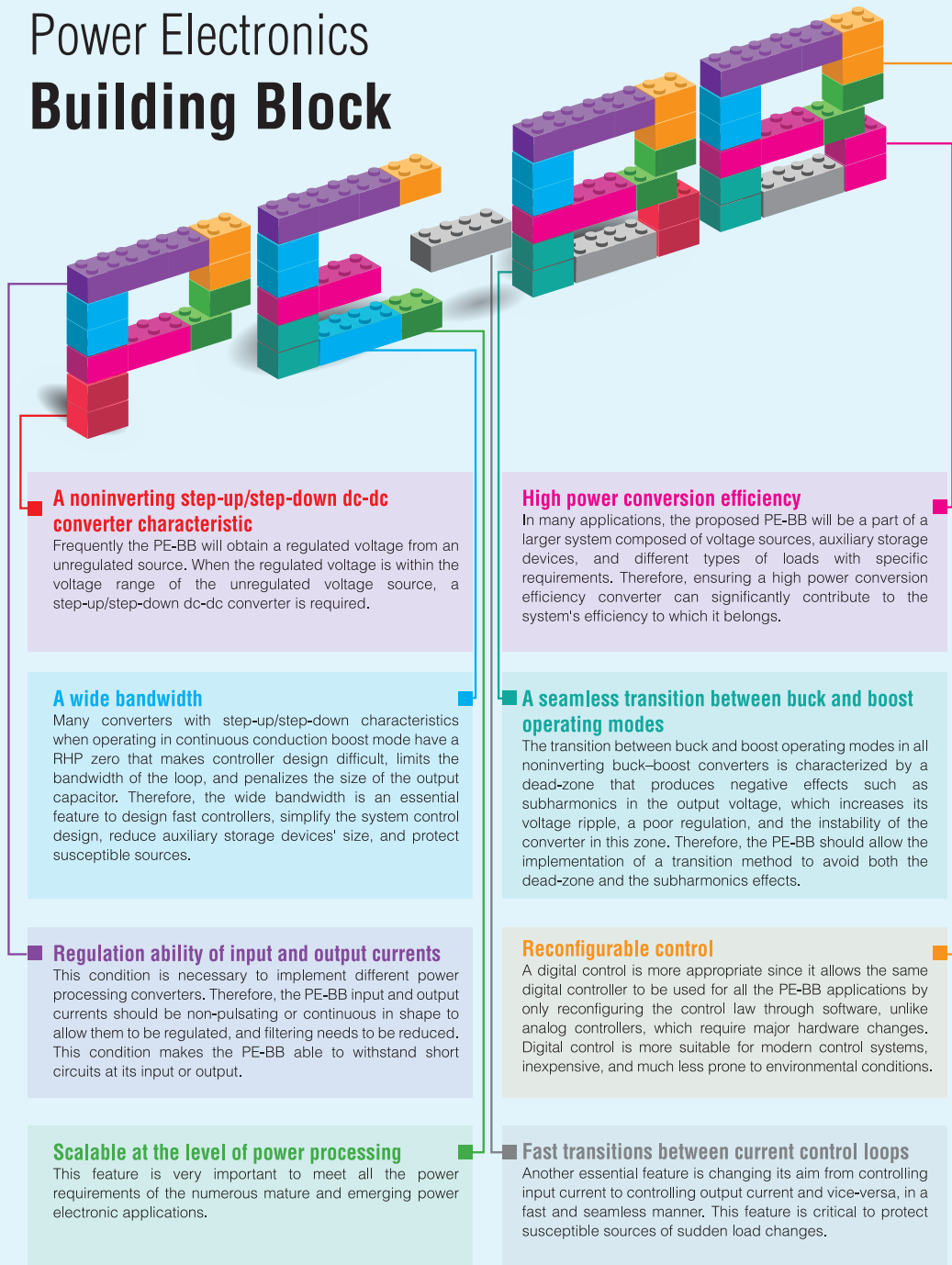


Fig. 2: PE-BB characteristics.

II. EVOLUTION OF THE VERSATILE BUCK-BOOST CONVERTER

The first study of the unidirectional VBB converter was published in [7] (see Topology I in Figure 3). Considered to be the original topology, exhibiting a non-inverting step-up/step-down characteristic, making it useful for many power processing applications. Combining an RC damping network and coupled inductors eliminates the RHP's zeros during the continuous conduction boost mode operation, ensuring a wide bandwidth facilitating controller design. To achieve high power conversion efficiency, depending on the operation mode, one of the switches operates at high frequency while the high-side diode or MOSFET of the other switch is permanently in ON-state and the low-side MOSFET-diode is in OFF-state.

As it evolved from the original voltage-controlled converter towards the VBB converter (see Figure 3) [7], its ability to control input or output current was reported in [21]. However, two significant challenges had to be solved first before being considered a versatile converter. The first challenge was to ensure that controlling input current could be changed to controlling output current, and vice-versa, fast and seamlessly [22]. The second challenge, solved in [23], was to improve the poor transition caused by a dead-zone between step-up and step-down modes.

This unidirectional converter version's versatility was verified by successfully using it in all the converter stages of three different structures of fuel cell hybrid power systems [24]–[26]. In each of these hybrid power systems, the VBB converter modules were controlled with various objectives (regulation/limitation of the current or the voltage, either at the input or the output sides) that changed dynamically in response to a master control strategy. The same module for all the dc-dc converters within each hybrid structure reduced manufacturing times and cost, simplified modeling and control design tasks, and allowed a fair experimental efficiency comparison between the hybrid power systems. Therefore, the VBB converter shows scalability at the level of power processing.

Hitherto, from the topology's point of view, three significant changes have been proposed concerning the original structure. The first change, presented in [27], [28] and shown in Figure 3 (Topology I), was the switch's bidirectional implementation, improving conversion efficiency. The coupled inductors for this power stage are designed following the transformer model to obtain a predictable coupling coefficient, as shown in Figure 3 (Topology II), where L_m is the magnetizing inductance, L is the leakage inductance, and the coupling coefficient is given by $k = L_m / \sqrt{L_m(L + L_m)}$ [31]. The coupled inductors with turns ratio $N1/N2 = 1$ and $k = 0.5$ resulted in identical control-to-output transfer functions between the operation modes.

The second change was implementing the converter coupled inductors symmetrically using a 1:1 transformer, constructed with a pair of tightly coupled inductors of turns ratio $N1/N2 = 1$ with a magnetizing inductance L_m . Two identical non-coupled inductors $L_A = L_B = L$ were connected in series with the primary and the secondary of the transformer, where $L_m = M$, $L_1 = L_A + M$ and $L_2 = L_B + M$, and therefore $L_1 = L_2$ [29] (see Topology III in Figure 3). This converter offered outstanding performance in a stand-alone photovoltaic application, but unlike the original non-symmetrical implementation of the coupled inductors, the control-to-output transfer functions (current or voltage) were different for both operation modes.

The third change was another design of the coupled inductors with a low parasitic winding-to-winding capacitance to improve the converter's efficiency in high-voltage applications, as shown in Figure 3 (Topology IV) [30]. In this case, instead of the unusually symmetrical arrangement of three different magnetic elements in [29], two loosely coupled inductors with an equal number of turns were coiled around a single core. The pair of loosely coupled inductors' magnetic coupling coefficient was $k = 0.5$. Therefore, primary self-inductance L_1 was equal to secondary self-inductance L_2 ($L_1 = L_2 = L$), and their mutual inductance was $M = L/2$. This modification performed exceptionally well in electric vehicle applications [30].

So far, the VBB converter has all the major desired features of a PE-BB (see Figure 2); however, the reconfigurable control has not been discussed. The first control techniques for the VBB converter were analog controls [7], [21], [22], which were replaced by hybrid analog-digital controls [24]–[26] and, more recently, by various digital strategies [27], [28], [30].

Therefore, the VBB converter has all the PE-BB features shown in Figure 2. However, there are pending challenges to improve VBBs such as including galvanic isolation into the topology and model its DCM operation in unidirectional implementation. Nevertheless, topology IV of the

VBB converter is already a powerful candidate to be a PE-BB because it collects the advantages of the preceding VBB converter versions and is designed for high voltage applications, but has not yet been tested outside dc-dc applications. In this regard, the section below will show that using the same VBB converter module can be extended to ac-dc, dc-ac, and ac-ac applications, thus confirming that it is a PE-BB.

TABLE 2 - VBB CONVERTER'S COMPONENTS AND PARAMETERS

Parameter	Value or type
Maximum voltage	400 V
Rated Power	3.2 kW
Switching frequency f_s	100 kHz
Output capacitor C_o	6x R75PW44704030J, 28 μ F, 630 V
Damping capacitor C_d	MKP1848S62070JP2F, 20 μ F, 700 V
Intermediate capacitor C	4x R76PN33304030J, 1.32 μ F, 630 V
Coupled inductor	$M = 135 \mu$ H and $L = 270 \mu$ H, 77908 Magnetics core, 80 turns (18 AWG)
Damping resistance R_d	2x BPR10100J in parallel, 5 Ω , 10 W, 500 V
MOSFET driver	UCC27714D
Power semiconductors $Q_1 - Q_4$	SCT2450KEC

III. EXPERIMENTAL RESULTS

This section discusses some illustrative experiments to validate using the same VBB converter as a PE-BB in dc-dc, ac-dc, dc-ac, and ac-ac power processing applications. Table 2 lists the proposed PE-BB parameters and components. In all the power processing applications, a low-cost TMS320F28335 digital signal processor is used to program all the proposed controls and show the proposed PE-BB's reconfigurable ability. To demonstrate the PE-BB structure's considerable potential, basic digital proportional-integral (PI) control has been used for all the power processing purposes in the following subsections.

A. Dc-dc applications

The configuration of the VBB converter for dc-dc applications is shown in Figures 4 (a) and (b). Two different cases are proposed: converter output current control (see Figure 4 (a)) and converter output voltage regulation using a double loop (see Figure 4 (b)). For the output current control, dc voltage supplies are connected at the converter's input and output to ensure the operation mode. In each mode, the current reference was changed from 4 A to 8 A while the output current is well regulated with fast transitions (see Figure 4 (a)). For the output voltage regulation, a double loop scheme is implemented using the previous PI current control for the inner loop and an additional PI for the outer loop. The results show the large-signal response when the output voltage reference is increased by 20 V in both modes (see Figure 4 (b)). It demonstrates what is already well known in dc-dc applications: that the PE-BB performs remarkably well.

B. Ac-dc applications

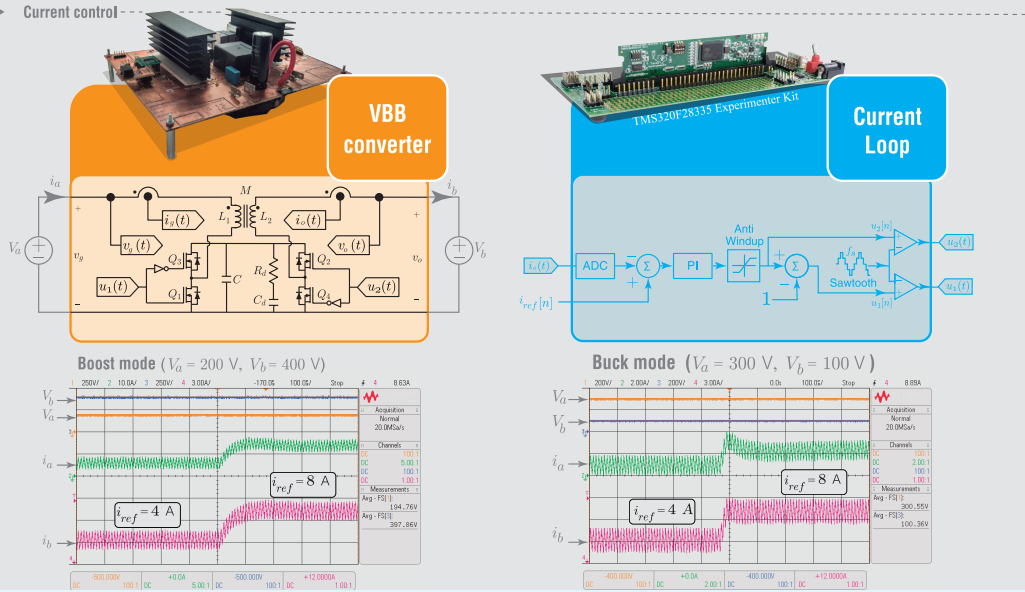
Figure 4 (c) shows the VBB converter's generalized block diagram as a PE-BB for ac-dc rectifiers. A normalized rectified sinusoidal reference is synchronized to the line input voltage and multiplied by the desired peak current value to obtain the input current loop reference to achieve a high PF. The same PI current control described in the dc-dc applications is used to track the rectified sinusoidal current reference. Experimental results show that the PE-BB input current is in phase with the input voltage while the desired peak current changes from 4 A to 8 A. In the experiment, the converter output voltage is fixed to 200 V, which is lower than the peak value of the input voltage that corresponds to the rectified voltage, ensuring operation in both modes in each grid semi-period. The results show good current reference tracking under changes of the operation modes and current reference, thus validating the use of the proposed PE-BB topology in ac-dc applications.

C. Dc-ac applications

Figures 5 (a) and (b) show the results of using the VBB converter for on-grid and off-grid inverter applications. A full-bridge unfolding stage follows the converter with an inductive output or a capacitive input filter, depending on the application. A sine wave reference unity block is used to supply the output current reference for the on-grid inverter and the output

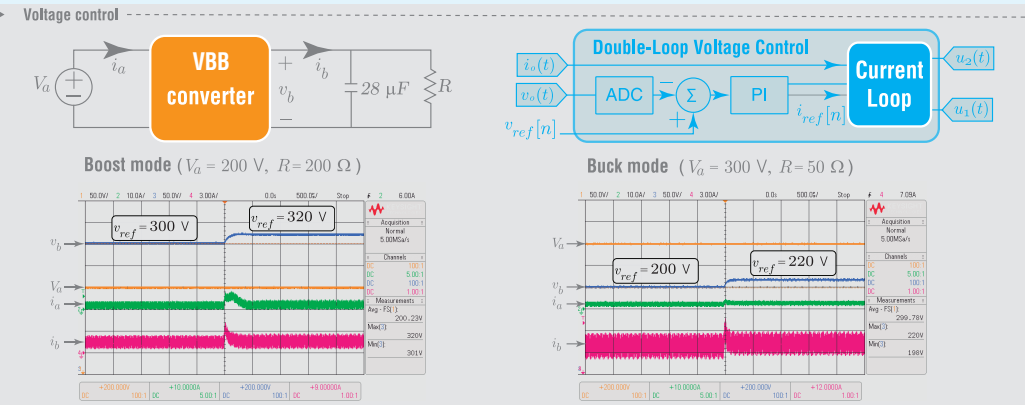
Dc-dc applications

Current control



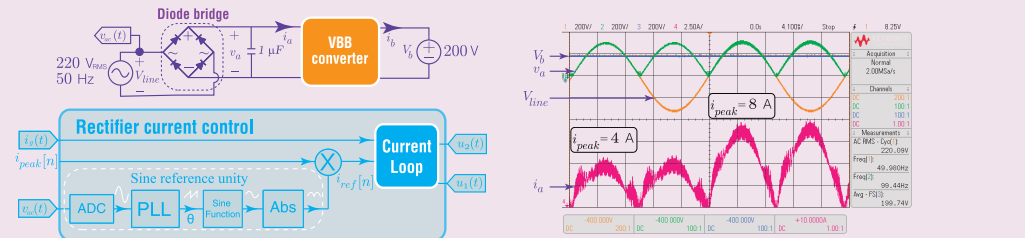
(a)

Voltage control



(b)

Ac-dc applications



(c)

Fig. 4: The VBB converter as a PE-BB: (a,b) dc-dc, and (c) ac-dc applications

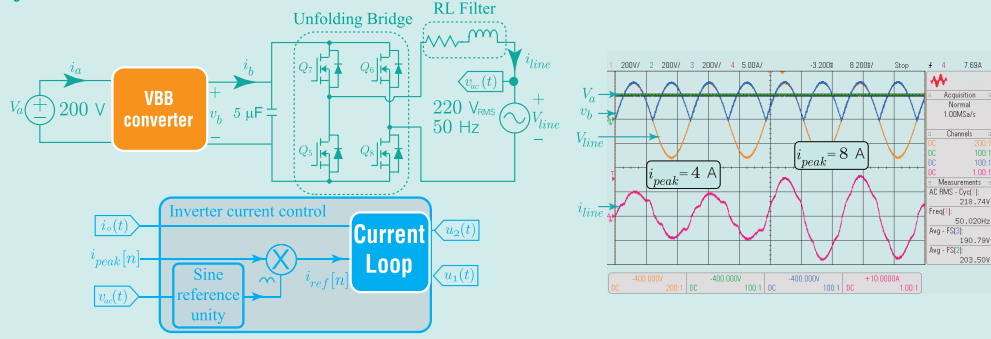
voltage reference for the off-grid inverter. In the case of an on-grid inverter(see Figure 5 (a)), a PI current loop like the one presented in the dc-dc application is used to regulate the output current and ensure tracking of the line output voltage. Like the previous ac-dc application, the PE-BB operates in boost and buck modes while the peak current reference changes from 4 A to 8 A. In the off-grid inverter (see Figure 5 (b)), the double loop voltage control presented in the dc-dc application is used to regulate the output voltage. The experimental results show that an excellent sinusoidal waveform is generated on the load side despite the PE-BB transitions between operation modes and the sudden load variations (50% to 100%). All these experimental results validate the excellent performance of the VBB as a PE-BB.

D. Ac-ac applications

Figure 5 (c) shows the VBB converter's generalized block diagram as a PE-BB for ac-ac conversion. An intuitive way to construct an ac-ac converter is using an ac-dc converter and a dc-ac converter in a cascade connection. However, in this subsection, the proposed PE-BB benefits are demonstrated by performing the ac-ac conversion in a single stage. To do so, the intermediate capacitance-voltage of the VBB converter is regulated at 200 V using the boost side of the converter. This is similar to the ac-dc application presented above but with an additional PI loop to regulate. On the other hand, the converter's buck stage is used to control the converter output current, as in the on-grid inverter case presented above. The experimental results are for a highly demanding application that mimics a low voltage wind generator (the frequency of which depends on wind speed) to the grid (constant frequency). In the results, the input line voltage frequency is changed from 50 Hz to 100 Hz and to 150 Hz. As is shown, the input current waveform responds perfectly to the changes in the input line voltage frequency while the output current proportionally tracks the output line voltage.

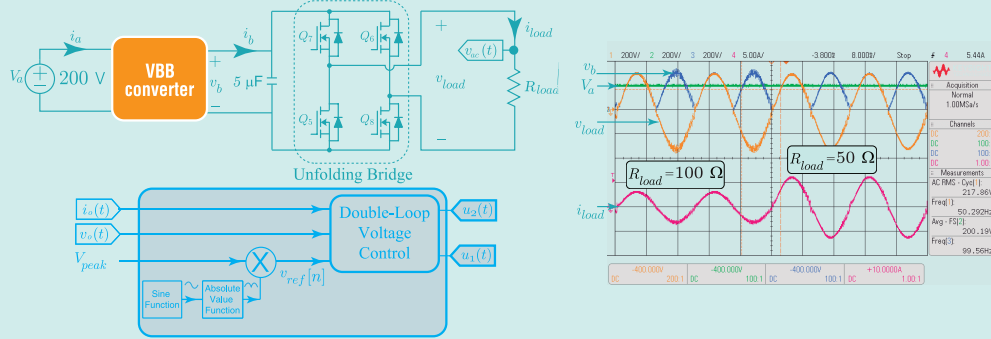
Dc-ac applications

On-grid inverter



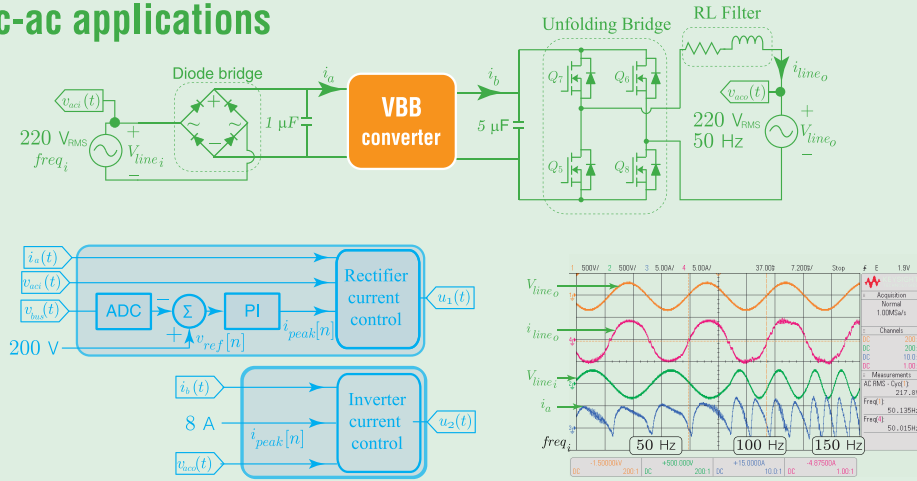
(a)

Off-grid inverter



(b)

Ac-ac applications



(c)

Fig. 5: The VBB converter as a PE-BB: (a,b) dc-ac, and (c) ac-ac applications.

IV. FUTURE CHALLENGES AND WORKS IN PROGRESS

Future work will improve the connectivity by including galvanic isolation in the topology and therefore extending its applications that are not yet explored at present such as ac-dc, dc-ac and ac-ac.

A challenge of great interest is, instead of using a rectifier bridge followed by a dc-dc structure, to propose a bridgeless or semi-bridgeless structure for the ac-dc case. This will also allow to propose a dc-ac without an unfolding bridge.

Finally, a work in progress is the modeling of the VBB converter as PE-BB in DCM, this modeling is important not only from the point of view of academic literature, but also in documentary and commercial literature. The results of these analyses are fundamental for designing reliable and robust controllers in critical applications.

V. CONCLUSION

This article discusses the VBB converter as PE-BB. The state-of-the-art was summarized, and the main characteristics of a non-isolated PE-BB were defined. The VBB converter's advantages were illustrated by briefly describing the topological evolutions, control techniques, and applications used to date. The experimental results of the VBB converter as PE-BB confirmed that it could be used not only as a dc-dc converter, but also as an ac-dc rectifier and dc-ac inverter, and in ac-ac applications. Although other control techniques can be applied, the results show that the VBB converter is easily controllable using proportional-integrator-based control loops. These controls have good dynamic responses and are simple enough to be easily standardized together with the efficient power conversion stage. The experimental results confirmed the versatility and excellent performance of the VBB converter as PE-BB.

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