

Experimental validation of a basic module based on a single-stage AC-DC converter, feasible to solid-state transformer applications

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Keywords

«Interleaved Converters», «Power Factor Correction», «Pulse Width Modulation (PWM)», «Smart Power», «Transformer».

Abstract

This paper shows the experimental validation of a basic module from a single-stage ac-dc bidirectional power converter, which is feasible for solid-state transformer applications. The proposed converter is based on the dual active bridge (DAB) using an interleave technique. The converter can be modularized and applied at high voltage in a three phase system operating as rectifier or inverter. The topology is briefly presented and experimental results from a small-scale prototype are discussed to validate its operation principles and control strategy. The results show that the control strategy is able to operate the converter properly maintaining all DC bus on reference value. The converter is also capable of operate with a high power factor and a low harmonic distortion. Simulation results are shown from a prototype that is under construction with a higher power and magnetic integration.

Introduction

An application that has received great attention in several current scenarios is the solid-state transformer (SST), which consists in a transformer that uses a power converter operating at medium frequency [1].

The objective of SSTs is to replace the line frequency transformers, while desirable aspects such as voltage regulation, reactive power compensation, and power factor correction are necessary. Besides, they present prominent advantages compared to conventional transformer, which typically present high weight and volume. The first application to take advantage of the aforementioned characteristics was railway traction, since overall dimensions and weight are critical issues [2]. In this context, SSTs operating at medium frequency present high power density.

Despite this advantage, the semiconductor maximum blocking voltage is a limitation to use the SST in high voltages. Nowadays, the maximum blocking voltage is found to be 15 kV [3]. Thus, the use of topologies with a single module is quite difficult at high voltages, as the use of modular and multilevel approaches is required.

This type of topology divides the semiconductors stress as it is possible to operate at higher voltages. In addition, the use of several modules allows the operation with spare modules to increase the reliability of the structure as well as achievement of easy maintenance [4].

Nowadays, with the proposal of novel topologies and semiconductor technologies, it is possible to increase the efficiency of SSTs.

The SST also allows improved power quality. In fact, they are able to perform power factor correction as well as minimize the current harmonic distortion depending on the module configuration. Moreover, renewable energy applications may led to the use of SSTs in distribution systems due to the existence of dc links [5].

Proposed topology

Fig. 1 (a) presents the topology studied in this work, which was firstly presented in [6]. The structure is composed of a dual active bridge (DAB) [7] using an interleaving technique by coupled windings [8]. The dc/dc stage manages power transfer and provides medium-frequency operation to the transformer. The interleaved windings share the current through the semiconductors, what reduces their stress. The topology also employs a leg operating at low frequency, which allows the modulation of positive and negative voltages. All the switching states of the structure are described in [9].

Fig. 1 (b) shows the same topology with magnetic integration, as the interleaved windings associated with the medium-frequency transformer allow minimizing overall dimensions and losses.

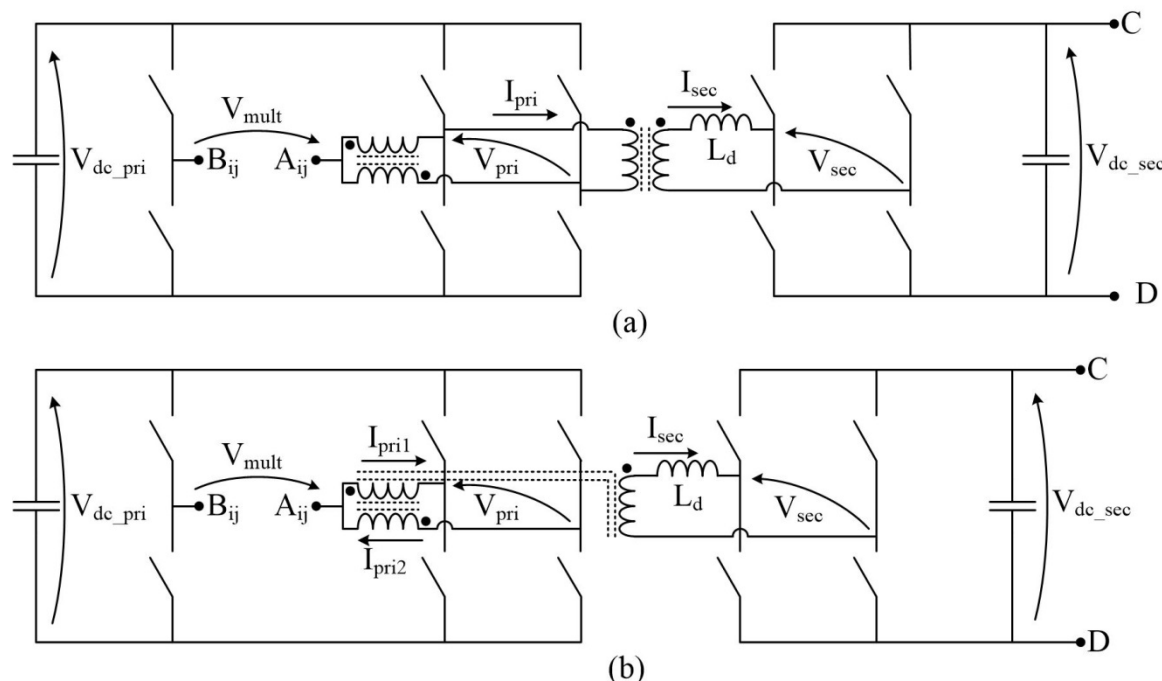


Figure 1: (a) Proposed converter; (b) modified converter with coupled magnetic elements.

This structure can be used as a module in a cascade structure to achieve a higher voltage as seen in Fig.2 (a). Besides, this cascade structure can be used in three-phase applications as seen in Fig. 2 (b).

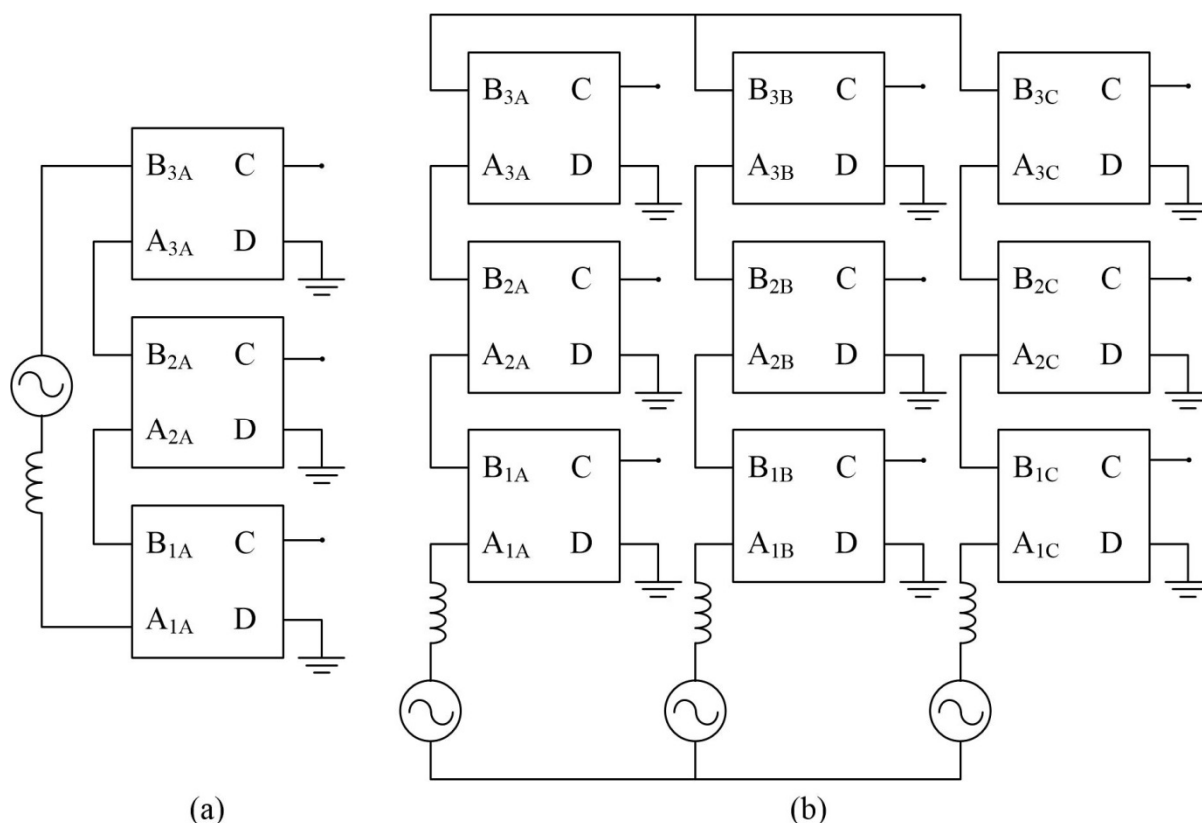


Figure 2: (a) Cascade structure; (b) Three-phase Structure;

A 8.33-kW module is currently under construction, which is part of a 75 kW-three phase topology. The module specifications are given in Table I.

Table I: Specifications of the module.

Specification	Abbreviation	Value
Voltage across the dc link in the primary side	V_{dc_pri}	544 V
Voltage across the dc link in the secondary side	V_{dc_sec}	650 V
Output power	P_o	8.33 kW
Switching frequency	f_s	20 kHz
Line frequency	f_r	60 Hz

The mathematical model and simulation was properly derived in order to allow the loss calculation and validate the control strategy. A small-scale prototype of the module was also implemented to validate the theoretical assumptions according to the specifications given in Table II.

Table II: Specifications of the small-scale prototype

Specification	Abbreviation	Value
Voltage across the dc link in the primary side	V_{dc_pri}	400 V
Voltage across the dc link in the secondary side	V_{dc_sec}	400 V
Output power	P_o	1 kW
Switching frequency	f_s	20 kHz
Line frequency	f_r	60 Hz

Simulations results

Fig. 3 shows the simulations results from a single module considering the setup described in Table I.

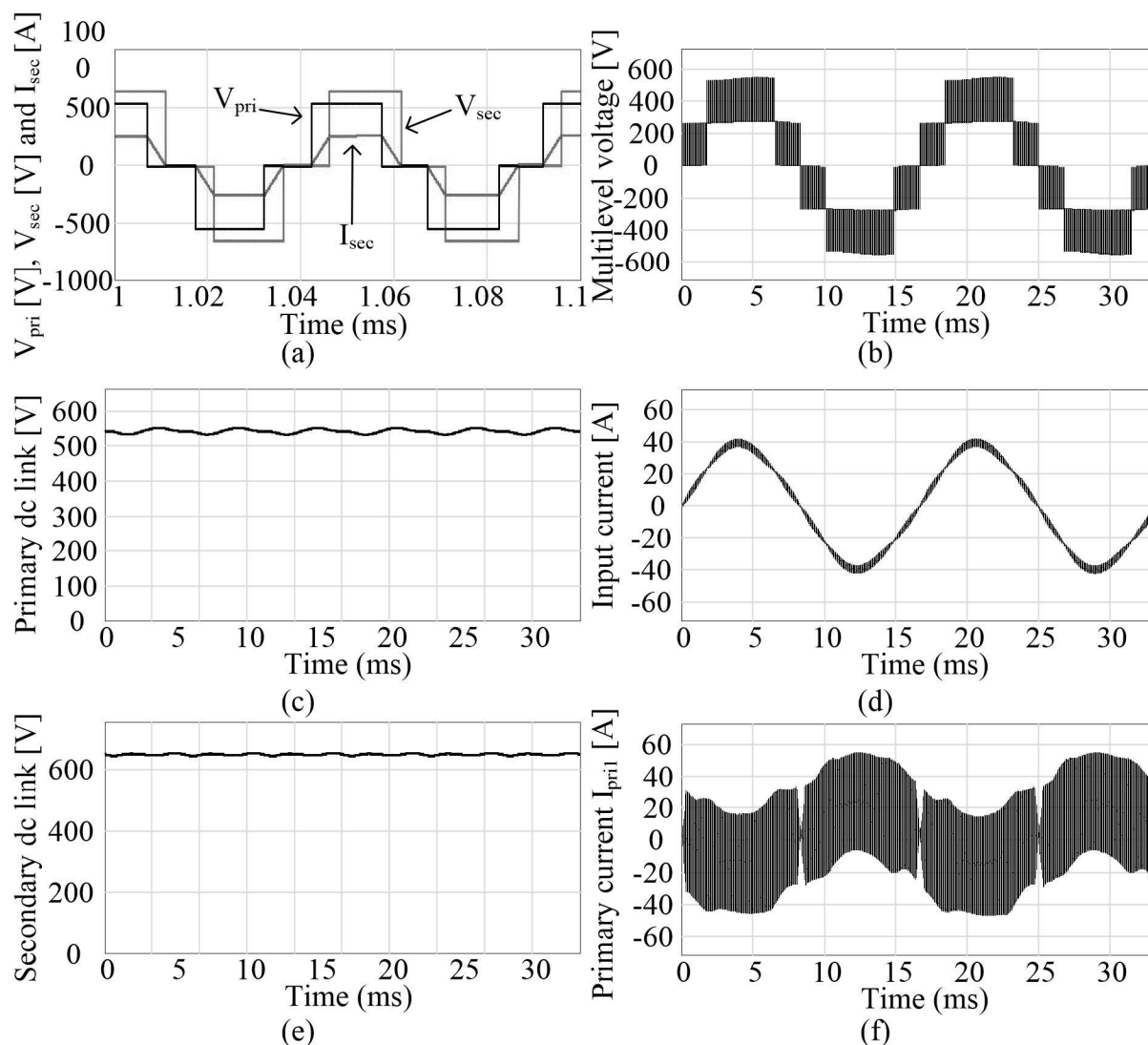


Figure 3: Simulation results in steady-state condition (a) Primary Voltage, Secondary voltage and secondary current; (b) Multilevel voltage; (c) Primary dc link; (d) Input current (e) Output dc link (f) Primary current with magnetic integration.

Fig. 3 (a) shows the transformer voltages and current through the secondary winding. Current is multiplied by 10 to better visualize. It is possible to note the phase shift between primary and secondary voltage. Fig. 5 (b) presents the multilevel voltage V_{ab} with five levels. Fig. 5 (c) and Fig. 5 (e) corresponds to the voltage across the primary and secondary dc link respectively. Both dc links are regulated at the correspondent voltage. Fig. 5 (d) shows the input current. The total harmonic distortion (THD) is 5.56 % and power factor is 0.998. Fig. 5 (f) shows the primary current. This current is the sum of half input current and the transformer input current. This addition occurs because was considered the magnetic integration showed in Fig. 1 (b). With this magnetic integration the rms current remains almost the same reducing total magnetic volume and losses.

Before build the full scale module, a preliminary experimental result was obtained with a small scale prototype.

Preliminary experimental results

Fig. 4 shows the experimental prototype, as the setup considering one module described in Table III.

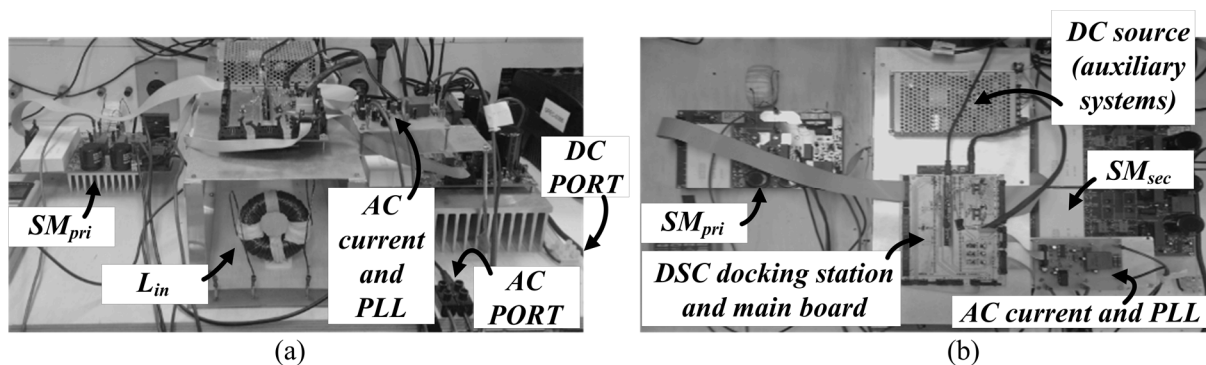


Figure 4: Small-scale prototype (a) Front view; (b) Superior view.

The preliminary prototype uses discrete IGBTs (insulated gate bipolar transistors) and a driver manufactured by Semikron®. The primary-side and secondary-side capacitors provide a voltage ripple of 10 %. The input current and magnetizing currents in the primary side and secondary side of the transformer are measured. The voltage sensors are used to measure ac input voltage, as well as the voltages across the dc links in the primary and secondary sides. The prototype uses a two-core DSC (digital signal controller) model TMS320F28377D to control the converter. One core was used to perform analog-to-digital (A/D) conversion and control, while the second one is dedicated to the modulation algorithm implementation, which is detailed in [9]. The system has a control loop for the primary-side and secondary-side dc-link voltages, power factor correction, PLL (phase locked loop), and control of the magnetizing current.

Table III: Preliminary experimental setup considering one module.

Device	Model	Quantity	Values
Discrete IGBT (IR)	GP50B60PD1	10	600 V/33 A
Driver (SEMIKRON)	SKHI 61 (R)	2	-
DC-link secondary-side capacitor	B43304-H2687-M	2	680 μ F/450 V
DC-link primary-side capacitor	B43503-S5477-M	2	470 μ F/450 V
Current sensor (LEM)	HO 8-NP/SP33	3	8 A
Voltage sensor (LEM)	LV20-P	3	10-500 V
Ferrite toroidal cores (Magmattec)	MMT002T4416	1	-
	MMT139T6325	2	-
Iron dust cores (Magmattec)	MMT034T7713	1	-

Fig. 5 shows some experimental results obtained from the prototype. Fig. 5 (a) shows the transformer voltage and current. It is possible to note that primary voltage is phase-shifted with respect to the secondary voltage. The transformer current is multiplied by a factor of 40. Fig. 5 (b) presents the multilevel voltage, as a five-level waveform is represented. Fig. 5 (c) corresponds to the voltage across the primary-side dc-voltage, which is regulated at 400 V. The same behavior is verified in Fig. 5 (e) for the output dc link. Fig. 5 (d) presents the input current, where the total harmonic distortion (THD) is 7.9 % and power factor is 0.982. Fig. 5 (f) shows the magnetizing current, whose average value is null.

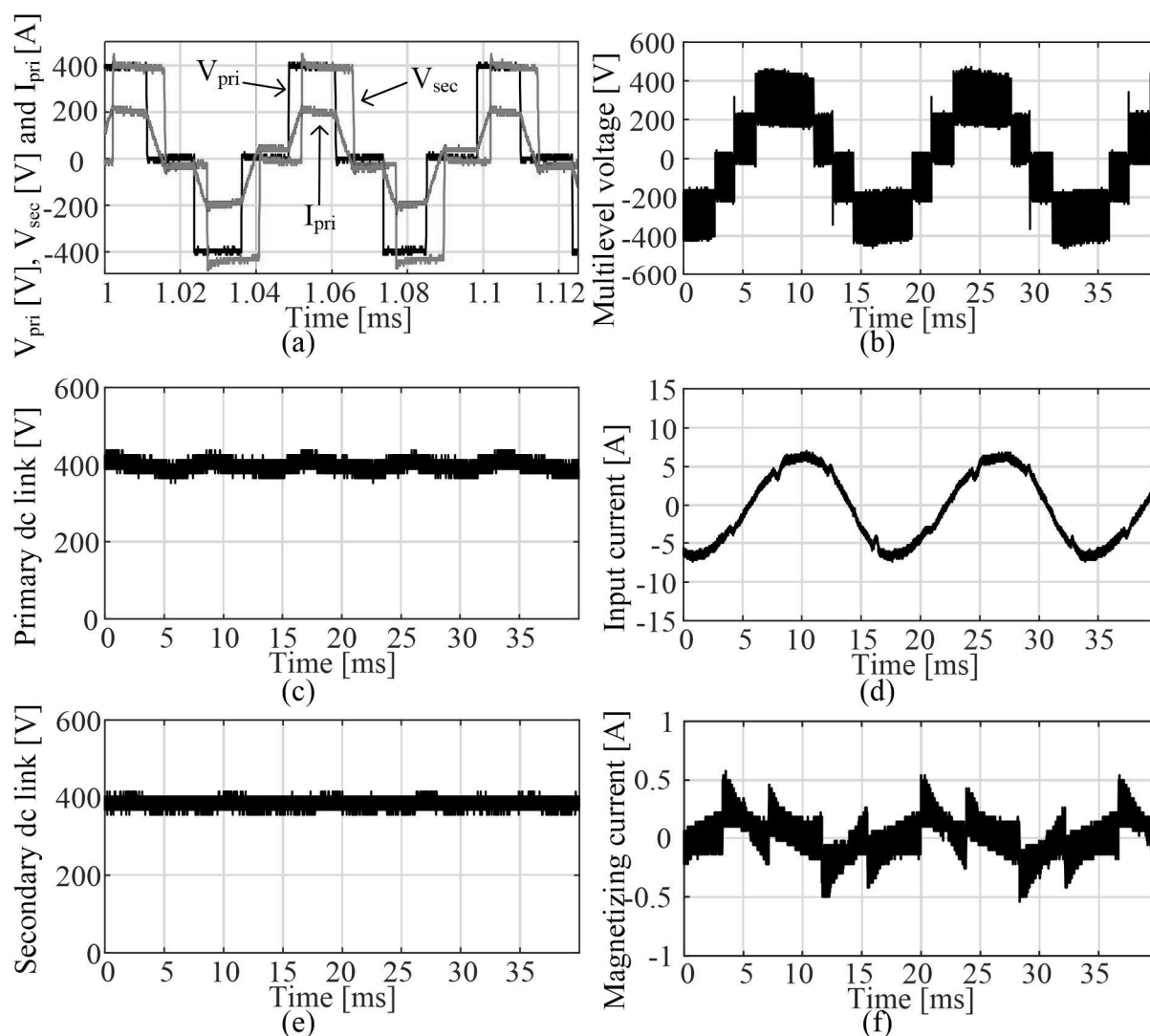


Figure 5: Experimental results in steady-state condition (a) Primary Voltage, Secondary voltage and primary current; (b) Multilevel voltage; (c) Primary dc link; (d) Input current (e) Output dc link (f) Primary magnetizing current.

Conclusion

This work has presented the experimental validation of a single stage ac-dc converter for SST applications. The converter has all the necessary characteristics to be used in a modular structure for high voltages and three-phase systems. A small-scale prototype was implemented, as the results validate the accurate behavior of the control loops in steady-state condition. A high power factor correction was achieved and a low harmonic distortion for input current.

The small-scale prototype gave enough knowledge about the converter operation making possible the construction of a higher power version. This high power version is already simulated and the mathematical model is done too. Analysis about noise and isolation are under study to making the final setup.

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