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A Highly Efficient and Compact Bidirectional DC-AC Converter for Home Electricity Management Systems

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ABSTRACT

The management of electricity demand still raises a huge interest for end-users at the household level. Smart home electricity management systems (HEMS) have recently emerged both to warrant uninterruptible power and high power quality, and decrease the cost of electricity consumption by either shifting it in off peak time or smoothing it. Such systems require a bidirectional DC-AC converter, specifically when the energy flows from a DC source (e.g., batteries) to an AC one (i.e., the AC grid), and *vice versa*. This article highlights the relevance of a bidirectional DC-AC converter based on sinusoidal waveforms from the generation of sine half-waves. Such a converter is composed of a DC-DC stage equivalent to an adjustable output voltage source and a DC-AC stage (H-bridge) which are in series. The results of a complete experimental procedure prove the feasibility to warrant a high efficiency (higher than 95%) of the whole converter, and a high power quality of the output signals in terms of total harmonic distortion, while avoiding the use of a bulky filter, as is the case with a conventional H-bridge.

Keywords

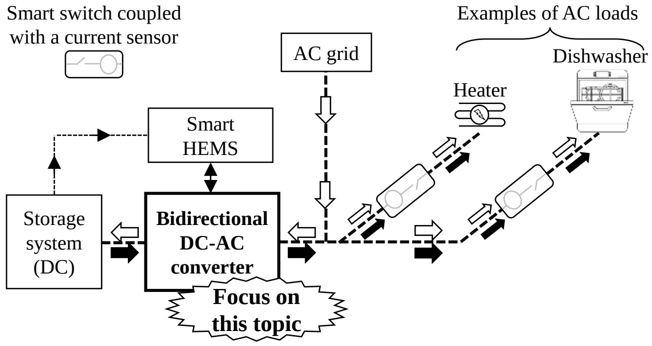
Smart home electricity management systems; bidirectional DC-AC converter; high efficiency; high power quality.

1. INTRODUCTION

At the moment, power management strategies play an increasingly important role in power quality regulation for micro-grids [1]. One of the major challenges consists in controlling power flows to meet various operational objectives (e.g., cost minimization, guaranteed delivery, or security) by adjusting the power flow from or to the AC grid, the distribution of energy resources, and the loads' controllability. In individual housing, this kind of strategy, also called smart home electricity management system (HEMS), can typically be implemented, for example, to promote the integration of renewable energies, and protect the electricity distribution system from a possible power outage [2].

Figure 1 shows an example of smart HEMS that has been recently discussed in the literature [3]. Three main objectives can be achieved using this kind of strategy: uninterruptible power, high power quality, and management of the cost of electricity consumption by either shifting it in off peak time or smoothing it.

Such a smart HEMS requires the implementation of a storage system such as batteries. Thus, the AC loads can be supplied in two ways i.e., either from the AC grid, or an inverter in the situation where the storage system relieves the AC grid. These two operating modes can be managed by a bidirectional DC-AC converter [4]. To improve the stability of the AC grid, this converter must be designed considering the following key elements: high efficiency and robustness, low total harmonic distortion (THD), and current control and voltage adaptation.



⇨ The AC loads are directly supplied by the AC grid

➡ The AC loads are supplied by an inverter in the situation where the storage system relieves the AC grid

Figure 1. Example of a smart HEMS [3].

Existing DC-AC converters are dominated by two main topologies: the first one is based on a perfectly well-known H-bridge; the second one uses multilevel structures. Such topologies are, for the most part, VSCs (voltage-sourced converters), because their input is typically equivalent to a voltage source. From a conventional H-bridge, it is possible to design a converter which is composed of two or three levels. This kind of topology offers a multitude of advantages, such as a low number of semiconductor devices, and the control circuits which are easier to design, and especially their control loops which are straightforward to implement [5, 6]. However, this kind of topology usually requires a very bulky low-pass filter to optimize the THD-parameter. Multilevel converters, among other things, enable this filter to be smaller and lighter. Nevertheless, Karimi et al. have recently pointed out that the performances of each category depending on the number of DC sources, and the number of semiconductor devices that must be controlled [7]. In particular, the higher the number of levels, the higher the number of DC sources, and the higher the power devices to be controlled. Multilevel converters enable also to decrease the constraints across the semiconductor power devices.

The aim of this article is to demonstrate experimentally the relevance of a bidirectional DC-AC converter that has been very underdeveloped in the literature [8]. The proposed topology is

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composed of two bidirectional stages which are in series: a DC-DC stage, and a DC-AC one. In the inverter mode, the DC-DC stage enables to generate a full wave rectified sine wave. Then, this signal is inverted each half period through the DC-AC stage. In the rectifier mode, the DC-AC stage acts as a full bridge, and the DC-DC stage is used as a power factor corrector (i.e., PFC-Boost).

More specifically, this article points out the design and test of a bidirectional DC-AC converter used in smart HEMS that has the following main features: high efficiency (i.e., higher than 95%), high compactness through the use of wide band gap (SiC) power devices (i.e., SiC MOSFETs), and high power quality (THD of the output signals lower than 8%), while avoiding the use of a bulky filter.

This article is composed of two main sections. In section 2, the topology of the proposed bidirectional DC-AC converter with the main characteristics previously quoted is discussed. Section 3 highlights the results of a complete experimental procedure, and proves the relevance of such a topology.

2. NEW BIDIRECTIONAL DC-AC CONVERTER TOPOLOGY PROPOSAL

2.1 General Architecture

Figure 2 shows the general architecture of the bidirectional DC-AC converter proposed in this article. Such a topology is based on the electricity flow which is from a DC source such as batteries to an AC one (i.e., AC grid), and *vice versa*. The whole converter is composed of two stages which are in series: a DC-DC stage that operates at 300 kHz, and a DC-AC stage that operates at 50 Hz.

As can be seen in Figure 2, the DC-DC stage is designed to generate a rectified sine wave. It is composed of two wide band-gap semiconductor devices (reference: SCT3080AL; 30 A, 650 V SiC MOSFETs; Rohm Semiconductor). These power switches enable, among other things, to increase the switching frequency to optimize the compactness of the whole converter. The inductance named *L* (see Figure 2) is calculated to neglect the current ripple due to the high switching frequency (i.e., 300 kHz) of the power devices. Therefore, the DC-DC converter acts as a controllable voltage source. It is possible to vary the output current by adjusting the voltage named *Vc* (see Figure 2) from a modulation stage. It has a major interest, especially when the output current decreases drastically. In such cases, it is possible to decrease the *Vc*-voltage. In particular, when the *Vc*-parameter is higher than the voltage from the AC mains, the output current has a positive value, and *vice versa*. Therefore, the electrical energy transfer is performed, either from the storage system to the AC grid (i.e., inverter mode), or from the AC grid to the storage system (i.e., rectifier mode).

The DC-AC stage is in charge of inverting a half sine wave out of two to get a full sine wave output signal. This stage is composed of four 47 A, 500 V MOSFETs (reference: IRFPS43N50KPBF, Vishay). Their switching frequency is equal to 50 Hz. This low frequency enables the use of MOSFETs manufactured on a silicon substrate. The power devices' turning-on and off are performed with zero-crossing of the AC mains to minimize the losses.

The use of a DC-DC converter coupled with an H-bridge has many advantages comparing to existing topologies:

- Standard DC-DC converter and H-bridge are well-common topologies.
- Most of topologies use an H-bridge composed of at least four switches which operate at high frequency. In the topology described in this article, only two power devices (inside the first stage) operate at high frequency (i.e., 300 kHz). All the switches inside the H-bridge operate at low frequency (i.e., 50 Hz).
- At high frequency, it is of utmost importance to take into consideration the delay between two switches in the same leg for safety reasons. With only one leg at high frequency, the safety delay is easier to control.
- At high frequency, the capacitance used to modulate the *Vc*-voltage is low (about 13 µF). Many other topologies consider that the use of AC-type capacitor is mandatory.

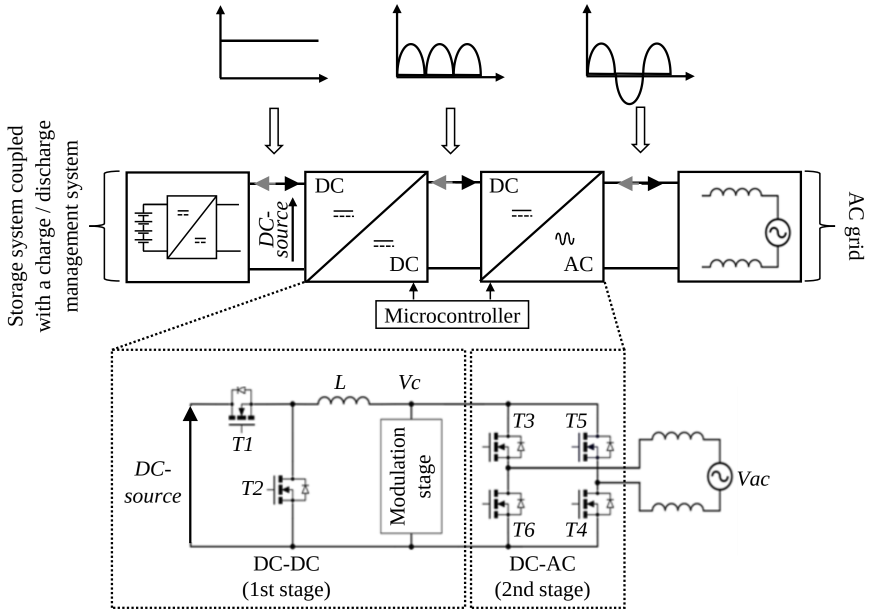


Figure 2. General architecture of the proposed bidirectional DC-AC converter.

2.2 Modulation of the Output Voltage of the DC-DC stage

As can be seen in Figure 3, one possible solution to adjust the *Vc*-voltage of the DC-DC stage consists in connecting *n*-quadrupoles in parallel. Each quadrupole is composed of a capacitor and a power switch which are in series.

The aim of such a solution is to fix the ripple of the *Vc*-voltage. In that case, there are $2^n - 1$ possibilities to adjust the equivalent capacitance of the system. Thus, an adaptation to many loads can be achieved using this solution. Moreover, the efficiency of the DC-DC stage is not so much penalized in that case.

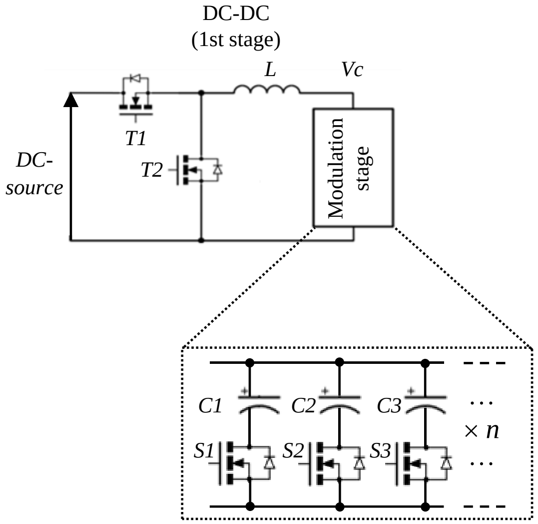


Figure 3. One possible solution to adjust the *Vc*-voltage.

In this section of the article, the DC-source is supposed to be equal to 400 V. Three capacitances coupled with three switches (i.e., *C1-S1*, *C2-S2*, and *C3-S3*) are used (see Figure 3) to modulate the *Vc*-voltage. Therefore, as can be seen in Table 1, there are seven possibilities to modulate the *Vc*-parameter. From Equation (1), the value of each capacitance is sized depending on the ripple of the *Vc*-voltage (ΔV), and the current (I) flowing through the load. The ΔV-parameter is supposed to be equal to 1% of the peak value of the *Vc*-voltage. For example, if the *C2*-capacitor is only used (i.e., *S2* is on; *S1* and *S3* are off), then its capacitance (i.e., 1 µF) is sized to warrant a load current about 1.2 A.

$$C = \frac{I \cdot \Delta t}{\Delta V} \qquad (1)$$

- I is the current flowing through the load.
- Δt is constant depending on the duty cycle (α). $\Delta t = 1 / F \times \alpha$, where F is the switching frequency (i.e., 300 kHz).
- ΔV is constant depending on the the peak value of the *Vc*-voltage (*Vc_peak*). $\Delta V = 1\% \times Vc\_peak$, where *Vc_peak* is supposed to be equal to 325 V.

Table 1. One possible solution to modulate the *Vc*-voltage: truth table.

C3 – S3 **(*C3* = 10 µF)**	***C2 – S2*** **(*C2* = 1 µF)**	***C1 – S1*** **(*C1* = 68 nF)**	**Load current**	**Equivalent capacitance**
OFF	OFF	ON	82 mA	68.0 nF
OFF	ON	OFF	1.2 A	1.0 µF
OFF	ON	ON	1.3 A	1.1 µF
ON	OFF	OFF	12.0 A	10.0 µF
ON	OFF	ON	12.1 A	10.1 µF
ON	ON	OFF	13.2 A	11.0 µF
ON	ON	ON	13.3 A	11.1 µF

2.3 Operating Modes

To simplify the study, the operating modes of the bidirectional DC-AC converter are explained during the positive side of the AC grid voltage.

2.3.1 Inverter Mode

As can be seen in Figure 4, in the inverter mode, the DC-DC stage enables to generate a full wave rectified sine wave. The magnitude of this rectified sine wave can be adjusted from the duty cycle. In that case, the DC-DC acts as a Buck converter. From the DC-AC stage of the whole converter, the output signal of the DC-DC stage is inverted each half period.

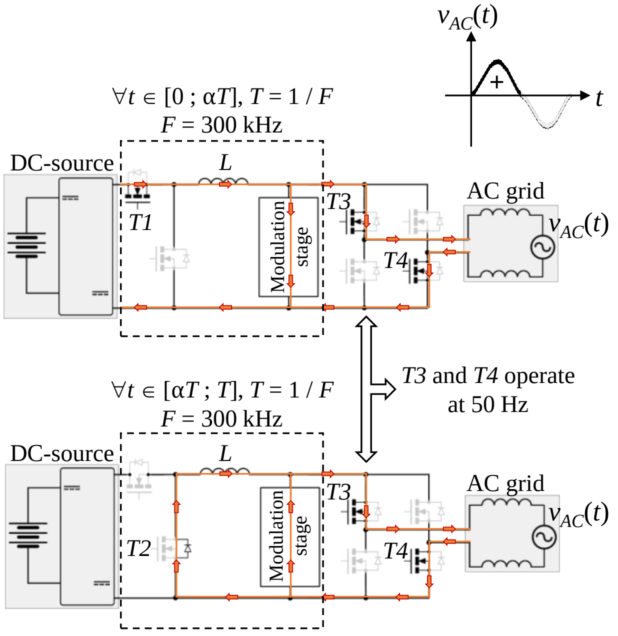


Figure 4. Operating modes of the proposed bidirectional DC-AC converter: inverter mode.

2.3.2 PFC-Boost Mode

In the rectifier mode, the power flows from the AC grid to the DC-source. In this kind of operation, the most important objective is to control the absorbed current. This one must have a sinusoidal waveform. From the modulation stage of the DC-DC converter, the THD-values of the absorbed current are about 40%. The strategy described in Section 2.2. is not fully satisfactory. As a consequence, a power factor correction (PFC) is mandatory. In particular, the aim is to be compliant with the IEC 61000-3-2 standard.

In this article, the PFC is performed thanks to the DC-DC stage of the proposed bidirectional DC-AC converter. Figure 5 gives the operating phases. In that case, the DC-AC stage acts as a full bridge. The DC-DC stage acts as a PFC-Boost converter where the body diodes of the SiC MOSFETs play an important role.

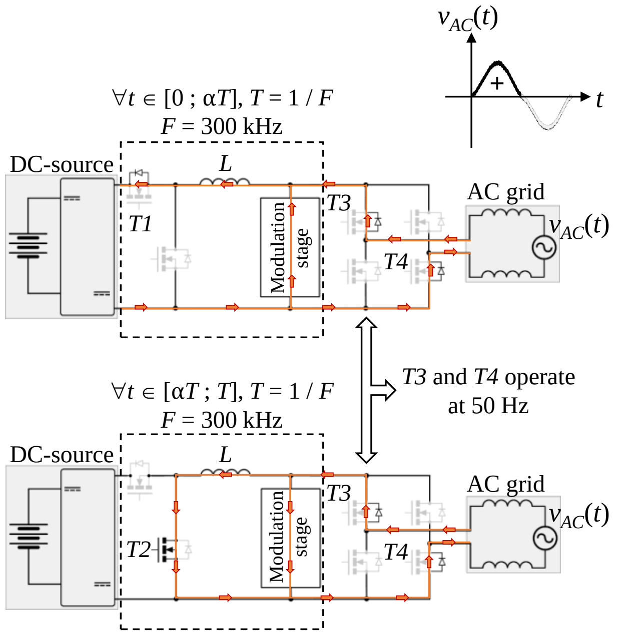


Figure 5. Operating modes of the proposed bidirectional DC-AC converter: PFC-Boost mode.

3. MAIN RESULTS AND DISCUSSION

3.1 Experimental Test Setup

The operation modes of the bidirectional DC-AC converter described in this manuscript are validated at low power (i.e., lower than 1.5 kW) through a complete experimental test procedure.

Figure 6 gives the illustration of the first prototype of the whole converter. This one is composed of a DC-DC stage, a DC-AC stage, a modulation stage, and a power supply (i.e., +5 V, and +12 V) to supply the onboard electronics. The whole converter is powered by a STM32F407VG microcontroller.

A 3 kW programmable DC power supply (reference: SM300-10, Delta Electronika) is used to simulate the storage system (i.e., the DC-source). Of course, this DC power supply has the same behavior as the output of batteries coupled with a charge / discharge management system. It is important to note that this system is not described in this article. The SM300-10 programmable DC power supply is composed of two independent outputs (i.e., each channel can be adjustable from 0 to 300 V for the voltage, and from 0 to 10 A for the current). The output of the DC-AC stage of the whole converter is connected to a resistive load (1,300 W rheostat; from 0 to 11.5 Ω; 10 A; reference: ECO2-106, Langlois). The aim is to be sure that the main operating phases of the proposed bidirectional DC-AC converter are well contained. Of course, in the near future, the final prototype of the whole system will be tested using non-linear loads.

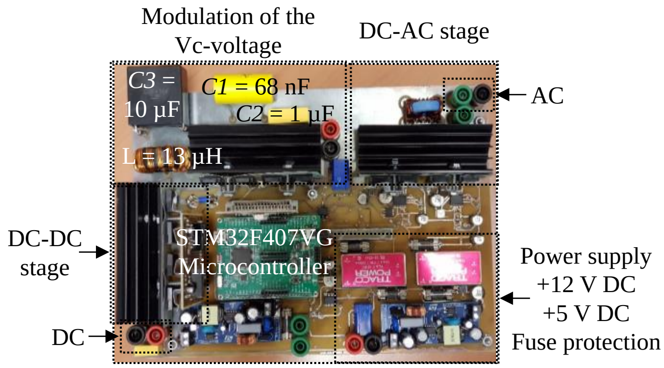


Figure 6. Prototype of the bidirectional DC-AC converter.

A high voltage differential probe (reference: P5205, Tektronix), and a 15 A AC/DC current probe (reference: TCP202, Tektronix) are used to measure the output voltage and output current, respectively. Three watt meters (reference: PX 110, Metrix) are used: the first one at the output of the DC-source, the second one at the output of the DC-DC stage, and the last one at the output of the DC-AC stage. Finally, the THD of the output voltage / current is measured using a clamp-on harmonic power meter (reference: F27, Chauvin Arnoux). This kind of power meter can measure a THD-value up to the rank no. 25, with frequencies between 0.5 Hz and 20 kHz.

3.2 Validation of the Operating Modes of the Bidirectional DC-AC Converter

3.2.1 Inverter Mode

In this section of the article, the aim is to validate the operation of the bidirectional DC-AC converter in the inverter mode. Figure 7 gives examples of output signals. In that case, the measurements are performed in the following conditions:

- Input voltage (i.e., DC voltage): 300 V.
- Output voltage (i.e., AC voltage): 170 V RMS.
- Output power: 600 W.

In the inverter mode, the whole converter generates quasi sinewave signals. It is important to note that the inverter is not connected to the AC grid. The resistive load used in this experimental procedure is slightly inductive (i.e., about 360 µH and 285 µH at 120 Hz and 1 kHz, respectively). Thus, the current through the load is smoothed.

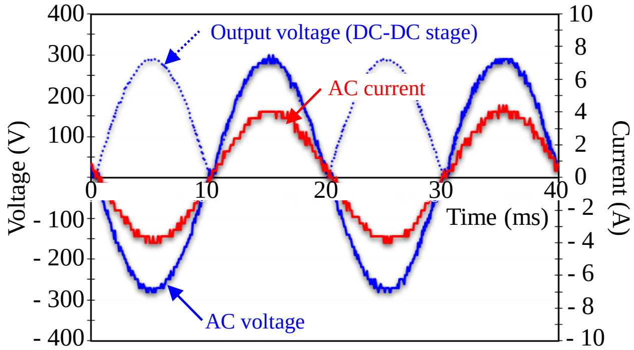
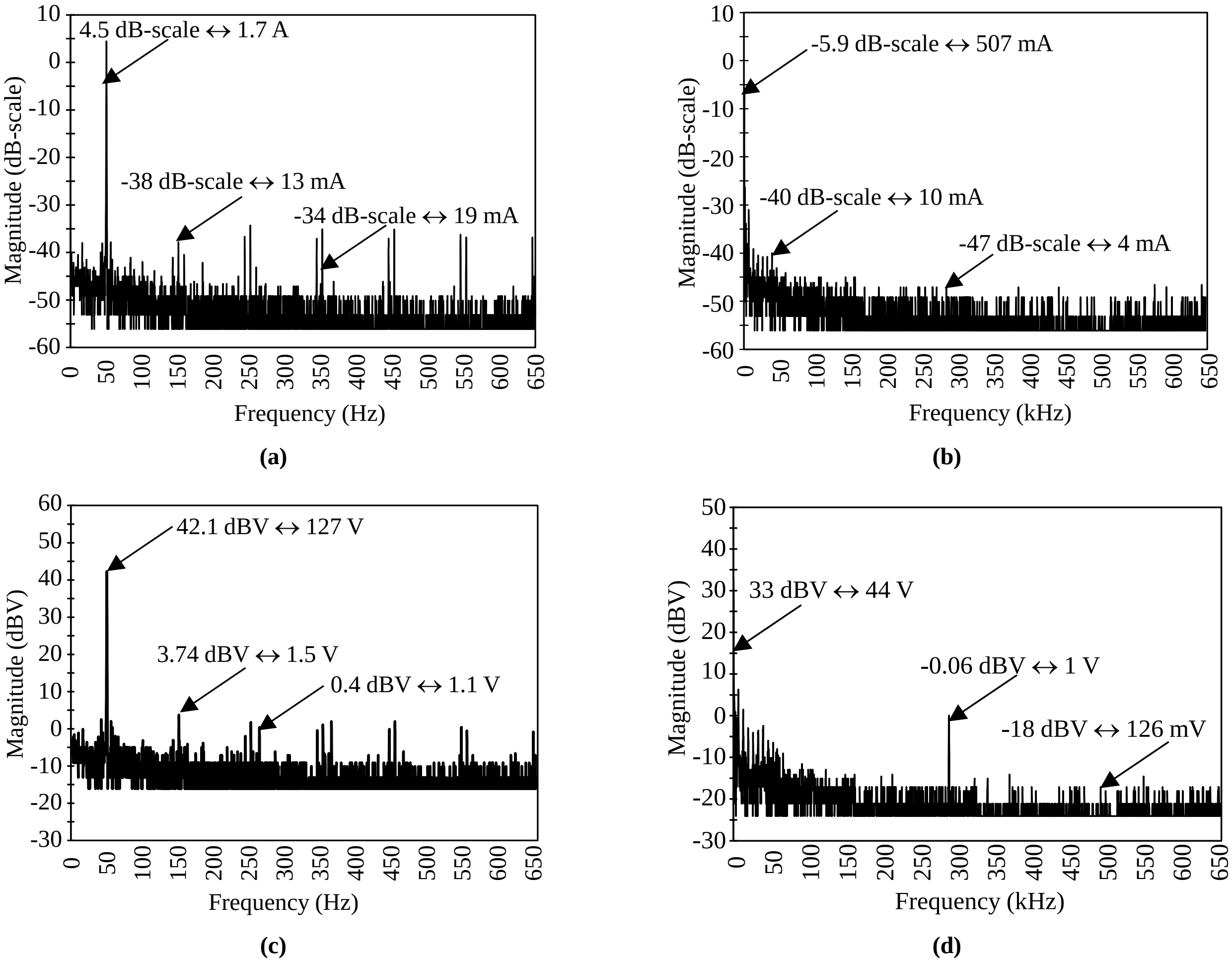


Figure 7. Experimental validation of the inverter mode: output signals.

Figure 8 shows the harmonic spectra of the output signals both at low frequency and high frequency, either for the current (see Figure 8 (a) and Figure 8 (b)) or the voltage (see Figure 8 (c) and Figure 8 (d)). The main contribution of each spectral decomposition is due to the fundamental, because of the quasi sinewave signals. The harmonics are reduced, whatever the output signal. In the experimental conditions described above, the THD-values of the output signals are lower than 8% both for the current and the voltage. In comparison with a 5-level topology described in the literature (THD-value about 37%), under approximately the same experimental conditions, the THD-value is here very low [9]. As a consequence, the topology proposed in this article is validated in the inverter mode.



(a) **(b)** **(c)** **(d)**

Figure 8. Harmonic spectra of the output signals in the inverter mode (experimental results): (a) Output current at low frequency; (b) Output current at high frequency; (c) Output voltage at low frequency; (d) Output voltage at high frequency.

3.2.2 PFC-Boost Mode

In this section of the article, the aim is is to demonstrate the operation of the bidirectional DC-AC converter in the rectifier mode. Above all, the aim is to prove the feasibility to create a power factor correction. Specifically, the sinusoidal current absorption is carried out thanks to the control of the transistor named *T2* (see Figure 2) of the DC-DC stage. The experimental tests are also performed at low power to avoid deteriorating the prototype of the whole converter.

Figure 9 highlights the effective operation of the rectifier in the following conditions:

- Input voltage (i.e., AC voltage): 100 V (peak value).
- Output voltage (i.e., DC voltage): 300 V.
- Output power: 120 W.

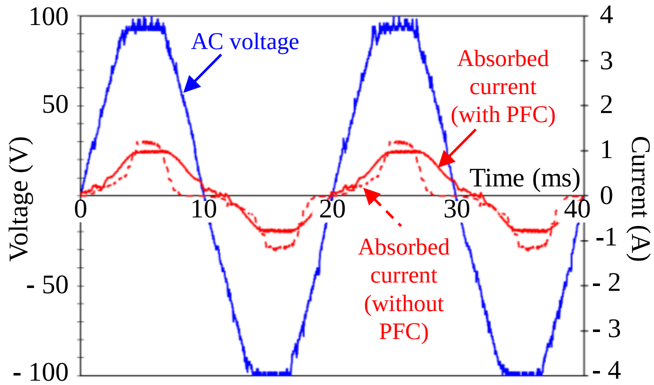


Figure 9. Experimental validation of the rectifier mode with a sinusoidal current absorption.

Figure 10 shows the harmonic spectrum of the output current.

These experimental results exhibit the benefits of a sinusoidal current absorption. In particular, the PFC mode solves the problem of time offset between the AC voltage and the absorbed current. With the first prototype of the converter, the THD-value of the absorbed current is slightly lower than 8%. This value can still be optimized through the appropriate control of the DC-DC stage.

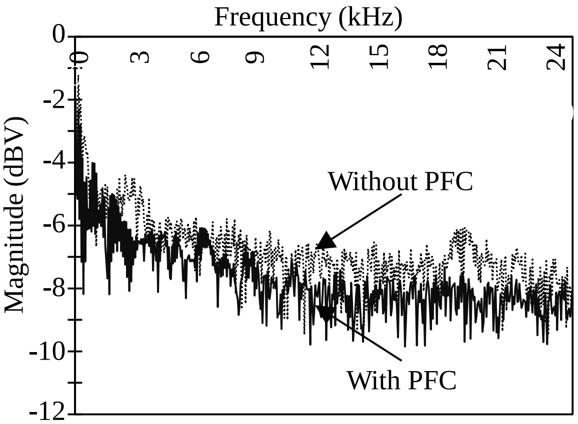


Figure 10. Harmonic spectrum of the output current in the rectifier mode (experimental results).

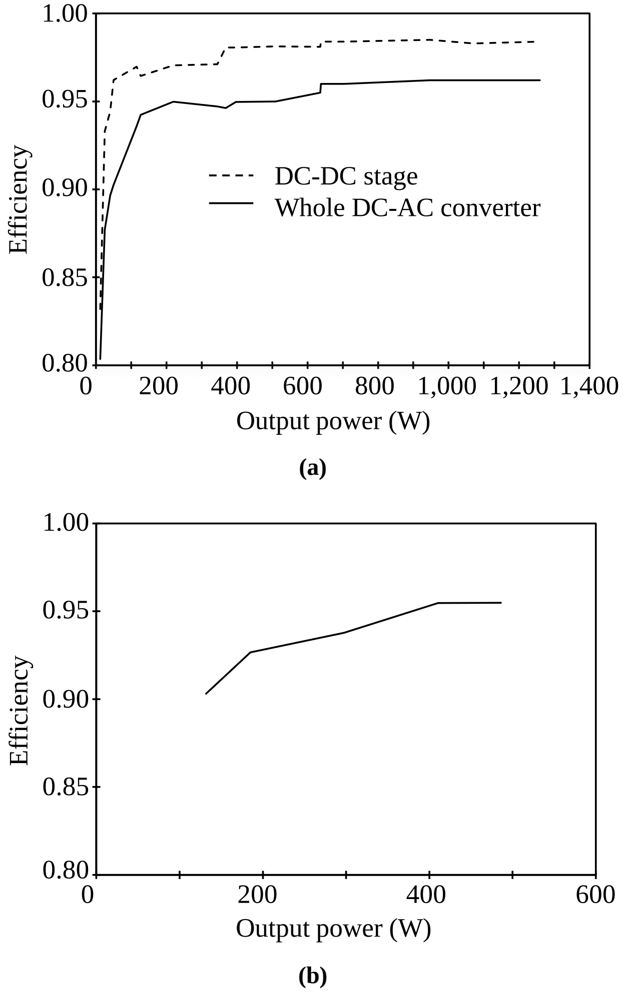
3.3 Efficiency of the Bidirectional DC-AC Converter

Figure 11 shows the evolution of the efficiency of the bidirectional DC-AC converter depending on the output power. Regarding the inverter mode (see Figure 11 (a)), the output power range is between 10 W and 1.3 kW. The experimental results exhibit that the efficiency of the inverter can reach 96%. It must be noted that these results depend on the overall topology of the DC-AC converter. Even if the efficiency of the DC-DC stage is very good (i.e., about 98.5%), it would be difficult to improve the efficiency of the overall DC-AC converter, because this topology is composed of two stages in series.

Regarding the rectifier mode (see Figure 11 (b)), the output power range is from 100 W to 500 W. The first experimental results are very satisfactory, because the efficiency of the rectifier can reach 95.5% at low power.

In this first version of the prototype of the bidirectional DC-AC converter, the losses are shared between the MOSFETs and the passive devices (i.e., mainly due to the inductance of the DC-DC stage). It is important to note that the inductance of the DC-DC stage was designed in the laboratory. The typical ferrite core was prohibited because it generates high iron losses. Thus, a high flux core was used, because it is particularly suited for high frequencies.

As can be seen in Figure 11 (a), the efficiency of the bidirectional DC-AC converter in the inverter mode is approximately equal to 96.2% at the output power of 1,070 W. In that case, the global losses are about 42 W (i.e., about 18 W in the MOSFETs, and 24 W mainly due to the inductance of the DC-DC stage). It is possible to evaluate the conduction losses, and the dynamic losses (i.e., turn-on and turn-off switching losses) from the main features (in particular, the on-resistance, rise time, and fall time) of each MOSFET. The global conduction losses and turn-on / turn-off losses equal 4.2 W and 13.8 W, respectively. It is possible to decrease the losses in the MOSFETs by changing the reference of the SiC devices used in the DC-DC stage. In particular, the second version of the prototype of the whole converter will use two 36 A, 900 V SiC MOSFETs (reference: C3M0065090D, Cree). Their rise time (i.e., 11 ns instead of 26 ns) and fall time (i.e., 9 ns instead of 16 ns) should help to reduce the global switching losses by approximately half. Therefore, it would be possible to increase the efficiency of the whole converter of almost half a percentage point in the same output power conditions.



(a)

(b)

Figure 11. Efficiency of the bidirectional DC-AC converter (experimental results): (a) Inverter mode; (b) PFC mode.

4. CONCLUSIONS

This article points out the relevance of a bidirectional DC-AC converter that can operate in smart HEMS, especially when the electrical energy flows from a DC-source (e.g., batteries) to the AC grid, and *vice versa*. The proposed topology is composed of two stages which are in series: a DC-DC stage (composed of SiC power MOSFETs that are controlled at 300 kHz) and a DC-AC one (an H-bridge composed of silicon MOSFETs that are controlled at 50 Hz). This kind of topology enables to generate sine waves to optimize the power quality of the output signals.

The first results of a complete experimental procedure are highly promising.

The main achievements of this study are summed up below:

1. The complexity of the topology is minimized in comparison with existing multilevel converters. In particular, the proposed converter avoids the use of a bulky filter, as is the case with a conventional H-bridge.
2. The efficiency of the bidirectional converter is slightly higher than 95%.
3. The THD-values of the output signals (either for the current or the voltage) are about a few percent, whatever the operation mode of the DC-AC converter (i.e., inverter or rectifier).
4. The compactness of the whole system is minimized, in particular through the use of wide band-gap semiconductor devices (i.e., SiC MOSFETs).

In this article, a first prototype of the bidirectional DC-AC converter was designed and tested at low power (i.e., lower than 1.5 kW). Moreover, the whole system was not connected to the AC grid. It will be interesting to test a grid-connected prototype of the converter. Finally, its operating modes will have to be validated for its targeted nominal power (i.e., 3 kW).

5. ACKNOWLEDGMENTS

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