Isolated Single Stage Bidirectional AC-DC converter with power decoupling and reactive power control to interface battery with the single phase grid

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***Abstract*— An isolated single stage bidirectional AC-DC converter with a series-connected buffer to power decoupling is proposed to interface battery with the single phase grid. None electrolytic capacitor is used in the proposed structure. The converter is a modified AC-DC DAB series-resonant single phase converter where a third active bridge is used to power decoupling and it is series-connected with the rectified grid voltage active bridge. A very practical bidirectional power decoupling technique which controls the voltage amplitude in the series-connected buffer (SCB) is proposed. Unlike existing structures, two independent time-variant duty ratios is applied on both AC active bridges (rectified grid and the series-connected buffer) and fixed duty ratio on DC side (battery). The proposed modulation allows the power decoupling of the low frequency AC grid voltage variations in the series-resonant circuit. As a result, the steady-state response of the proposed AC-DC converter with SCB is equivalent of a DC-DC DAB with a series-resonant circuit. Decoupled close loop control for the grid current and for the SCB voltage are implemented. Furthermore, reactive power in the grid is compensated in the tank circuit with fixed duty ratio on DC side. Bidirectional power flow is controlled with phase shift modulation. High efficiency is obtained due to Zero Voltage Switching (ZVS) in all MOSFETs. Finally, the 1kW prototype is validated experimentally**

Keywords*— *DC/AC; bidirectional power decoupling; Dual active bridge; series-resonant circuit; reactive power control; single-stage converter; bidirectional power flow; ZVS.

I. INTRODUCTION

The integration of the battery to the single phase grid has boosted the development of new technologies of power converters [1]. For this purpose, the Dual-Active-Bridge (DAB) AC-DC converter with or without tank circuit [2]-[8] has focused the attention of researchers because its many advantages like galvanic isolation, high frequency (HF) switching with very few losses, single stage conversion, etc. However, the principal limitation of this converter is the use of the electrolytic capacitor like a buffer energy for power decoupling which reduces the lifetime converter [9]. To resolve this limitation, two solutions have been proposed in the bibliography: power decoupling on DC or on AC side [10]. The first solution is analyzed in [11]. The authors propose to reject the low frequency current in DC bus adding an additional leg in the active bridge. However with this approach, the power decoupling is only done in the output bus and do not for the HF transformer. A power decoupling on AC side is proposed in [12] where a series-connected buffer (SCB) with the grid active bridge is used. The SCB voltage is controlled to power decoupling. The authors propose a half bridge (unipolar) for the SCB, a half cycloconverter for the grid voltage modulation and, a full bridge on DC side (PV). A very complex modulation is proposed by the authors where independent time-variant phase shift modulation with a fixed duty ratio control is applied to modulate SCB voltage and the grid voltage. Time-variant duty ratio is applied on DC side. The chosen modulation cause a non-linear relationship between the SCB voltage, the grid current and the tank circuit impedance. Because this high complexity, the authors do not implement the close loop control in the experimental results, nor do explain how the tank circuit or HF transformer are designed.

A different approach is presented in [13]. The authors propose a very practical modulation power decoupling technique controlling the AC voltage in an additional port. However, the authors do not validate the proposed modulation in a DAB AC-DC converter. Instead of that, the modulation is validated only with a typical VSI and an active filter parallel-connected to the DC Bus.

This paper proposes to modify the structure presented in [12]. The proposed changes are the following: (1) the half cycloconverter is replaced by a synchronous rectified cascaded with an active bridge (AB) and, (2) the unipolar SCB is replaced by an AB. These changes allow to introduce a novel modulation: (1) on AC side, the SCB and the grid voltages are modulated using independent time-variant duty ratios with zero phase shift. (2) On DC side, a fixed duty ratio with a phase shift modulation is applied for power flux control. On the other hand, the power decoupling technique proposed in [13] is modified for a bidirectional power flow. The novel power decoupling technique is implemented using time-variant duty ratios on AC side. This approach allows: (1) power decoupling in the tank circuit and, (2) to replace the electrolytic capacitor on DC side by a film capacitor. Therefore, the proposed converter has a steady-state response like a DC-DC DAB series-resonant converter [14]. Bidirectional active and reactive power flow can be controlled with the proposed modulation. Furthermore, a decoupled close loop control for the SCB voltage and for the grid current is implemented. Finally, simulations and experimental results validate the power converter functionality.

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II. THE PROPOSED CONVERTER

The proposed AC-DC converter with power decoupling is shown in Fig.1. The L_o, L_i inductors and C_o, C_i capacitors are chosen to filter the current ripple in switching frequency. The grid voltage v_i is rectified using an unfolded bridge. Three actives bridges (AB) are used to modulate the rectified grid (RG) voltage $|v_i|$, the SCB voltage v_c and the battery voltage V_b respectively. The switching frequency f_s is chosen higher than the tank circuit resonance frequency $f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$.

The modulation for the unfolding bridge is given by

$$s_\omega = sgn(\sin(\omega_i t)) \qquad (1)$$

The general proposed modulation for the ABs is (see Fig.2)

$$m_p(t) = s_p(t) - s_{p+1}(t) \qquad (2)$$

Where

$$s_p = sgn\left(cos\left(\omega_s t - \frac{\alpha_p}{2} - \varphi_p\right)\right) \qquad (3)$$

$$s_{p+1} = sgn\left(cos\left(\omega_s t + \frac{\alpha_p}{2} - \varphi_p\right)\right) \qquad (4)$$

$$\varphi_p \;\epsilon\; \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad \text{And} \;\; p = 1, 3, 5 \qquad (5)$$

And:

$$sgn(x) = \begin{cases} 1, & when\ x \geq 0 \\ 0, & when\ x < 0 \end{cases} \qquad (6)$$

Besides, for each AB, the signals commands are (see Fig.1)

$$\begin{cases} \text{RG AB:} & p = 1,\ \alpha_p = \alpha_i \ \text{ and } \ \varphi_p = 0 \\ \text{SCB AB:} & p = 3,\ \alpha_p = \alpha_{fa} \ \text{ and } \ \varphi_p = \varphi_c \\ \text{BAB:} & p = 5,\ \alpha_p = \alpha_o \ \text{ and } \ \varphi_p = \varphi \end{cases} \qquad (7)$$

Where the control signals α_i, α_{fa} and α_o are duty ratio angles while φ_c and φ are phase shift angles respectively.

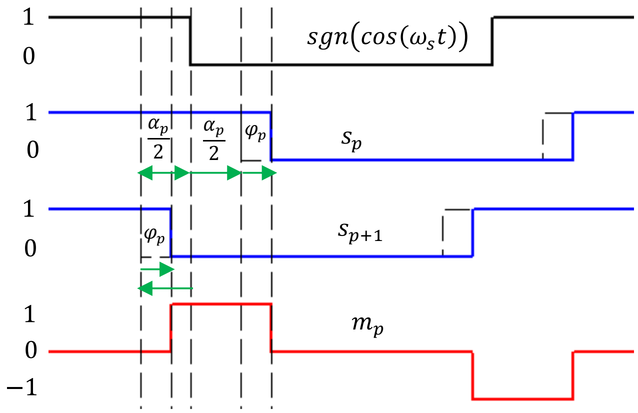

Figure 2. Proposed general modulation for each AB

III. BIDIRECTIONAL POWER DECOUPLING TECHNIQUE

Considering sinusoidal voltage and current in the grid

$$v_i(t) = V_m\, sin(\omega_i t) \qquad (8)$$

$$i_i(t) = I_m\, sin(\omega_i t - \theta) \qquad (9)$$

The power $p_i(t)$ in the grid is

$$p_i(t) = P_i \cos(\theta) - P_i \cos(2\omega_i t - \theta) \qquad (10)$$

Therefore, in order to have power decoupling at DC source, the power $p_c(t)$ in the SCB has to be

$$p_c(t) = i_c(t) \times v_c(t) = P_i \cos(2\omega_i t - \theta) \qquad (11)$$

Besides, considering no losses in the converter, the power P_o at DC source is

$$P_o = V_b I_b = p_i(t) + p_c(t) = P_i \cos(\theta) \qquad (12)$$

Notices that, the DC power has not low frequency $2\omega_o$ component therefore, a film capacitor can be used to filter the switching ripple at DC current.

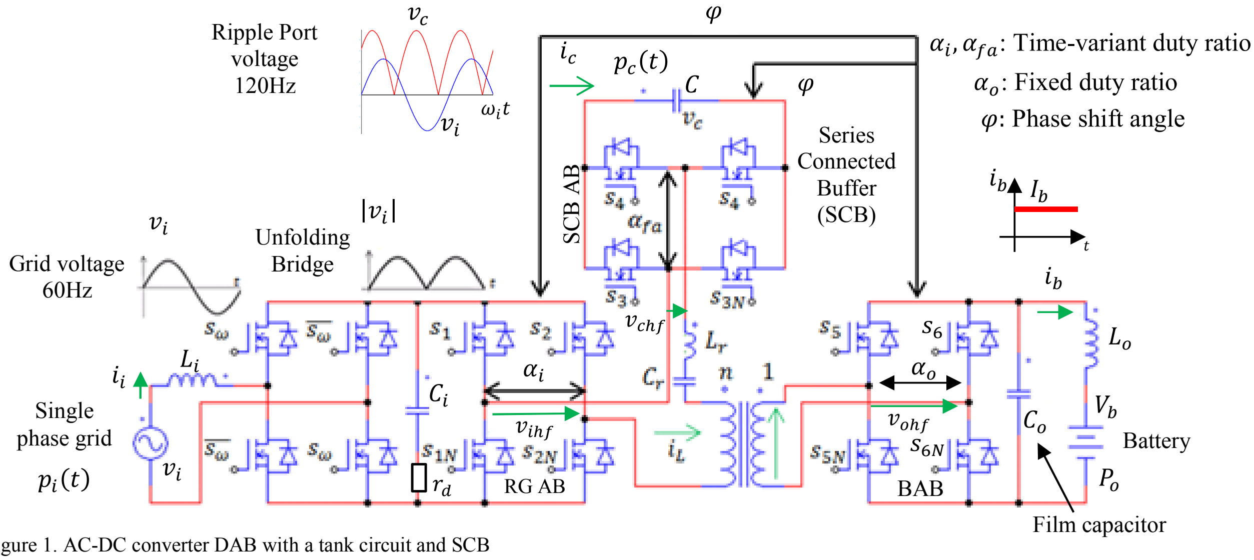

Figure 1. AC-DC converter DAB with a tank circuit and SCB

According [13], the SCB power given by (11) can be obtained if the v_c voltage is controlled as

$$v_c(t) = |v_{cref}| \ \underline{\text{Where}} \ \ v_{cref} = V_c \cos(\omega_i t + \beta) \qquad (13)$$

And the current $i_c(t)$ in the SCB capacitor is given by

$$i_c(t) = C\frac{dv_c(t)}{dt} = \begin{cases} -C\omega_i V_c \sin(\omega_i t + \beta);\ \ if\ v_{cref} \geq 0 \\ +C\omega_i V_c \sin(\omega_i t + \beta);\ \ if\ v_{cref} < 0 \end{cases} \qquad (14)$$

Replacing (13), (14) in (11)

$$p_c(t) = -\frac{C\omega_i {V_c}^2}{2}\sin(2\omega_i t + 2\beta) \qquad (15)$$

Therefore, comparing (15) with (11), in order to have bidirectional power flow decoupling, the β angle and the V_c amplitude are

$$V_c = \left(\sqrt{\frac{2|P_i|}{C\omega_i}}\right) \ \ \underline{\text{And}} \ \ \beta = \begin{cases} +\frac{\pi}{4} - \frac{\theta}{2};\ \ if\ P_i \geq 0 \\ -\frac{\pi}{4} - \frac{\theta}{2};\ \ if\ P_i < 0 \end{cases} \qquad (16)$$

It is means, the proposed power decoupling technique can be used to bidirectional power flow and reactive power in the grid.

IV. STEADY-STATE RESPONSE

Equivalent tank circuit on the primary side of the HF transformer is shown in Fig.3.

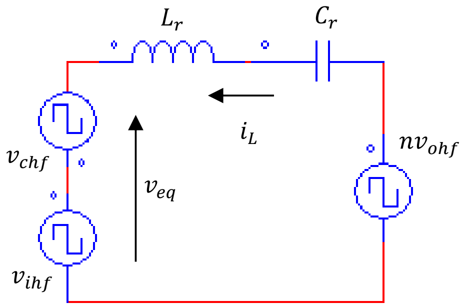

Figure 3. Steady-state analysis with the equivalent tank circuit

The signal m_p given by (2) can be expressed using Fourier series as:

$$m_p = \sum_{k=1,3\ldots}^{\infty}\frac{4}{k\pi}\cos\left(k\left(\frac{\pi}{2} - \frac{\alpha_p}{2}\right)\right)\sin\big(k(\omega_s t - \varphi_p)\big) \qquad (17)$$

Therefore v_{ihf}, v_{chf} and v_{ohf} (see Fig.1) can be expressed as:

$$v_{ihf} = v_i \times \sum_{k=1,3\ldots}^{\infty}\frac{4}{k\pi}\cos\left(k\left(\frac{\pi}{2} - \frac{\alpha_i}{2}\right)\right)\sin(k(\omega_s t)) \qquad (18)$$

$$v_{chf} = v_c \times \sum_{k=1,3\ldots}^{\infty}\frac{4}{k\pi}\cos\left(k\left(\frac{\pi}{2} - \frac{\alpha_{fa}}{2}\right)\right)\sin(k(\omega_s t - \varphi_c)) \qquad (19)$$

$$v_{ohf} = V_b \times \sum_{k=1,3\ldots}^{\infty}\frac{4}{k\pi}\cos\left(k\left(\frac{\pi}{2} - \frac{\alpha_o}{2}\right)\right)\sin(k(\omega_s t - \varphi)) \qquad (20)$$

Sinusoidal approximation can be considered if the switching frequency f_s is chosen $f_s \approx 1.1 f_r$ and the tank circuit is designed with a high quality factor Q . With these considerations, the voltages and the current in the tank circuit can considered as:

$$v_{ihf1}(t) = \left[\frac{4}{\pi}v_i \sin\left(\frac{\alpha_i}{2}\right)\right]\sin(\omega_s t) \qquad (21)$$

$$v_{ch1}(t) = \left[\frac{4}{\pi}v_c \sin\left(\frac{\alpha_{fa}}{2}\right)\right]\sin(\omega_s t - \varphi_c) \qquad (22)$$

$$v_{oh1}(t) = \left[\frac{4}{\pi}V_b \sin\left(\frac{\alpha_o}{2}\right)\right]\sin(\omega_s t - \varphi) \qquad (23)$$

$$v_{eq}(t) = \frac{4}{\pi}\left[v_i \sin\left(\frac{\alpha_i}{2}\right) - v_c \sin\left(\frac{\alpha_{fa}}{2}\right)\right]\sin(\omega_s t) \qquad (24)$$

$$i_L = \frac{\frac{4v_i}{\pi}\sin\left(\frac{\alpha_i}{2}\right) - \frac{4v_c}{\pi}\sin\left(\frac{\alpha_{fa}}{2}\right)e^{-j\varphi_c} - n\frac{4V_b}{\pi}\sin\left(\frac{\alpha_o}{2}\right)}{jw_s L_r + \frac{1}{jw_s C_r}} \qquad (25)$$

If the duty ratios $\frac{\alpha_i}{2}$, $\frac{\alpha_{fa}}{2}$ are time-variant at a frequency ω_i and, as $\omega_s \gg \omega_i$ then, the low frequency time-variations from v_i, v_c, $sin\left(\frac{\alpha_i}{2}\right)$ and $sin\left(\frac{\alpha_{fa}}{2}\right)$ can be considered constants during one switching period. Therefore, the grid current i_i and the SCB current i_c can be found calculating the average currents, it is means:

$$i_i = \frac{1}{2\pi}\int_0^{2\pi}(m_1 \times i_L)\, d(\omega_s t) \qquad (26)$$

$$i_c = \frac{1}{2\pi}\int_0^{2\pi}(m_3 \times i_L) d(\omega_s t) \qquad (27)$$

Where m_1 and m_3 are the modulation signals of the RG AB and the SCB AB respectively. Resolving (26) and (27), it can be probed that the only way to have decoupled control for the current grid i_i and for the SCB voltage v_c is when the phase shift angle φ_c is equals to zero. Therefore, the averaged AC currents can be calculated as:

$$i_i = I_m\, sin\left(\frac{\alpha_o}{2}\right) sin\left(\frac{\alpha_i}{2}\right) \qquad (28)$$

$$i_c = I_m\, sin\left(\frac{\alpha_o}{2}\right) sin\left(\frac{\alpha_{fa}}{2}\right) \qquad (29)$$

Where:

$$I_m = \frac{8n}{\pi^2 Z\left(F - \frac{1}{F}\right)} \times V_b\, sin(\varphi) \qquad (30)$$

Note in (28) and (29) that i_i and i_c depend on the duty ratio $\frac{\alpha_o}{2}$ then, if $\frac{\alpha_o}{2}$ is fixed, decoupled control for i_i and i_c can be obtained using independent time-variant duty ratios $\frac{\alpha_i}{2}$ and $\frac{\alpha_{fa}}{2}$, where the phase shift angle φ controls the power flow. This approach is completely different of the modulation proposed in [13]. Finally, the commands signal φ, $\frac{\alpha_i}{2}$ and $\frac{\alpha_{fa}}{2}$ can be calculated comparing (8) with (28) and (14) with (29), it is means:

$$\varphi = \arcsin\left(\frac{I_m}{K}\right);\ \underline{\text{Where}}\ \ K = \frac{8n}{\pi^2 Z\left(F-\frac{1}{F}\right)\sin\left(\frac{\alpha_o}{2}\right)} V_b \tag{31}$$

$$\frac{\alpha_i}{2} = \omega_i t - \theta \tag{32}$$

$$\frac{\alpha_{fa}}{2} = \arcsin\left(\frac{i_c}{I_m}\right) \tag{33}$$

Where the phase θ, define the reactive current injected to the grid and it is defined by (9). Besides, according (33), $\frac{\alpha_{fa}}{2}$ has a real values if

$$I_m \geq i_c \tag{34}$$

It is means, the control of the grid current and the SCB voltage can be decoupled using independent time-variant duty ratios $\frac{\alpha_i}{2}$ and $\frac{\alpha_{fa}}{2}$ respectively. The power flow is controlled by the phase shift angle φ. On the other hand, with the proposed structure and modulation, power decoupling is obtained in the tank circuit. Indeed, using time-variant duty ratios control on AC side and, considering $\omega_s \gg \omega_i$, the equivalent modulated v_{eq} (see Fig.3) can be calculated replacing (32) and (33) in (24), it is means:

$$v_i \sin\left(\frac{\alpha_i}{2}\right) = \frac{V_m}{2}\cos(\theta) - \frac{V_m}{2}\cos(2\omega_o t - \theta) \tag{35}$$

And $v_c \sin\left(\frac{\alpha_{fa}}{2}\right)$ can be calculated as

$$v_c \sin\left(\frac{\alpha_{fa}}{2}\right) = \frac{v_c i_c}{I_m} = \frac{P_o}{I_m}\cos(2\omega_o t - \theta)$$

$$v_c \sin\left(\frac{\alpha_{fa}}{2}\right) = \frac{V_m}{2}\cos(2\omega_o t - \theta) \tag{36}$$

Replacing (35) and (36) in (24)

$$v_{eq} = \frac{4}{\pi}\left[\frac{V_m}{2}\cos(\theta)\right]\ \sin(\omega_s t) \tag{37}$$

According with (37), for a given reactive power in the grid, the equivalent modulated voltage v_{eq}, in steady-state response, is power decoupled from low frequency time-variations $2\omega_o$. In others words, in switching frequency, v_{eq} has a constant amplitude which decreases according with the reactive power injected to the grid. In order to compensate this voltage decreasing, fixed duty ratio $\frac{\alpha_o}{2}$ on DC side can be applied according (23). Therefore, the proposed converter can be considered like a DAB series-resonant DC-DC converter [14], where the tank circuit and the HF transformer can be designed for maximal transfer power ($\theta = 0$), it is means:

$$Z = \sqrt{\frac{L_r}{C_r}}\ ;\ F = \frac{f_s}{f_r}\ ;\ f_r = \frac{1}{2\pi\sqrt{L_r C_r}};\ Q = \frac{Z}{\frac{8}{\pi^2} n R_o}\ ;$$

$$R_o = \frac{V_b^2}{P_o};\ n = \frac{\left(V_m/2\right)}{V_b} \tag{38}$$

V. SIMULATIONS

A DC/AC converter was designed using the parameters from Table I. The parameters L_r, C_r and n were calculated using (38) while the SCB capacitor C using (16). The simulations were performed in PSIM software. For all simulated cases, a close loop control for the grid current and the SCB voltage is done, however the control strategy is not cover in this article.

TABLE I. DC/AC CONVERTER PARAMETERS

Parameter	***Value***
Converter Power	1kW
Grid amplitude V_m	$220\sqrt{2}$ V
Battery voltage V_b	120V
Grid frequency	60 Hz
Switching frequency	50kHz
Quality Factor Q	4
Frequency Ratio $F = f_s/f_r$	1.1
Resonant Inductor L_r	278μH
Resonant Capacitor C_r	44ηF
Turn ratio transformer n	1.3 : 1
SCB maximal voltage V_c	600 V
DC filter Film Capacitor C_o	10 μF
AC filter Film Capacitor C_i	1μF
AC filter inductor L_i	5mH
SCB Capacitor C	15 μF
Dumping Resistor r_d	0.47 Ω
Dead Time	300ns
Time step	100ns

The first power flow analyzed case was from the grid to the battery, considering zero reactive power at the grid. The results are shown in Fig. 4 for five grid periods.

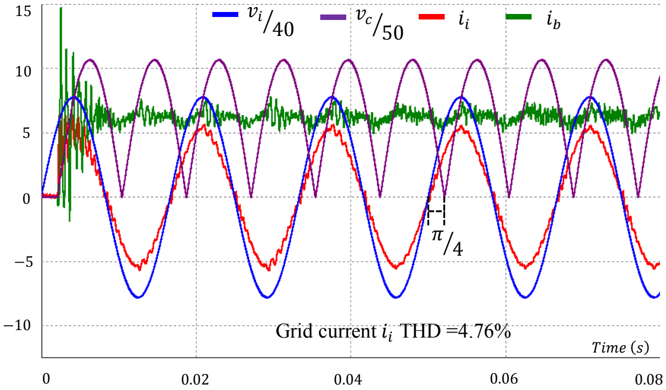

Figure 4. Simulated case: grid to battery power flow for 800W.

It can be observed zero reactive power in the grid (according (8) and (9), $\theta = 0$). Besides, grid current has very low THD. On the other hand according (16), for $P_i = +800$W, power decoupling is obtained when $v_c \approx 532\left|\cos\left(\omega_i t + \frac{\pi}{4}\right)\right|$ therefore, $\frac{v_c}{50} \approx$

$10.64\left|\cos\left(\omega_i t+\frac{\pi}{4}\right)\right|$ (see fig.4). However, not ideal conditions like dead time and steady-state error in grid current and SCB voltage cause a little low frequency ripple $2\omega_o$ in the battery current.

On the other hand, the tank circuit current i_L is shown in fig.5 for four grid periods.

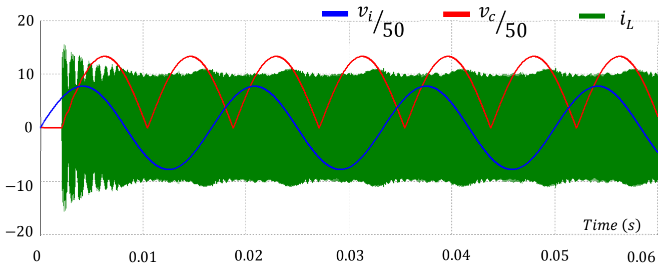

Figure 5. Power decoupling in the tank circuit current

It can be observed that, with the proposed modulation, the tank circuit current is power decoupled from AC low frequency grid voltage variations and, it has a quasi-constant amplitude (steady-steady error in the grid current and in SCB voltage cause the little low frequency variations). Therefore, the proposed converter with the SCB has a steady-state responses like a DAB series-resonant DC-DC converter.

The same analyze can be done when the power flow goes from the battery to the grid considering zero reactive power at the grid. The results are shown in Fig. 6. Fewer THD in the grid current is obtained. According (16), for $P_i=-800\mathrm{W}$ power decoupling is obtained when $v_c\approx 532\left|\cos\left(\omega_i t-\frac{\pi}{4}\right)\right|$ therefore, $\frac{v_c}{50}\approx 10.64\left|\cos\left(\omega_i t-\frac{\pi}{4}\right)\right|$.

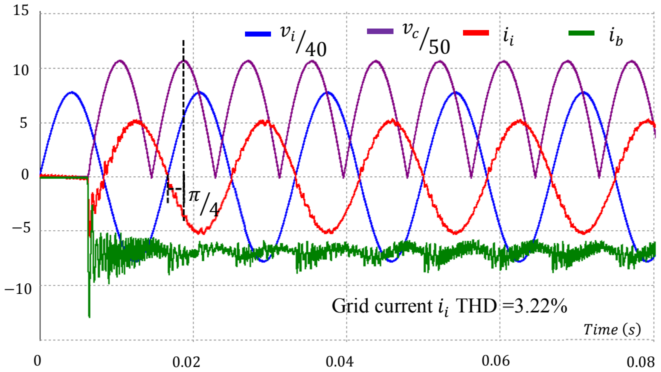

Figure 6. Simulated case: power flow from the battery to the grid for -800W

Finally ZVS mode is shown in fig. 7 for $\omega_i t=\frac{\pi}{2}$. In this case, ZVS is obtained in all active bridge because $i_L<0$ for positive transition of v_{bhf} and $i_L>0$ for positive transition of v_{ihf} and v_{chf} respectively. However, ZVS mode will be lost on AC active bridges when $P_i>0$ and time-variant duty ratio is applied.

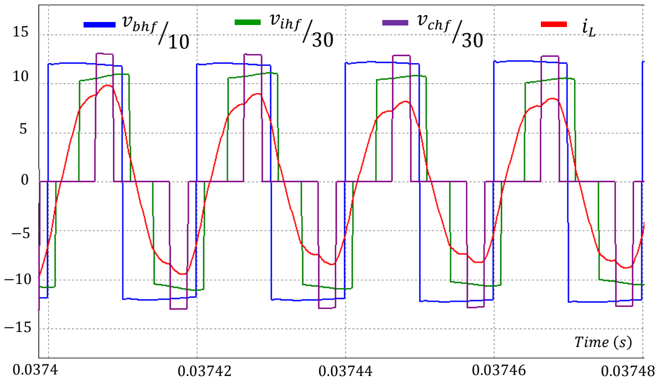

Figure 7. ZVS mode for all active bridges

VI. EXPERIMENTAL RESULTS

A general 1kW prototype converter was implemented using Table I. The components list is shown on Table II.

TABLE II. COMPONENTS LIST

Component	*Description*
Battery active bridge MOSFET	INFINEON IPP200N25N3G, 250v, 20mΩ
Unfolding bridge MOSFET	INFINEON IPW65R019C7FKSA1, 650v, 19mΩ
SCB and AC active bridge MOSFET	SIC MOSFET CREE C2M0080120D, 1200V, 98mΩ
Transformer	1:1.3[1]
Resonant Inductor L_r	278 UH[2]
Resonant Capacitor C_r	0.044UF[3]
Current and voltage Sensor	LA25NP, LV25P

[1] Primary: 10 turns, 800x0.071 Litz wire. Secondary: 13 turns, 28x0.28 Litz wire. EE55 3C90 CORE.
[2] 39 turns, 28x0.28 Litz wire. 2mm dual air gap. EE55 3C90 CORE.
[3] 2x0.022uF. Code: 940C30S22K-F.

The prototype is shown in fig. 8. The embedded controlled used was the FPGA Cyclone IV of the DE0Nano from Terasic.

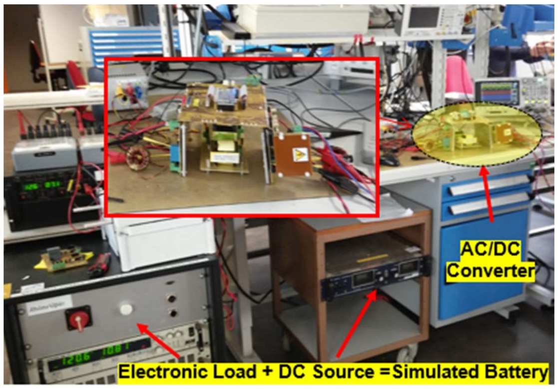

Figure 8. 1kW DC/AC single stage laboratory prototype

The first results are shown in fig.9 and fig.10 for $P_i=480W$. A perfect AC source was used to validate the converter functionality. Stability problems were presented in higher powers of 500W. Future projects will be focus to resolve the stability control problems and to validate the bidirectional power flow.

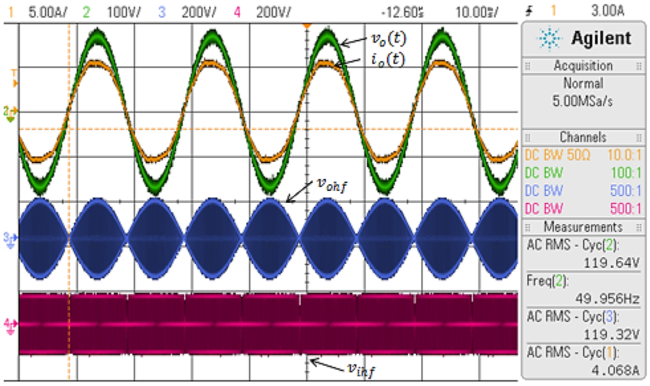

Figure 9. Power Flow from the grid to the battery for 480W operation.

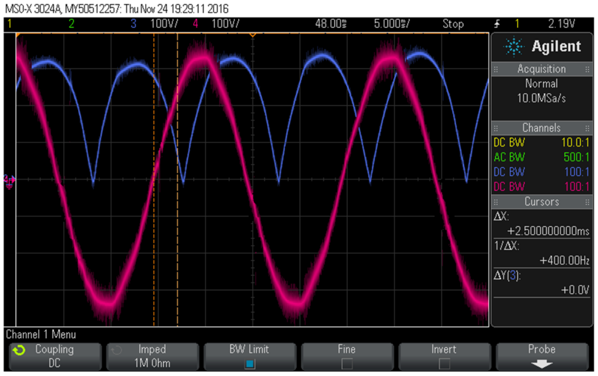

Figure 10. SCB voltage for 480W operation

VII. CONCLUSIONS

A bidirectional single stage AC-DC converter with power decoupling using a SCB is proposed to interface battery to single phase grid. Bidirectional reactive and active power flow in the grid can be controlled. It has been shown that, if the rectified grid AB and the SCB AB are modulated with not phase shift angle and independent time-variant duty ratios, the control of the SCB voltage and of the grid current can be decoupled. Besides, this structure allows power decoupling in the tank circuit having a steady-state response equivalent of a DAB series-resonant DC-DC converter. Reactive power in the grid is compensated using a fixed duty ratio on DC side. Bidirectional power flow is controlled using phase shift modulation. Comparing with the analogous AC-DC structure without series-connect buffer this structure allows (1) power decoupling in the tank circuit and HF transformer (2) simple converter design and (3) decoupled control. However, a dumping resistor has to be inserted and besides, a more complex controller has to be implemented in order to decrease the THD in grid current. Simulations and experimental results validate the converter functionality. High efficiency can be obtained due to ZVS in all active bridges MOSFET. Future projects will be focus to resolve the stability control problems and to validate experimentally the bidirectional power flow.

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