Three-port power electronic system for energy storage and recovery using a parallel connection of a Power Factor Corrector boost and a Dual Active Bridge

A. Rodriguez, A. Vazquez, D.G. Lamar, M.M. Hernando

Power Electronic Supply Systems Group. University of Oviedo.
Campus de Viesques s/n. Edificio 3. 33204. Gijon. Spain.
Email: rodriguezalberto@uniovi.es

Abstract **— The increasing demand of an intermediate storage of electrical energy in battery systems, in particular due to the use of renewable energy, has resulted in the need of more intelligent power supply systems. Bidirectional DC/DC power converters with galvanic isolation and efficient and low harmonic distortion AC/DC conversion to connect the mains line to the load are usually required in multiple applications. In this paper a three-port power supply system which interconnects the single-phase line with both an active load and both a battery is proposed. Considering the specifications of a particular application, different topologies for the power supply system have been analyzed. After a theoretical evaluation, the optimum of the studied configurations has been developed and tested in all modes of operation demanded by the application. To accomplish all the requirements of the different operation modes of the power supply system, digital control has been used to control the bidirectional converter and the global system.**

Keywords **— Dual Active Bridge, Power Factor Correction, energy recovery system, multi-port power supply system.**

I. INTRODUCTION

Energy efficiency is one of the challenges of the new millennium. A more intelligent use of electrical energy (higher efficiency, energy recovery, etc.) and the flexible use of clean energy sources are on the leading edge of society concerns. The next generation of power supply systems should be more flexible, more competitive, more performing (efficient, durable, with higher autonomy, etc.) and in general more intelligent.

Some new applications, such as electrical vehicles, hybrid or fuel cell supplied, renewable energy generators, local energy generation, etc., try to comply with all these demands [1]-[4]. These technologies usually require an energy storage device, to lay up possible extra energy and supply the network during high demand periods thanks to this stored energy. The increasing demand of an intermediate storage of electrical energy in battery systems, in particular due to the use of renewable energy, has resulted in the need of advanced power supply systems, with different functionalities and operation modes.

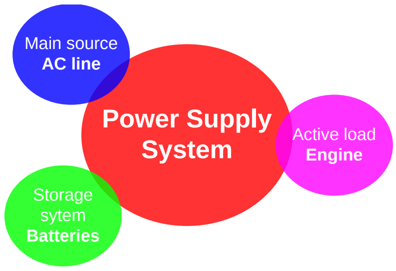


Fig. 1 Three-port power supply system.

A good example of this technology is a supply system that recovers generated energy in a regenerative braking process of an active load (i.e. a DC or AC motor drive). This energy is stored up in a battery for future use. The overall power supply system efficiency increases using this recovering method, because the breaking energy is now recycled, instead of being wasted. There are many power supply systems that match with this scheme, such as a solar plant installed in a house or an electric motor drive.

In this sense, a three-port power supply system with different operation modes can provide all the functionalities required by a load which not only must be supplied but also can generate energy that should be stored. Figure 1 shows a very simple picture of a conventional three-port power supply system. In this system the three ports are: the main power source (mains), the energy storage device (battery) and the load (an engine). With this architecture, different operation modes can be implemented. For example: the storage device may be charged from the main source or from the load (if it is able to generate energy), the load may be supplied by the primary source, by the storage device or by both of them (for instance in a high energy demand situation) and a possibility not considered in the proposed system is to transfer the energy generated by the load to the main source. Bidirectional DC/DC power converters with galvanic isolation (to connect the storage system to the load) and low harmonic distortion AC/DC conversion (to connect the primary source to the load), are usually required in the aforementioned applications.

In this paper a three-port power supply system with the previously mentioned operation modes is presented. Different topologies for the converters that compose the power supply system and different configuration in the connection have been analyzed in section II. In section III, the optimum three-port configuration will be analyzed. This configuration is based on two converters; both converters are described and their functionality will be presented. After the theoretical analysis of the possible configuration of the power supply system, a prototype has been developed and tested in different operation modes. The experimental results are summarized in section IV. Finally, in section V some conclusions are presented.

II. Specifications of the System and Configuration Selection

The power electronic system under development must fulfill the following specifications:

- The main power source is the single-phase power distribution line (European range, 230 Vrms and 50 Hz). Maximum contracted power of 2 kW.
- The system must keep a constant voltage of 500V at the load (an engine supplied by an inverter), which can demand or generate power: the maximum demanded power is 5 kW and the maximum generated power is 1.7 kW.
- The energy storage device is a battery of 48V that may be charged from the power generated by the active load or from the main power source.

Figure 2 (a) shows the basic diagram of the proposed three port system. One port is the main distribution line (in European range), the second port is connected to a 48 V battery and the third port connects the active load with the global system. The power supply system must work in the following operation modes: in mode 1 the battery must be charged by the line; in mode 2, the energy generated by the active load must be stored in the battery; in mode 3 the load must be supplied by the power supply system (the line, the battery or both). All these operation modes can be seen in Fig. 2 (b), (c) and (d).

It is important to remark that the battery is connected directly to the three port system. For safety reasons, the power either flowing or from to the battery must introduce galvanic isolation. Moreover the battery can be considered as a load or a source, therefore a bidirectional converter has to be connected to it. The AC/DC conversion is limited to 2 kW maximum power and the power factor is desirable to be as high as possible. The maximum power of the active load is 5 kW.

Taking into account all these specifications and operation modes some appropriate configurations for the power supply system, shown in Fig. 3, have been studied. To evaluate all configurations, the current and voltage stresses of the semiconductors have been calculated. An optimization of commercial semiconductor for all configurations has been carried out. Moreover, the volume and weight of the magnetic components and capacitors have been evaluated by commercial references. With these data, an estimation of efficiency, cost, weight and volume for each configuration is achieved and the results can be compared to select the theoretically better configuration.

The first configuration, shown in Fig. 3 (a), is a two stage topology, where both converters are connected in cascade.

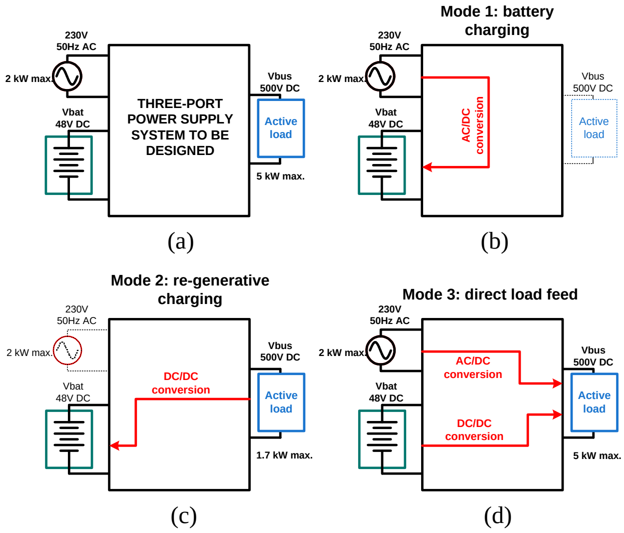


Fig. 2. Basic diagram of proposed three-port power supply system. (a) Specifications. (b) Operation mode 1. (c) Operation mode 2. (d) Operation mode 3.

The first stage is an AC/DC converter. It provides a Power Factor Correction (PFC) and regulates the 48 V over the battery. For this first stage a low cost flyback converter is proposed. In this case a PFC boost converter is not considered because the output voltage is lower than the rectifier input voltage. So the AC/DC must buck and boost the input voltage with galvanic isolation. Also this choice is looking for the lowest cost and volume solution. The second stage is a bidirectional DC/DC conversion. This stage provides galvanic isolation and voltage regulation over the load. In this case, a Dual Active Bridge (DAB) converter is proposed.

This cascade topology is based on pre-regulators topologies, which are widely used in PFC applications [5]-[6] where the efficiency is the main goal of the system.

There are several advantages forwarding this option. First one, both converters can work independently. This means that the control feedback loop can be different for each stage. In this sense, a well-known control technique can be used for both converters, which is more desirable. Second, both converters can be designed as one stage power supply. Both advantages translate in a low cost solution. On the other hand, there are some disadvantages. The more important ones are the voltage and current stresses. First of all, it is well known that flyback converter has lower efficiency than boost PFC converters. This is based on the high voltage stress that semiconductor suffers in buck-boost family converters. Moreover, the second stage (DAB converter) must be designed to provide a power as high as 5 kW. Therefore, the magnetic elements and the voltage and current stresses of the semiconductors are higher.

The second configuration is shown in Fig. 3 (b). This is a three stage topology. The third stage is just the same as the first proposed topology, a DAB converter. The first and second stages are composed now for two converters connected in cascade: a PFC boost converter plus a half bridge converter. In this case, there are three power conversions: first, AC to DC rectifier conversion (PFC boost converter); second, DC to DC conversion (half

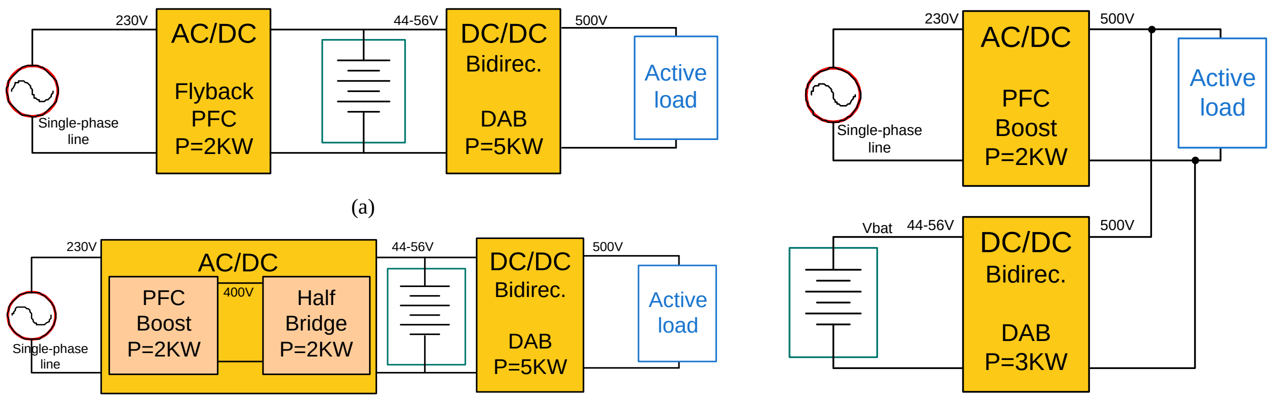


Fig. 3. Different configuration for the electronic power system under study. (a) Cascade configuration. One stage for the AC/DC. (b) Cascade configuration. Two stage for the AC/DC. (c) Parallel configuration.

bridge converter); and third, DC to DC conversion (DAB converter).The idea behind this approach is to obtain a better efficiency at the expense of increased volume and cost. The first stage only provides the PFC. A high voltage ripple in the middle conversion is allowed, so a volume reduction is achieved by capacitor decrease. The half bridge stage must regulate the battery current and its control loop must be designed to neglect the PFC boost output current ripple. The third stage provides, again, the bidirectional conversion.

This choice is more efficient than the previous one, because each stage is optimized only for one objective. Nevertheless, this is a high cost solution. Three converters must be designed and also their feedback control loops. This is a higher complex option. Furthermore, this option does not solve the high stresses on the bidirectional stage. This option has not any advantage from this point of view.

The last proposed topology is a two stage parallel structure. This option is shown in Fig. 3 (c). In this case, two converters are connected in parallel in order to obtain a stress reduction in the bidirectional converter. The first stage is a PFC boost converter. In this case its output is connected to a high DC voltage bus (500 V), therefore a high efficient topologies without galvanic isolation can be used (i.e. PFC boost). The second stage is a DAB converter. It provides the bidirectional conversion again. The DAB high voltage side is the DC bus, and the low voltage side is the 48 V battery.

This choice has two main advantages. First of all, the PFC boost output current ripple can be neglected by the DAB converter control loop when the battery is charged from the mains. This idea is just the same to the previous mentioned three stage topology. Now, in this scenario, the battery is connected to the DAB converter. In the previous topologies (two stages and three stages) this battery is directly connected to PFC AC/DC output. So, in these topologies galvanic isolation is needed in the first or second stage. In this choice, no galvanic isolation is needed in the first stage, because the PFC boost converter is connected to a high voltage bus. These two advantages translate in a volume and cost reduction. Less magnetic elements and output voltage electrolytic capacitors can be used in this option.

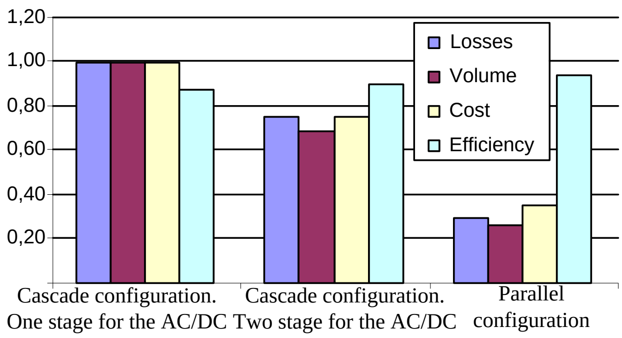


Fig. 4. Comparison between the different topologies. Normalized values except efficiency.

Another good advantage arises from the parallel connection: now, the DAB converter may manage only a 3 kW maximum power. In this particular case, both converters can fed simultaneously the load: the PFC boost converter gives 2 kW and the DAB converter provides the additional 3 kW. The DAB maximum power reduction decreases the semiconductor stresses and the volume of the magnetic materials in this converter.

This choice also has some disadvantages. First, to reduce the losses and to increase the overall system efficiency when the load is demanding full power, a complex control strategy must be implemented. A control strategy must be implemented to adequately share power both from the mains and from the battery.Therefore, this control strategy must decide which converter is regulating the voltage load, and which is un-regulated. Also, when the load plays the role of power source (generating energy), this control strategy must detect it and the PFC boost converter must be disconnected from the high voltage bus and the DC/DC converter must adequately forward energy to the battery. And last, when the battery must be charged from the AC source line, the control strategy must control both converters working as pre-regulator and post-regulator. This control strategy has a high level, in addition to the individual control of each converter that must be implemented.

Regarding the battery recharging process from the mains, a second disadvantage arises. In this particular case, two conversions are made in the parallel configuration for battery recharging, resulting in a lower efficiency in this operation mode.

These three configurations are studied in terms of losses estimation, volume, component cost comparison and an efficiency approach of overall system. The results of this study are summarized in Fig. 4. All the terms shown are normalized, except the efficiency. As can be seen, all the aforementioned advantages and disadvantages of each topology are confirmed in the theoretical analysis. Therefore, the worst option is the two stage topology, where the two converters are connected in cascade. The losses, volume and cost are higher than the other two options. The three stage topology has good results regarding the efficiency and volume. Nevertheless, cost and losses are large, as it has been previously mentioned for this choice. The best results obtained in terms of efficiency and losses are the parallel topology. All the profits of this topology are listed before. For these reasons, this topology has been chosen to develop this three-port power supply system. However, no analysis of the proposed controls of each configuration (and effort quantification for this control) is made in this comparison study. From this point of view, the parallel option is the worst possible solution. Hence, this is a challenging option, where some new special control techniques can be proposed and verified, as will be presented in the following sections of this paper.

III. PROPOSED CONFIGURATION

The proposed and implemented configuration of the power supply system, shown in Fig. 5, is composed by two converters, an interleaved PFC boost as AC/DC converter and a DAB as bidirectional DC/DC converter. In this section the main characteristics of these two converters are described.

A. *AC/DC converter. Interleaved PFC boost*

A two phase interleaved PFC boost converter working in Continuous Conduction Mode (CCM) have been chosen in order to reduce the input current ripple and looking for an efficient conversion and low harmonic distortion [7]-[9]. The prototype of this converter can be seen in Fig. 6. One of the main advantages of interleaving converters is the input and output current high frequency ripple decrease. This effect is based on the phase-shift applied to each phase. In this particular case, S2 is driving with a 180º phase shifted signal applied to S1. The input current, i_{IN} is the sum of both inductor currents, i_{L1} and i_{L2}. The total input current ripple is cancelled when these two inductor currents are added. In other words, looking from the input full-bridge diode rectifier, the input current is a signal with a frequency ripple twice than the switching frequency. Following this reasoning, the ouput voltage ripple, at high frequency, applied to the output capacitor, C_{OUT}, is twice the switching frequency. This means that compared to a single phase PFC boost converter operating in the same conditions, the output capacitor and the EMI input filter can be reduced.

Obviously, another advantage of interleaved converters is the current stresses reduction. Each phase in an interleaved converter must manage a part of the total current of the full converter, in particular $i/_N$, being N the number of phases and i the total current. So, in the proposed two phase interleaved PFC boost converter, each transistor, diode and inductor manage half of total

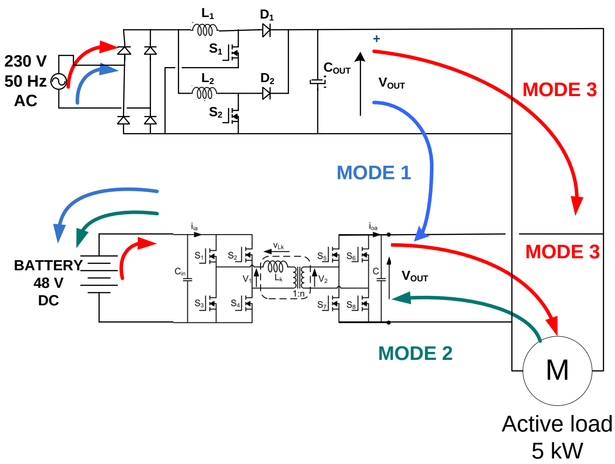


Fig. 5. Proposed three port power supply system.

current, comparing to a single phase PFC boost converter.

Interleaved converters have also some disadvantages regarding an increase of the number of components (in this case, twice than non-interleaved solution, that means a higher cost), and unbalancing currents for each phase. However, at these power levels these disadvantages are reduced. In this case, an analog control with linear multiplier and mean current measurement for each phase with feed-forward is adopted, in order to keep balance current operation, using well-known commercial analog controllers on the market.

Another important problem of this converter and in PFC boost converters in general, is the diode reverse current due the recovery behavior in high voltage diodes, which involves high losses. To improve the overall efficiency of the converter, Schottky Silicon Carbide (SiC) diodes are used instead of Ultrafast ones, so the reverse current is neglected and losses attached to this effect are reduced [10]-[11]. A prototype has been developed and tested to verify its functionality, and the design specifications are shown in Table I.

TABLE I
COMPONENTS AND SPECIFICATIONS OF THE INTERLEAVED PFC BOOST

Input voltage : Output voltage	230 Vrms 50 Hz: 500 V
Maximum output power	2 kW
Switching frequency	100 kHz
Full-bridge diode rectifier	GSIB1540
MOSFET (per phase)	SPW24N60C3 CoolMos (Infineon)
Diode (per phase)	IDD12SG60C SiC (Infineon)
Inductance (per phase)	680 µH Toroids 55438-A2 (Magnetics)
Analog Controller	UCC28070 (Texas Instruments)

Figure 7 shows the input voltage and the input current waveforms measured at full load and nominal input and output voltages (2 kW, 230 Vrms and 500 V). As can be seen, the input current is sinusoidal with low harmonic content and the power factor measured was 0.998. The efficiency is plotted in Fig. 8 for the minimum, nominal and maximum input voltage. In all these cases the output voltage was 500 V.

Fig. 6. Picture of the interleaved PFC boost prototype.

As can be seen, the prototype has a good efficiency higher than 90% from light load to full load. The maximum peak efficiency is 96.2%, obtained at 1.5 kW.

B. Bidirectional DC/DC converter. Dual active bridge (DAB).

The DAB converter (Fig. 9 (a)) originally proposed in [12] and [13] and analyzed in more detail in [14]-[19], is a bidirectional DC/DC converter based on two active bridges interfaced through a high-frequency transformer, enabling power flow in both directions. Each bridge can be controlled with constant duty cycle (50%) to generate a high-frequency square-wave voltage at its transformer terminals (V_1, V_2).

Taking into account the leakage inductance of the transformer, the two square waves can be appropriately phase shifted to control the power flow from one DC-source to the other, so bidirectional power transfer can be achieved. The main operational waveforms of this converter are plotted in Fig. 5 (b) power is delivered from the bridge which generates the leading square wave. The direction of the power flow can be automatically changed by changing the sign of the phase-shift.

The component that mainly determines the power handle by the converter is the transformer leakage inductance. Generally, an additional inductance would be needed in series with the transformer leakage inductance to control the power. In this case, the highest inductance has been selected to handle the maximum power using (1):

$$L_{max} = \frac{V_o \cdot V_{in} \cdot T \cdot D_{max} \cdot (1 - D_{max})}{2 \cdot P_{max} \cdot n}. \qquad (1)$$

All the design specifications are shown in Table II.

The layout of the low voltage bridge is quite important because the high circulating currents at low voltage side of the converter (i.e. the side connected to battery). To maintain constant the input voltage in all the bridge, some interleaving capacitors have been used [20]. The more important parameter of the high voltage bridge is the parasitic output MOSFETs capacitance. The value of this parasitic element determines the ZVS operation in the DAB. At nominal voltages and full power all MOSFETs switch under ZVS conditions, but when the energy stored in the leakage inductance is not high enough to discharge the parasitic output capacitor of MOSFET transistor, the ZVS is lost (e.g. when the battery voltage decreases or when the power decreases). ZVS condition is lost when

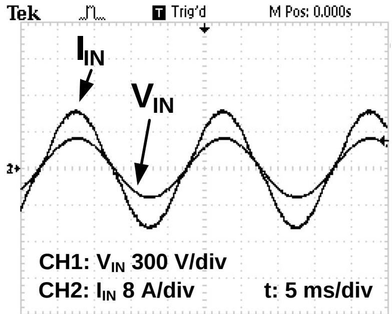


Fig. 7. PFC boost input voltage and input current at full load.

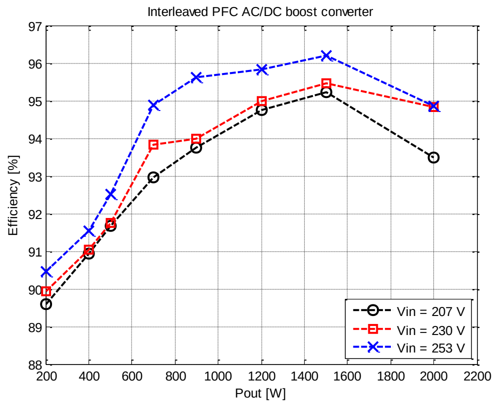
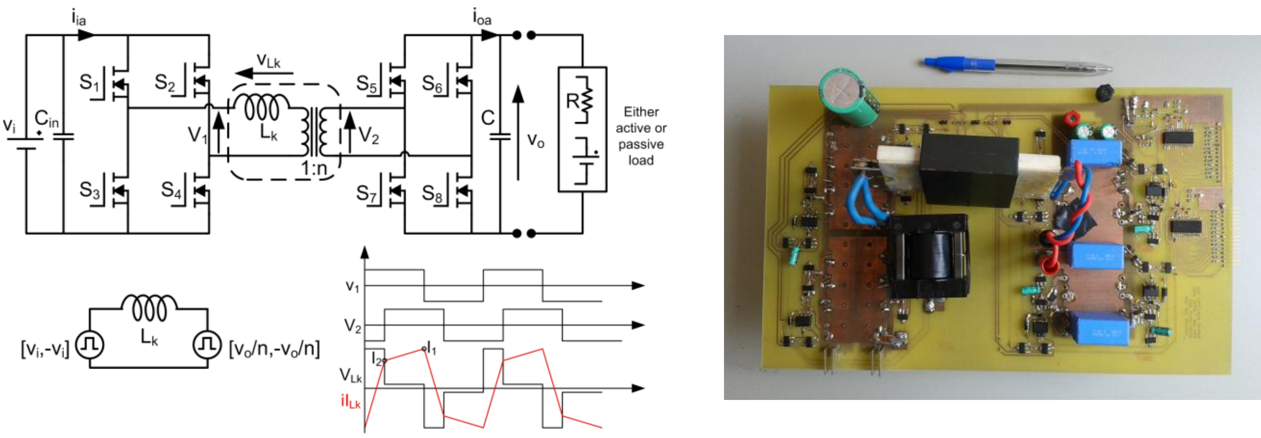


Fig. 8. PFC boost converter efficiency.

$$I_2 < \sqrt{\frac{4 \cdot C_{OSS} \cdot V_o^2}{L_k}}, \qquad (2)$$

being C_{OSS} the output parasitic capacitance of MOSFET, L_k the leakage inductance transistor and I_2 the current peak value shown in Fig. 9 (b). ZVS is generally lost first in the high voltage bridge. In the proposed DAB, (2) determines that ZVS will be lost at approximately an ouput power of 800 W.

When ZVS is lost, high switching losses and high ringing in the control signal, which can distort the behavior of the converter, appear. It is well known that for maintaining the ZVS condition in the high voltage bridge, the value of I_2 must be increased, for a given average output. The ZVS range can be slightly increased modifying the high voltage side (i.e. the supply voltage of the active load) when low power is handled, so that the value of I_2 is increased. Moreover, when the power is lower the switching frequency of the converter is increased, so that the phase-shift must be increased and ZVS can be achieved. Finally, when very low power is managed, the converter is turned-on and turned-off, in order to handle always a minimum amount of power that maintains ZVS. As the DAB converter is digitally controlled by an FPGA (Virtex 4), these three different control modes can be easily implemented.



(a) (b)

Fig. 9. DAB converter. (a) Basic structure, equivalent circuit and main waveforms. (b) Picture of the prototype.

TABLE II
COMPONENTS AND SPECIFICATIONS OF THE DAB

Input voltage : Output voltage	48 V: 500 V
Maximum output power	3 kW
Switching frequency	100 kHz
Low voltage Full Bridge	Each MOSFET 3xIRFB4310Z
High voltage Full Bridge	STW43NM60N
Transformer	Planar E64 with n = 1:10
Leakage inductance	3 turns in ETD39. Lk = 1 μH

IV. OPERATION MODES OF THE GLOBAL SYSTEM

The power supply system must comply with the previously detailed requirements in the different operation modes. An explicative block diagram of the proposed control method is shown in Fig. 10. An FPGA is used to control the DC/DC converter and the global system. The DC/DC converter can choose between two different regulators to control the voltage of the active load or the current through the battery. When the voltage regulator is chosen, the DC/DC converter works as voltage source, regulating the high voltage bus. However, with the current regulator the DAB works as current source. The high level control strategy may choose which regulator will be used, taking into account the selected operation modes. Moreover, this overall control can turn-on or turn-off the DC/DC converter, and also can disconnect the AC/DC converter from the high voltage bus. For each operation mode a different configuration of the control strategy is adopted and implemented as follows.

- Mode 1 (battery charging): in this mode the battery is charged from the main power source, the mains. In this case the active load does not consume power. The high voltage bus is regulated by the AC/DC converter, while the DC/DC converter determines the current profile to charge the battery. In this case, the DC/DC converter is working in current-mode and the power is being forwarded from the AC line to the battery. A different current reference should be used in the DAB converter, in order to change the battery current profile. This reference can be easily modified by the high level function of the control strategy. Basic protections techniques, such as over current or maximum peak current, are implemented in the DAB digital control to take care of the energy storage system.

- Mode 2 (energy recovery mode): the energy generated by the active load, instead of being lost, is used to charge the battery. This mode is similar to mode 1, but the main power source is now the active load instead of the input AC line. The DC/DC converter must regulate the active load voltage and the battery is charged directly from the current generated by the load. The AC/DC converter is disconnected from the high voltage bus which supplies the active load. It is important to remark that no current regulation is used in this mode (although over current and voltage protection are implemented), because the active load cannot regulate its voltage. Nevertheless, if the active load could regulate its voltage while it was generating (or recycling) energy, the DAB converter should operate in current- mode, as it has been explained for mode 1. A simplified power profile of this mode can be seen in Fig. 11.

- Mode 3: the energy demanded at the active load must be provided by the power supply system. The maximum peak power demanded is 5 kW. The power profile for this mode is shown in Fig. 11. The voltage which supplies the active load must be regulated and no

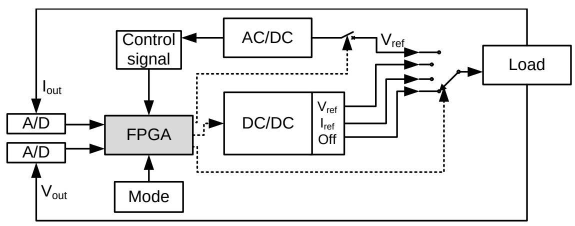


Fig. 10. Block diagram of the proposed control method.

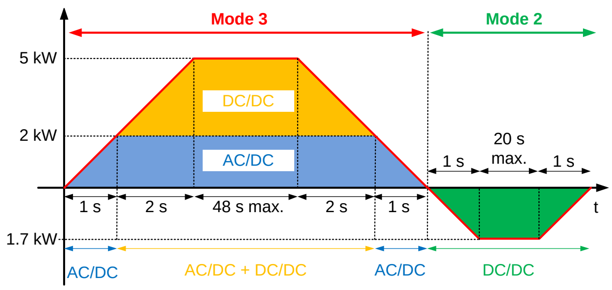


Fig. 11. Simplified power profile for modes 2 and 3.

charge profile is required. In mode 3 both converters feed the load. The AC/DC converter is the primary source. It will regulate the voltage in the 500 V DC bus till the load demands 2 kW (during the first second). Till this amount of power, the DC/DC converter is off and is turned-on just when the load demands more than 2 kW. In this transition, the AC/DC voltage loop error is clamped and this converter will work in saturation mode. Therefore the DC/DC converter starts to regulate the voltage of the active load and gives the extra power demanded. As mode 2, the DAB works in voltage-mode, regulating the voltage load. From 3 kW to the maximum power operation point, 5 kW, the AC/DC converter is working as source current and it is providing 2 kW; the DC/DC converter is supplying the difference, working as voltage-source (for 2 seconds). The active load is demanded the full power for a maximum of 48 seconds. When the power load decreases this process is reversed: the DC/DC converter is turned off when the load power is lower than 2 kW. As can be seen in Fig. 11, the load variation is slow and linear (2 kW per second), so no fast dynamic response is needed.

In mode 3, the control strategy will use a signal generated by the AC/DC control loop to turn on and off the DC/DC converter. In this case the analog controller used in the interleaved boost converter provides a special operation mode called saturation mode. When the load increases more than the maximum AC/DC converter (i.e. 2 kW), the interleaved boost converter stops regulate the output voltage and works like a current source clamped at 2 kW power. The output voltage error in the control loop is directly proportional to the power managed by the AC/DC converter. This signal, the voltage error of the output voltage loop, is clamped at 5 V when the interleaved boost converter is entering in this saturation mode. So, this signal is used to communicate both controllers and warns the high level control when the AC/DC converter is working in saturation mode. In other words, this signal is used to turn-on the DC/DC converter to feed the active load. All the power managed by the DC/DC converter is the difference between the increasing power demanded by the active load and the maximum limited peak power of the AC/DC converter (i.e. 2 kW). This control technique parallelizes both converters without problems.

Experimental results from mode 1 are shown in Fig. 12. In red, the 500 V voltage bus voltage is plotted. The yellow curve is the AC/DC output current. The current of through the leakage inductance of the DC/DC is plotted in green. In blue the DAB control signal can be seen. All these waveforms are taken when the charging process starts. At the beginning, the DC/DC converter is turned-off, so no current is forwarded to the battery. In this situation, the AC/DC converter works with no load (no current is forwarded from the AC input line). As can be seen, the interleaved PFC boost converter is regulating the high voltage bus. When mode 1 is chosen, the high level function of the control strategy turns-on the DC/DC converter, and the charging process begins. After a transient process, a constant current charging is shown. The AC/DC converter is regulating the 500 V bus voltage, and the DC/DC is regulating the battery current.

The same waveforms are shown in Fig. 13 when the system is working in mode 2. In this case the yellow curve is the current generated by the active load. The high

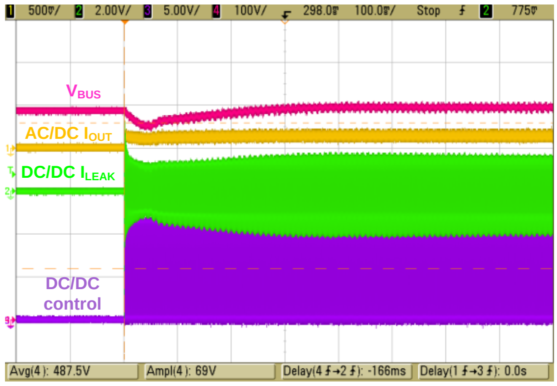


Fig. 12. Waveforms obtained in operation mode 1 (battery charging).

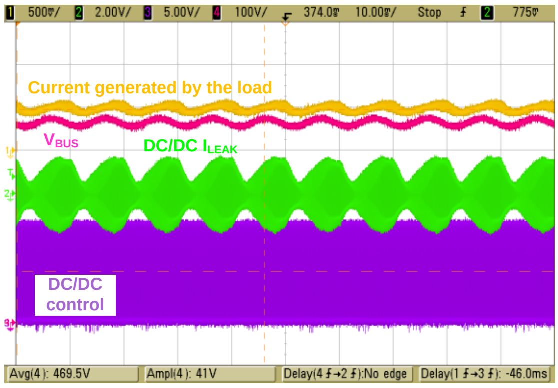


Fig. 13. Waveforms for operation mode 2 (re-generative charging).

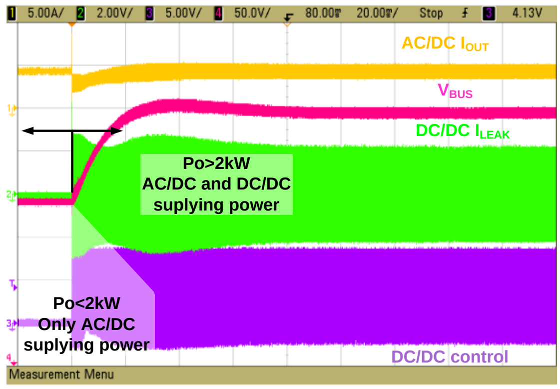


Fig. 14. Operation mode 3. Increase in the power demanded by the load and DC/DC converter is turned on.

voltage bus is plotted in the red plot. In green, the DC/DC current through the leakage inductance is shown. Finally the DC/DC gate signal control is plotted in blue. In this case, the AC/DC converter is disconnected from the high voltage bus. The DC/DC converter is now working in voltage mode, so it is regulating the 500 V voltage bus. The active load generates an average constant current with some low frequency ripple. As it has been previously mentioned, in this mode there is no current regulation, so all the current generated by the active load is forwarded directly to the battery.

Experimental results for mode 3 are shown in Fig. 14. The AC/DC output current is plotted in yellow. In red, the voltage load. The DC/DC current through the leakage inductance is shown in green. And finally, the DC/DC control is plotted in blue. All these waveforms are taken when the load increases its demanded power more than 2 kW. In the beginning, the DC/DC converter is off, and the AC/DC converter is feeding the load. When the load increases more than 2 kW, the AC/DC converter enters in saturation mode. This can be seen on the left of Fig. 14, where the voltage bus is less than 500 V. Then, the voltage error signal is clamped to 5 V and the high level control turn-on the DC/DC converter. After a transient process, the DAB starts regulating the voltage load again (the red curve is back to 500 V). This transient process is critical for both converters.

V. CONCLUSION AND FUTURE WORK.

This paper proposes a three-port power supply system which stored the wasted recovery energy from an active load in a battery until its later use. The converters that compose the system must behave in a different way depending on the required operation mode. The converters must control, as usual, their output or input voltage or current, but also the power supply system requires a higher level control strategy (generally digital) to change the working operation mode of the converters or even turn on and off each of them. The digital control developed gives the global system a great configurability, for example allowing easily changes in the charge profile of the battery.

A theoretical analysis of different topological options has been presented. The parallel structure proposed is the best solution in terms of cost, weight, volume and efficiency. A high level digital control strategy is proposed to control the overall three-port system. A prototype has been developed and experimental results have been obtained for each operation mode.

Based on these results some improvements have been found for future work. First of all, the PFC boost converter should be digitally controlled, in order to integrate both controllers in the same platform. Moreover, the digital PFC boost converter could be managed easier from the high level control strategy than the classical analog controller. Different power ratings could be implemented, in order to change it online based on the overall load state. In other words, different maximum peak power for saturation mode of the AC/DC converter could be achieved. Thus, the proposed three-port system can be adapted for different applications and loads ratings. The parallel proposed architecture also gives the opportunity to solve the ZVS problems in the DAB. In this sense, the DC/DC converter could be turned-on from a fixed power value that assures the ZVS condition (i.e. 800 W).

ACKNOWLEDGMENTS

This work has been supported by the Spanish Government under projects CONSOLIDER MICINN-10-CSD2009-00046 and MICINN-10-DPI2010-21110-C02-01and FPU grant AP2008-03380 and FPI grant BES-2011-044114.

REFERENCES

[1] C. Raga, A. Barrado, I. Quesada, A. Lázaro, C. Anocíbar, J. F. Sierra, “Comparison of two different electrical power architecture for electric vehicles applications based on fuel cell and supercapacitors”, IEEE Power Electronics Specialist Conference 2008 (PESC’08), pp. 1326-1330, June 2008.

[2] C. A. Ramos, C. Bordons, A. Romero, R. Giral, L. Salamero, “Minimum fuel consumption strategy for PEM Fuel Cells”, IEEE Transactions on Industrial Electronics, vol. 56, nº 3, pp. 685-696, March 2009

[3] A. Emadi, K. Rajashekara, S. S. Williamson, S. M. Lukic, “Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations”, IEEE Transactions on Vehicular Technology, vol. 54, nº 3, pp. 763-881, Mayo 2005

[4] Young-Joo Lee, A. Khaligh, A. Emadi, “Advanced Integrated Bidirectional AC/DC and DC/DC Converter for Plug-In Hybrid Electric Vehicles”, IEEE Transactions on Vehicular Technology, vol. 58, nº 8, pp3970-3980, October 2009

[5] Fernandez, A.; Ferreres, A.; Villegas, P.; Sebastian, J.; Alvarez, L.; , "Size comparison between a half bridge converter with an AICS and a two-stage boost converter operating in a narrow input voltage range," Power Electronics Specialists Conference, 2001. PESC. 2001 IEEE 32nd Annual , vol.4, no., pp.1793-1798 vol. 4, 2001

[6] Jindong Zhang; Jovanovic, M.M.; Lee, F.C.; , "Comparison between CCM single-stage and two-stage boost PFC converters," Applied Power Electronics Conference and Exposition, 1999. APEC '99. Fourteenth Annual , vol.1, no., pp.335-341 vol.1, 14-18 Mar 1999

[7] Haiping Xu; Xuhui Wen; Qiao, E.; Xin Guo; Li Kong; , "High Power Interleaved Boost Converter in Fuel Cell Hybrid Electric Vehicle," Electric Machines and Drives, 2005 IEEE International Conference on , vol., no., p.1814-1819, 15-15 May 2005.

[8] Huber, L.; Irving, B.T.; Jovanovic, M.M.; , "Closed-Loop Control Methods for Interleaved DCM/CCM Boundary Boost PFC Converters," Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE , vol., no., pp.991-997, 15-19 Feb. 2009.

[9] Nussbaumer, T.; Raggl, K.; Kolar, J.W.; , "Design Guidelines for Interleaved Single-Phase Boost PFC Circuits," Industrial Electronics, IEEE Transactions on , vol.56, no.7, pp.2559-2573, July 2009.

[10] Pit-Leong Wong; Lee, F.C.; , "Interleaving to reduce reverse recovery loss in power factor correction circuits," Industry Applications Conference, 2000. Conference Record of the 2000 IEEE , vol.4, no., pp.2311-2316 vol.4, Oct 2000.

[11] Hernando, M.M.; Fernandez, A.; Garcia, J.; Lamar, D.G.; Rascon, M.; , "Comparing Si and SiC diode performance in commercial AC-to-DC rectifiers with power-factor correction", Industrial Electronics, IEEE Transactions on, vol. 53, nº 2, pág. 705- 707, Abril 2006.

[12] R. W. DeDoncker, D.M. Divan, M.H. Kheraluwala, “A three-phase soft-switched high power-density dc/dc converter for high – power applications”, IEEE Transactions on Industry Applications, Vol. 27, pp. 63-73, January 1991.

[13] M. H. Kheraluwala, R. W. Gascoigne, D. M. Divan and E.D. Baumann, “Performance characterization of a high-power dual active bridge dc-to-dc converter”, IEEE Transactions on Industry Applications, vol. 28, pp. 1294-1301, November 1992.

[14] G. D. Demetriades, “On Small-signal analysis and control of the single and the dual active bridge topologies”, PhD. Thesis, KTH, Stockholm, Sweden, 2005.

[15] F. Krismer, J. W. Kolar, “Accurate power loss model derivation of a high-current dual active bridge converter for an automotive application”, IEEE Transactions on Industrial Electronics, vol. 57, no3, March 2010.

[16] Y. Xie, J. Sun, J. S. Freudenberg, “Power flow characterization of a bidirectional galvanically isolated hig-power DC/DC converter over a wide operating range”, IEEE Transactions on Power Electronics, vol. 25, no. 1, January 2010.

[17] F. Krismer, S. Round, and J. W. Kolar, “Performance optimization of a high current dual active bridge with a wide operating voltage range,” in Proc. IEEE PESC, Jun. 2006, pp. 1-7.

[18] F. Krismer, J.W. Kolar, “Accurate small-signal model for the digital control for an automotive bidirectional dual active bridge”, IEEE transactions on power electronics, vol. 24, no. 12, December 2009.

[19] Rodríguez, A.; Sebastian, J.; Lamar, D.G.; Hernando, M.M.; Vazquez, A.; "An overall study of a Dual Active Bridge for bidirectional DC/DC conversion", Energy Conversion Congress and Exposition (ECCE), 2010 IEEE , vol., no., pp.1129-1135, 12-16 Sept. 2010.

[20] Fernandez, A; Sebastian, J; Hernando, M.M.; Rodriguez, J., "Design Tips for a General Purpose Application PWM Inverter Based on a Low Cost Microcontroller". Power Electronics Specialists Conference, 2005. PESC ’05. IEEE 36th, pp. 786-791, 16-16 June 2005.