Battery-Utility Interface using Soft Switched AC Link Buck Boost Converter

Mahshid Amirabadi*, Hamid A. Toliyat* and William C. Alexander**

* Advanced Electrical Machines and Power Electronics Laboratory
Department of Electrical and Computer Engineering,
Texas A&M University
College Station, Texas 77840 USA
E-mail of Corresponding Author: Toliyat@ece.tamu.edu
Telephone: (979) 862-3034

** Ideal Power Converters, Inc.
Austin, Texas 78669 USA
Email: bill.alexander@idealpowerconverters.com
Telephone: (512) 560-0774

***Abstract*- In this paper a novel soft switched high frequency AC link converter is proposed for use as a battery-utility interface. The proposed configuration uses 10 bi-directional switches interfacing with an AC link consisting of an inductor and a parallel capacitance. The capacitance produces soft turn off in all operating conditions, and turn on always occurs with zero voltage. Utility scale battery systems are being developed to improve grid stability, provide peaking power, and to improve the penetration of renewable energy sources. In order to provide the required grid stabilization, power converters which can switch in a few milliseconds from charging batteries to supplying power to the electric grid are required, and this must be done at low cost with high powered converters.**

The AC link converter proposed is capable of such rapid switching speeds, due to its high frequency of internal operation. Power reversal speed is only limited by the resonance period of the input/output filters, which have low per unit reactance due to the current sourced nature of the converter and its high frequency of internal operation, which is made possible by the fully soft switched converter. Power reversal times of less than 1 ms are demonstrated by simulation.

I. Introduction

Electrical energy delivery should respond to the demand and supply instantaneously. One of the best choices is using rechargeable energy sources which can store the energy whenever there is excess energy and can supply the load during high demand times. For this purpose, high capacity battery systems which can rapidly switch between charge and discharge modes are required.

In such a system during times of excess energy, the battery will receive AC electricity from the grid. However the AC current should be converted to DC through a Power Conversion System (PCS) to be applicable for charging the battery. The DC electricity will be stored in the battery. Once stored energy is required a fast switch will be made from charge to discharge mode so that the battery can feed the load. Of course DC electricity should be converted to AC for this purpose.

Electrochemical batteries can switch between their charge and discharge modes very quickly; therefore the main challenge will be proposing a low cost and robust Power Conversion System (PCS), which can switch between charge and discharge modes rapidly.

The time to achieve power reversal on this converter is only limited by the resonance period of the input/output filters, which have low per unit reactance due to the current sourced nature of the converter and its high frequency of internal operation, which is made possible by the fully soft switched converter. Thus, with a nominal link frequency of 3,500 Hz, and a power cycle frequency double that at 7,000 Hz, the resonant frequency of our converter's I/O filters is about 1100 Hz, which allows a speed of response of less than 500 µS between full power charge and full power discharge.

II. Converter Topology and Principle of Operation

As shown in Figure 1, six bi-directional switches interface a link inductor to the three phase utility lines, while four bi-directional switches interface the same link inductor to the battery. Bi-directional power flow and battery-to-utility buck or boost is made possible by this arrangement. The converter transfers power entirely through the link inductor, which during battery discharge draws energy from the battery-side filter via the battery side switches and then discharges that same energy in a precisely controlled manner into the utility-side filter via the utility side switches. Reverse power flow occurs by simply reversing this process and may occur within one power cycle, although actual power reversals must accommodate the limited bandwidth of the I/O filters. That is, if the converter were interfacing with ideal voltage sources, power flow could be fully reversed in one power cycle (less than 150 micro-seconds with a 3.5 kHz link frequency, or a 7 kHz power cycle frequency), but actual power reversal is limited to one-half of a resonant cycle of the I/O filters, or about 550 micro-seconds for 1.1 kHz filters. This is extremely fast for a high power converter, and is about as fast as large synchronous generators can respond, but unlike generators, our converter has the advantage of having sufficient bandwidth to also produce active damping.

The AC link is formed by a low reactive rating inductor capacitor pair. In a completely indirect energy transfer operation, in the battery to utility power transfer direction (DC-AC mode) the DC input from the battery charges the link inductor. This inductive energy is then discharged to the output phases. The output current pulses are controlled precisely using an energy distribution scheme that ensures very low harmonics. In the battery charging process (AC-DC mode) the AC input from the utility charges the link inductor, and the inductive energy is then discharged to the battery.

With the available commercial switches a link frequency of 3.5 kHz may be used to for low d/dt at turn-off to produce low loss turn-off switching even with slow, higher power switches. All turn-on's are at zero voltage and turn off losses are low because of the capacitive buffer across them. The converter is essentially a PWM current source although all link flows are AC with no DC offset.

In the DC-AC converter case input switches are turned on to charge the link to the required level. The link is then allowed to resonate partially to allow it to swing to the voltage of the output phase to which it will discharge first. The link nominally discharges to two output phase pairs, the sequence and the pairs calculated so as to minimize the partial resonance times while meeting the desired harmonic levels. The various operating modes of the DC-AC converter are described below:

1) Mode 1: During this mode, depending on the polarity of the link current, S1i and S2i or S3i and S4i are turned on to allow the link to charge to a required level. The link current rises to the amount required to extract maximum power from the battery, as shown in Fig. 3.

2) Mode 2: At the end of mode 1, all the switches are turned off and the converter enters mode 2. During this mode, the link resonates partially until its voltage swings to the first output phase pair. As mentioned earlier, the link then discharges into the grid in two different modes to proportionately power the three output phases. The fact that the instantaneous sum of three phase phases is zero is used to advantage here.

3) Mode 3: Previously enabled output switches, corresponding to the selected phase pair, turn on at zero voltage as they become forward biased by the rising link voltage. The link then discharges to the output until specific system generated references are met. Again, the references are generated so as to achieve unity power factor at the output while maintaining strict harmonic levels

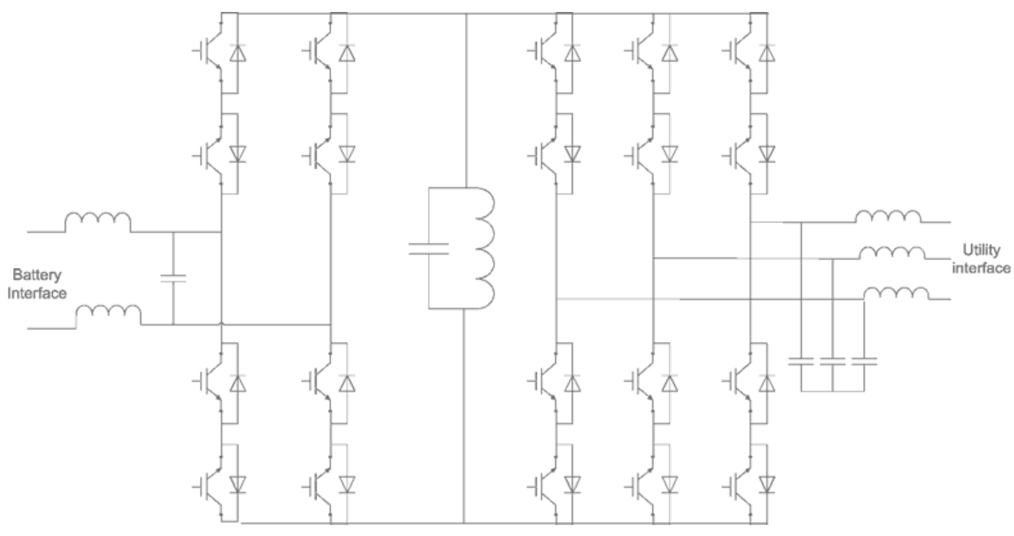
4) Mode 4: Switches are turned off to allow the link to resonate till its voltage becomes equal to the second output phase pair it will discharge to.

5) Mode 5: Switches become forward biased to allow the link to discharge to the second phase pair.

6) Mode 6: The link is allowed to partially resonate back to the input voltage to start the next charging cycle. Modes 7 to 10 are identical to modes 1 to 5 except that the link current is in the reverse direction. This can be seen in Fig. 3.

When the converter works in the AC-DC mode, there will be again 10 modes. During modes 1 and 3 the link will be charged through the utility and in mode 5 the energy stored in the link will be discharged into battery which will result in charging the battery.

Again modes 2, 4 and 6 are partially resonant modes. Figures 4 and 5 represent the AC-DC converter case.



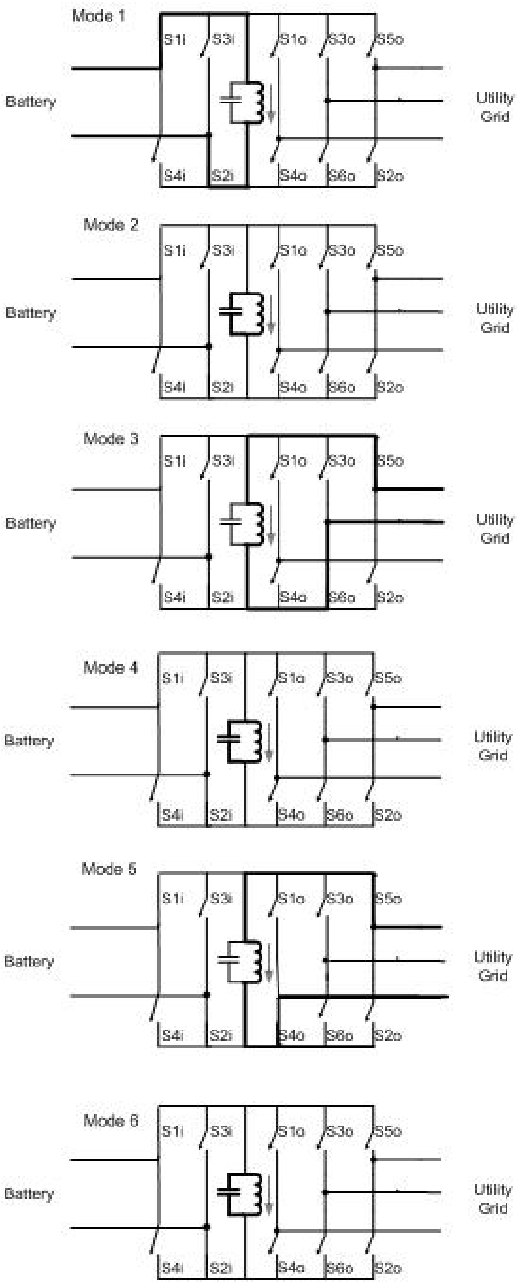


Figure 2 Circuit conditions for different modes for DC-AC case

The link inductor essentially has three operating states: 1. switched into the battery filter, 2. switched into the utility line filter, and 3. switched to neither side, when it exchanges current with the link capacitor and changes voltage polarity with restrained du/dt. The latter feature is the key to our converter's unique and highly advantageous properties, as the low du/dt produces a very soft turn-off, turn-on, and reverse recovery, giving very low switching losses despite the high power cycle frequency and the use of relatively slow IGBTs and rectifier grade diodes. The slower power devices allow for high power density and low switch costs. Each of these three states also has alternating polarities of link current. Note that the utility and battery side lines are never connected together, a feature which eliminates the need for transformers when multiple converters are used in parallel, as will likely normally be the case in large installations. This allows a single, much larger, more efficient, and lower cost transformer to be used to interface the battery storage facility to the utility.

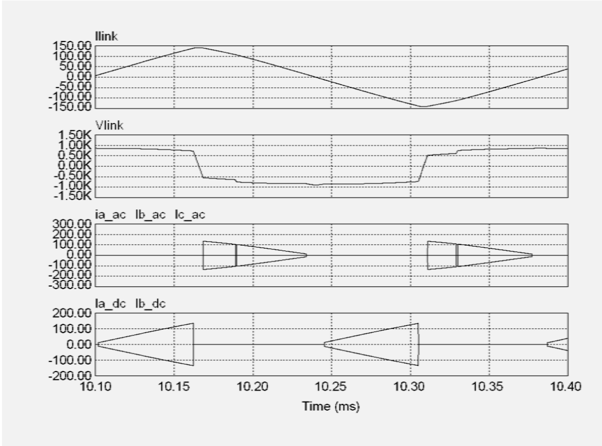


Figure 3 Relevant converter waveforms for DC-AC case

III. Simulation and Experimental Results

Simulations are performed for a 25kWconverter with a unity power factor. In these simulations at first the battery is discharging and the converter acts as DC-AC until 18ms, at this point, the load is decreased which means the battery can be charged, so the converter is turned off and after a few cycles it restarts working, but this time as an AC-DC converter to charge the battery. Figure 6 and 7, represents the DC side and AC side currents. As it can be seen the currents are smooth.

Figures 8 and 9 show the link voltage and link current, respectively. The DC side and the Ac side filtered voltages are represented in figures 10 and 11.

Bothe active and passive damping have been used in these simulations. Figure 12 represents some experimental results for a 15 kW prototype running at 15 kW. Link voltage and link current waveforms are shown in that figure. Voltage is 200V/div, and current is 50A/div, time is 40 µS/div. The small forward recovery voltage overshoot of the rectifier diodes can be seen at turn on. The low du/dt on the voltage is noticeable here.

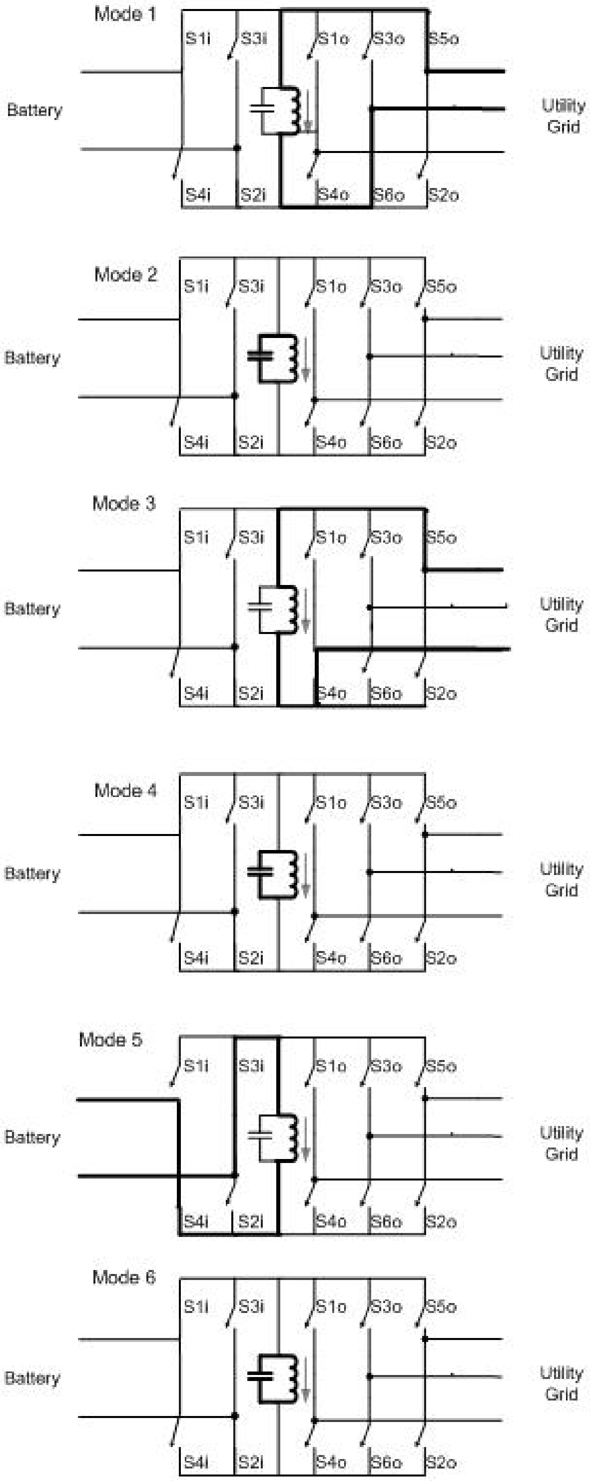


Figure 4 modes of operation for AC-DC case

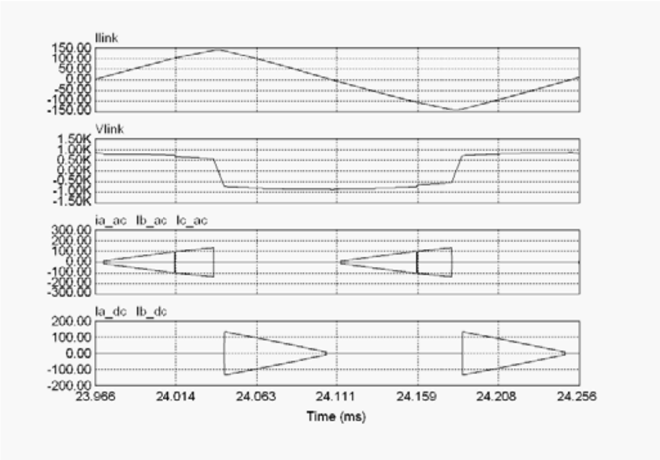


Figure 5 Relevant converter waveforms for AC-DC case

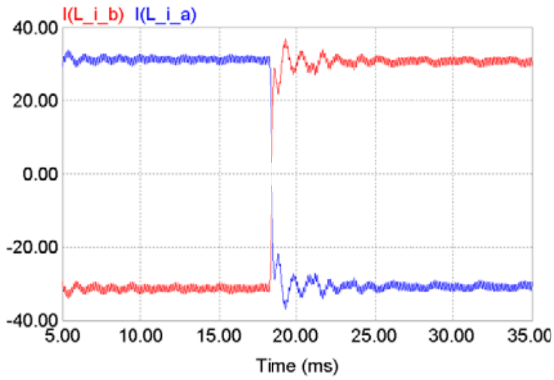


Figure 6 DC side Current

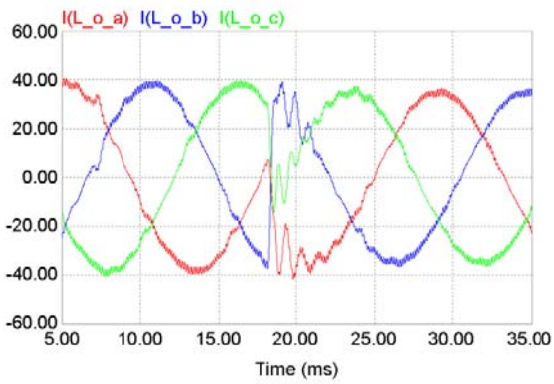


Figure 7 AC Current

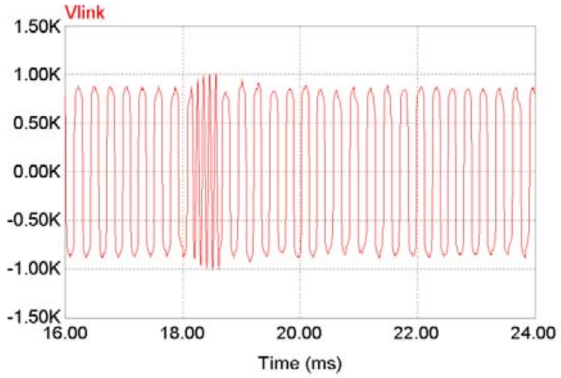


Figure 8 Link Voltage

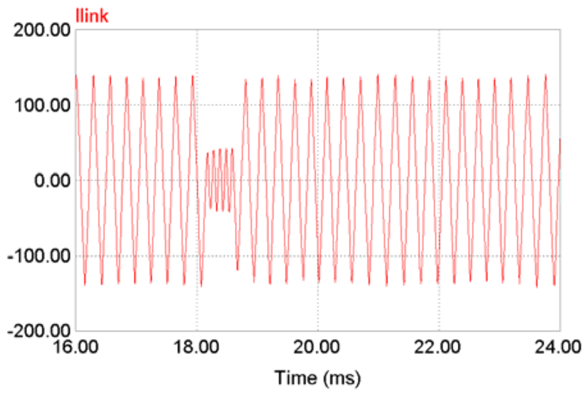


Figure 9 Link Current

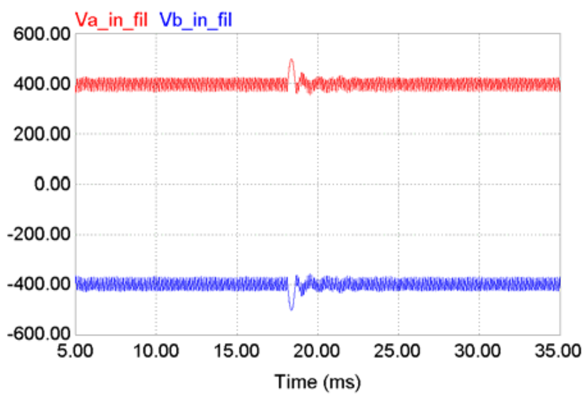


Figure 10 DC Side Voltages

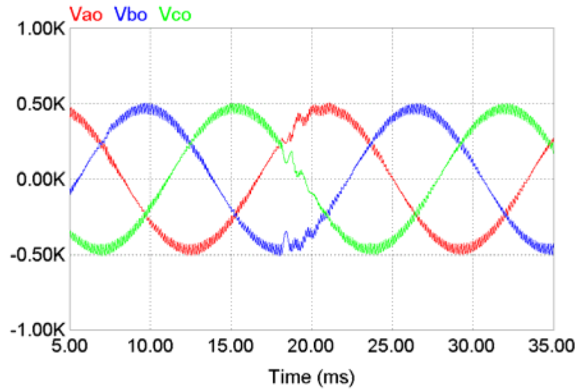


Figure 11 AC Side Voltages

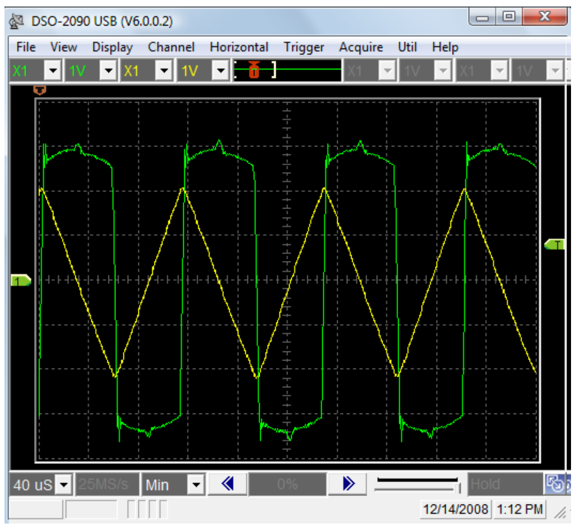


Figure 12 Link voltage and Link Current-experimental result

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