Soft Switched Ac Link Buck Boost Converter

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Abstract- **A novel soft switching high frequency link converter for medium and high power ac-ac and ac-dc applications is proposed. The proposed topology overcomes the shortcomings of conventional dc and ac link schemes and uses 12 bidirectional switches for a three phase to three phase configuration. An inductor-capacitor pair with low reactive rating forms the link. Switches turn on at zero voltage and their turn offs are capacitance buffered, resulting in low switching losses. Phase currents are synthesized using precisely controlled current pulses, which also allows for any desired input or output voltage or power factor. The converter can perform buck and boost operations in forward and reverse directions. The proposed topology promises size, weight and cost reduction while offering improved performance compared to existing converters.**

I. INTRODUCTION

Variable frequency drives typically have employed dc voltage or current links for power distribution between the input and output converters and as a means to temporarily store energy. The dc link based power conversion systems have several inherent limitations. One of the important limitations is the high switching loss and high device stress which occur during switching intervals. This severely reduces the practical switching frequencies. Additionally, while the cost, size, and weight of the basic voltage sourced PWM drive is attractive, difficulties with input harmonics, output dV/dt and overvoltage, EMI/RFI, tripping with voltage sags, and other problems significantly diminish the economic competiveness of these drives. Add-ons are available to mitigate these problems, but may result in doubling or tripling the total costs and losses, with accompanying large increases in volume and weight.

High frequency ac link converters have been suggested as an improved alternative. A high-frequency link allows the flexibility of adjusting the link voltage to meet the individual needs of the source and load sides and at the same time provides isolation between the two [1]. High frequency link converters improve the speed of response, and if the frequency is outside the audible range, reduce acoustic noise [2]. High frequency link power conversion has been employed very successfully in dc-dc converters [3]-[6]. This demonstrated the advantages and also the difficulties in working with high frequency links. Problems were associated with circuit topologies and also device capabilities. With increase in demand and with advancements in semiconductor technology, switches specifically designed for high frequency applications are becoming available. The use of resonant circuits in high frequency dc-dc converters has since been reported [7].

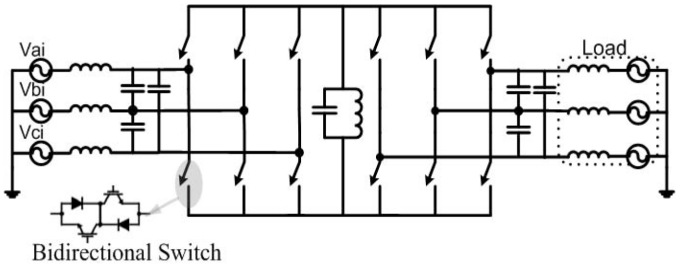


Fig. 1: Schematic of proposed topology

Ac-ac and dc-ac converters employing high frequency ac links have also been reported [8]-[12]. Most of these converters are designed for specific type of source/loads. Reference [1] reported a topology that provided one-step bidirectional power conversion for different kinds of loads/sources. This configuration used twelve bidirectional switches and employed Pulse Density Modulation (PDM) as a means to control the currents. The use of PDM reduces the system response because of usage of integral pulses of currents. Topologies that make use of twelve unidirectional switches, by providing a dc offset to the dc link, have also been suggested. Reference [13] proposes a topology with twelve unidirectional switches, without the dc offset. However, it is limited in operation response due to its inability to supply output current at low voltages or power factors, at link frequencies sufficiently high to avoid input/output filter resonances. Also, there is a large dead time due to the resonant 'fly back' which reduces the power capability by about 30%. This largely negates its advantage of using a lower numbers of switches compared to the proposed topology.

In this paper, a new soft switching ac link converter that overcomes the aforementioned drawbacks while offering superior control and significant economic advantage is proposed. It consists of 12 bidirectional switches and an ac link composed of a low reactive rating inductor-capacitor pair. The link is charged via high frequency current pulses from the inputs. The link so charged discharges into the outputs in a similar fashion. The current pulses are precisely modulated such that when filtered, they achieve unity power factor at the input while also meeting the reference output currents.

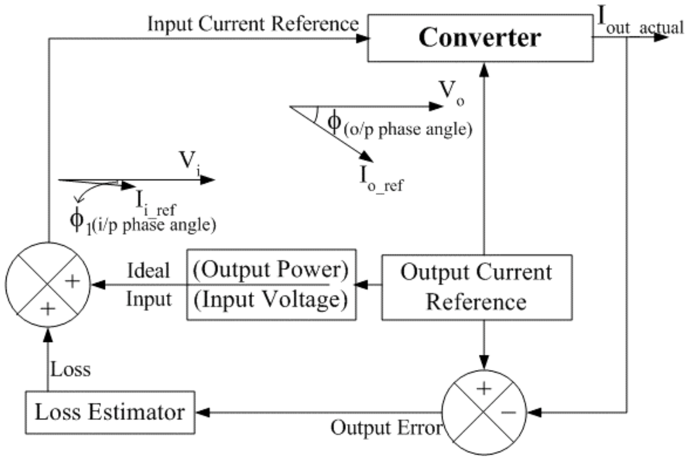


Fig. 2: Block diagram to show how the input reference is derived

Filtering is done by low-cost, low-loss and light weight capacitors. Inputs never directly connect to the outputs and hence there is inherent isolation between the two, which avoids any common mode voltage and enables grounding of both input and output neutral points. Full I/O galvanic isolation may be provided by a split winding version of the link inductor. Symmetrical arrangement of the power circuit also provides fully regenerative operation together with buck-boost capability. Simulation results are presented to back up the proposed topology. A 15 kW prototype is presently under construction.

II. PRINCIPLE OF OPERATION

The proposed soft switching bidirectional ac link converter is shown in Fig. 1. It consists of two full bridge circuits composed of reverse blocking bidirectional switches, a link composed of low reactive rating inductance and capacitance, and the filter capacitors.

The converter operates by charging the link from the inputs and then discharging the stored energy to the output. The converter is fed with the output current references. The link is charged to an amount which makes the discharging current exactly meet these references. Since charging and discharging take place separately, an estimate of how much the link needs to be charged to supply the output correctly is required. The controller handles this by translating the output references to input references. The input reference is derived by the simple equation that

$$\text{Input Power} = \text{Output Power} + \text{Losses}. \qquad (1)$$

Fig. 2 shows a block diagram of how the system works. RMS value of the output reference current is used to determine the RMS of the input current for an ideal converter. A loss component is added to this from the loss estimator to get the exact input command. The instantaneous value of the output reference commands could be phase shifted with respect to the output voltages as the load demands. Normally, the instantaneous values of the input current commands are in phase or are phase adjusted with respect to the input voltages so as to achieve unity power factor, but non-unity power factor may also be achieved if desired.

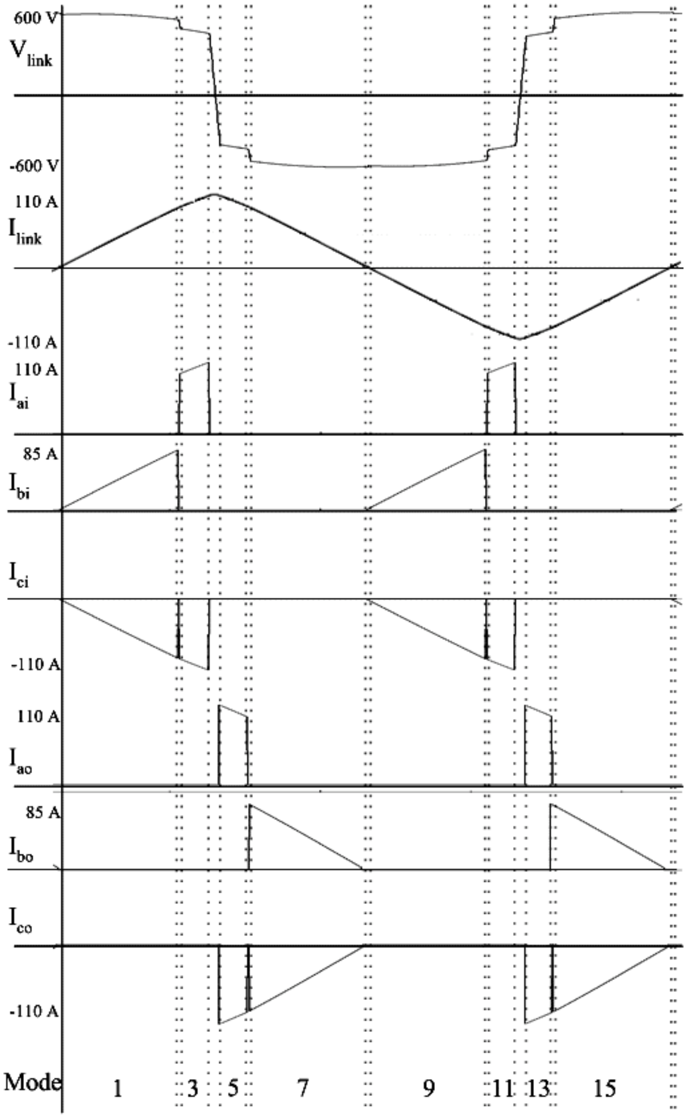


Fig. 3: Typical waveforms illustrating the operating principles of the proposed converter

Modes of Operation:

Each link cycle is divided into 16 modes, with 8 power transfer modes and 8 partial resonant modes taking place alternatively. Fig. 3 shows the important current and voltage waveforms over one link cycle. For a 15 kW, 460 V converters the link oscillates at about 10 kHz. Power is transferred twice during each link cycle. This is roughly at 20 kHz, thereby resulting in superior control and lesser filtering requirements. Zero voltage turn-on and capacitance buffered turn-off enables operation at this frequency. Medium voltage converters employing this topology are expected to have a link frequency of about 2.5 kHz.

There are three basic operations taking place through the 16 modes: energizing, partial resonance, & de-energizing. Modes 2, 4, 6, 8, 10, 12, 14 and 16 are the partial resonant modes and as evident from Fig. 3, they make up only a very small fraction of the link cycle time. The link is energized from the inputs during modes 1, 3, 9 and 11 and is de-energized to the outputs during modes 5, 7, 13 and 15. The various operating modes are explained below and their respective circuits are given in Fig. 4 and Fig. 5.

Mode 1 (Energizing): The link is connected to the input voltage pair having the highest voltage via switches which charge it in the positive direction. For the waveforms shown in Fig. 3, the link is connected to input phase pair BC through switches S3i and S2i. The link charges till I_{bi} averaged over cycle time, meets its reference value calculated from (1). The switches are then turned off.

Mode 2 (Partial resonance): The link capacitance acts as a buffer across the switches during turn off. This results in low turn off losses. All switches remain turned off and the link resonates till its voltage becomes equal to that of the input phase pair having the second highest voltage. This is the phase pair the link charges next from. In the example shown in Fig. 3, the link resonates till the link voltage becomes equal to V_{aci}.

Mode 3 (Energizing): Switches are turned on to allow the link to continue charging in the positive direction from the input phase pair having the second highest voltage. At the end of mode 2, the link voltage equals the voltage of this phase pair. Hence at the instant of turn on, the voltage across the corresponding switches is zero. This implies that the turn on occurs at zero voltage as the switches transition from reverse to forward bias. In the example in Fig. 3, the link charges till I_{ci} averaged over cycle time, meets its reference value calculated from (1). The switches are then turned off.

Mode 4 (Partial resonance): During this mode the link is allowed to swing to one of the output line voltages. The sum of the output reference currents at any instant is zero. One of them is the highest in magnitude and of one polarity while the two lower ones are of the other polarity. The converter uses this simple property to avoid any resonant swing back in the link. The charged link transfers power to the output by discharging into two output phase pairs. The two phase pairs are the one formed by the phase having the highest reference current and the second highest reference current, and the one formed by the phase having the highest reference current and the lowest reference current, where the references are sorted as highest, second highest and lowest in terms of magnitude alone. For example, if I_{ao}=10 A, I_{bo}=-7 A and I_{co}=-3 are the three output reference currents then phase pairs AB and AC are chosen to transfer power to the output. If V_{ab_o} and V_{ac_o} are the instantaneous voltages across these phases and V_{link} is the link voltage, the phase pair whose voltage has minimum difference with respect to V_{link} is chosen as the first one to discharge to. For example if V_{link}=500 V, V_{ab_o}=400 V and V_{ac_o}=300 V, AB is chosen as the first phase pair to discharge to.

Mode 5 (De-energizing): The output switches are turned on at zero voltage to allow the link to discharge to the chosen phase pair till the output current averaged over the cycle equals

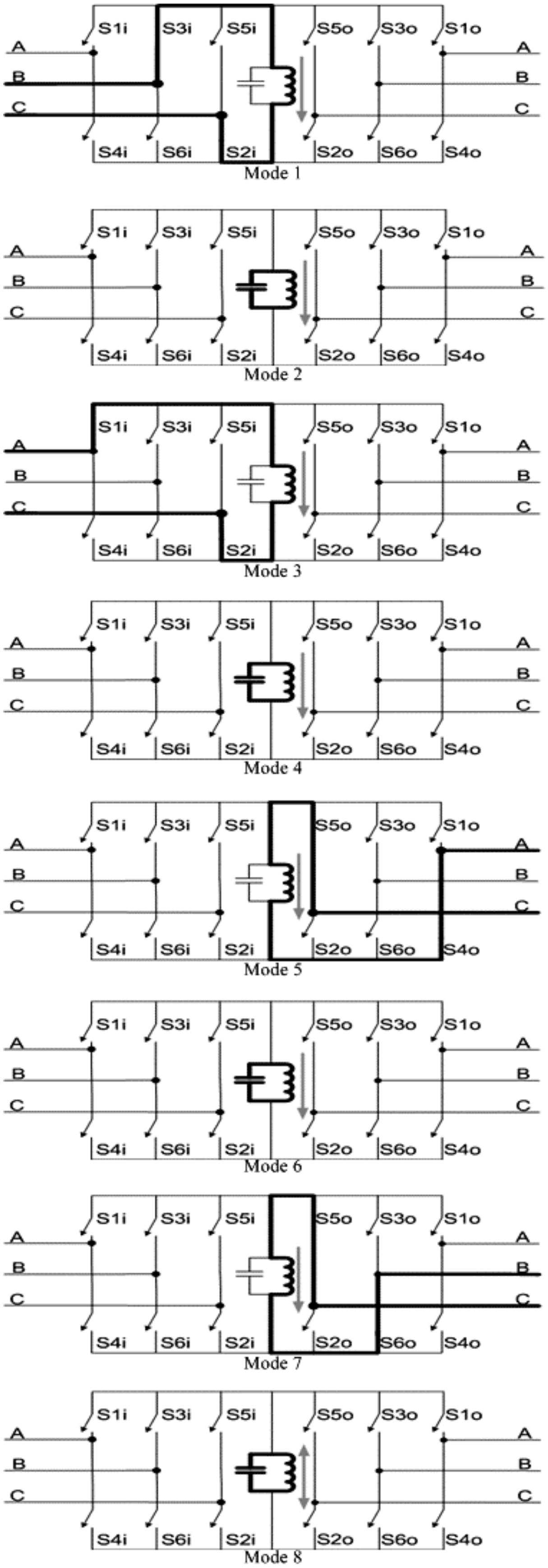


Fig. 4: Operating modes 1 to 8

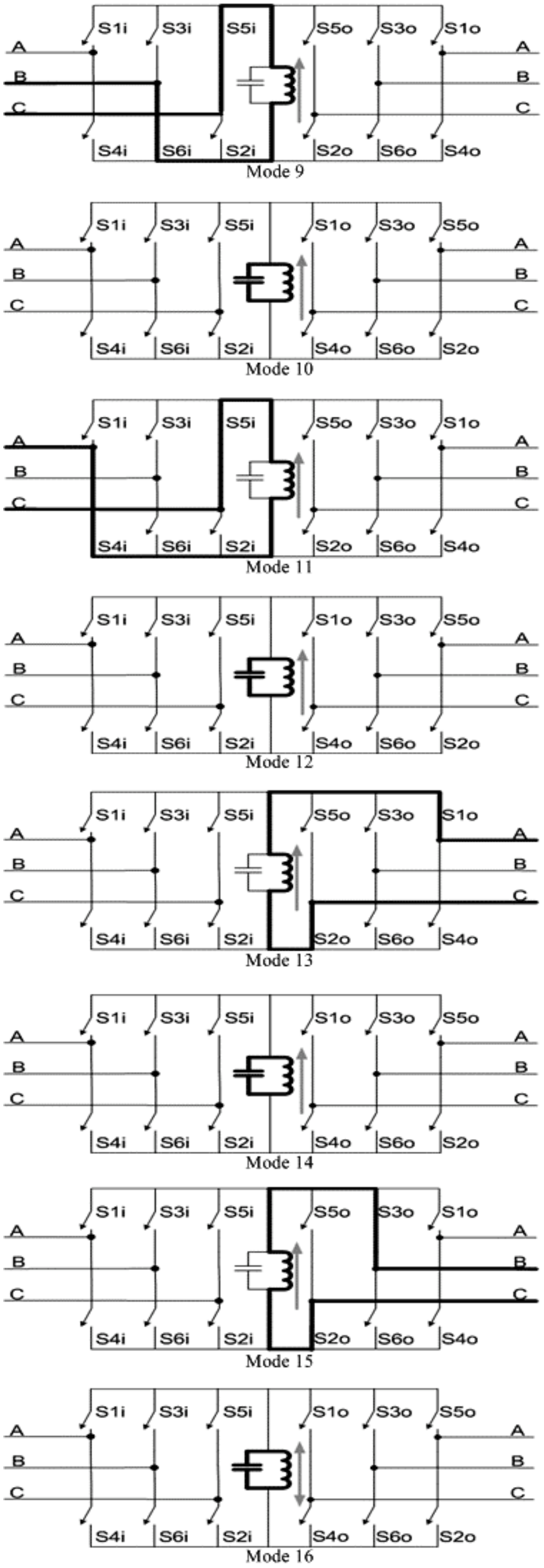


Fig. 5: Operating modes 9 to 16

the reference value of the lower phase.

Mode 6 (Partial resonance): All switches are turned off and the link is allowed to swing to the voltage of the other output phase pair chosen during Mode 4. For the example discussed before, the link voltage swings from V_{aco} to V_{bco}. This is also illustrated in Fig. 3.

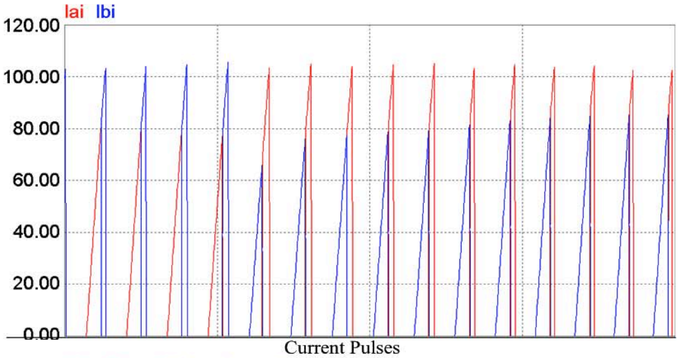
Mode 7 (De-energizing): During mode 7, the link discharges to the selected output phase pair till there is just sufficient energy left in the link for it to swing to the input phase pair having the highest voltage. When the losses are determined accurately, this would mean that the output references are accurately met. Any deviation from this is detected and the losses re-estimated to eliminate this error.

Mode 8 (Partial resonance): The link swings to the input phase pair having the highest voltage to be ready to charge the link in the reverse direction.

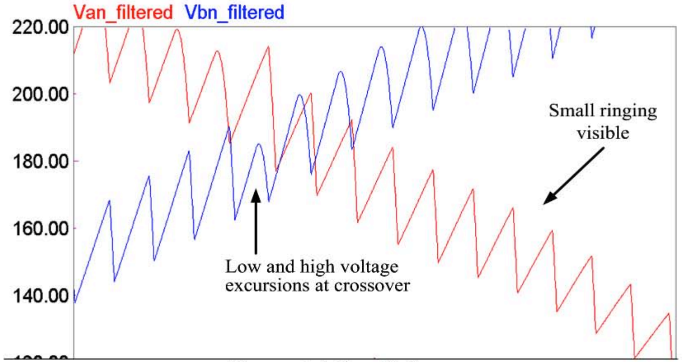
Modes 9 through 16 are similar to modes 1 through 8, except that the link charges and discharges in the reverse direction. For this, the complimentary switch in each leg is switched when compared to the ones switched during modes 1 through 8. This is seen comparing Fig. 4 and Fig. 5.

It is observed that the input is never directly connected to the output resulting in proper isolation between the two. Fully galvanic isolation can be achieved by using an isolation transformer in place of the link inductor. It can also be observed that the converter can operate without that link capacitor. However, since the topology is tolerant to such capacitance, a low cost, light weight, and efficient link inductor with high parasitic capacitance can be used. The inductor being used in a 15 kW three phase prototype weighs less than 5 Kg, with less than 3 Kg for the input line reactance, as compared to over 70 Kg for the input and output filters alone for a 15 kW VS-PWM drive required to produce comparable low harmonics on the input and output. Additional capacitance may be advantageously added to buffer turn-off losses, with the optimal link capacitance determined by balancing reduced turn-off losses against the resulting slight decrease in power throughput.

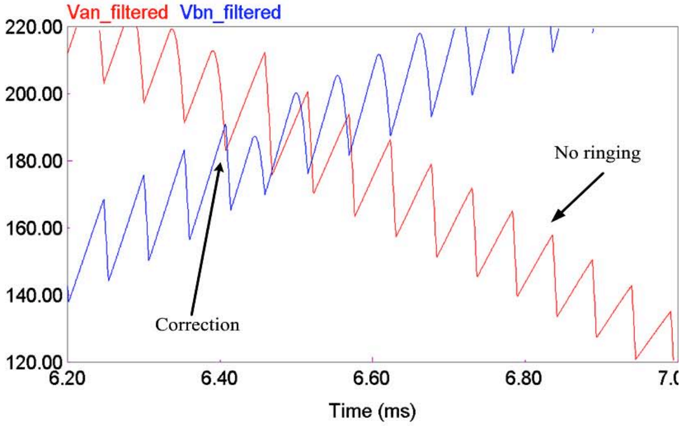
It must be noted as important that the current pulses are precisely modulated so that they are sinusoidal when filtered via the LC filters. Even slightly improper modulation triggers off ringing in the LC filters which should be avoided. One situation where there is ringing in the LC filters in spite of proper modulation of the current pulses is when the voltage of two phases cross each other. This situation is illustrated in Fig. 6. At the crossovers, the order of charging from the input phases reverses. The result is that the current pulse from the increasing phase is advanced whereas that from the decreasing phase is delayed. This causes the respective phase voltages to deviate from being sinusoidal and this triggers off small ringing in the filters. To avoid this problem, the controller uses a predictive algorithm to detect crossovers and draws a small



Current Pulses



Uncorrected Phase Voltages



Corrected Phase Voltages

Fig. 6: Required correction at voltage crossovers

percentage of extra charge from the decreasing phase. The correction and its effect are illustrated in Fig. 6.

III. SIMULATION RESULTS

Simulations were carried out for a 15 kW converter with unity power factor load. Both input and output were at three phase at 460 V. The link capacitance was 0.2 μF and the link inductance was 140 μH. Input current ripple with a 1500 Hz filter as shown in Fig. 7 is so small as to be almost imperceptible. The link voltage and current waveforms are shown in Fig. 8. Fig. 9 demonstrates the ability of the converter to operate with differing input and output common mode levels. Input and output voltages are phase shifted by about 50^{o} in Fig. 9. Fig. 10 shows the circuit board and the link inductor of the 15 kW prototype under construction. Fig. 11 shows the schematic used for simulation.

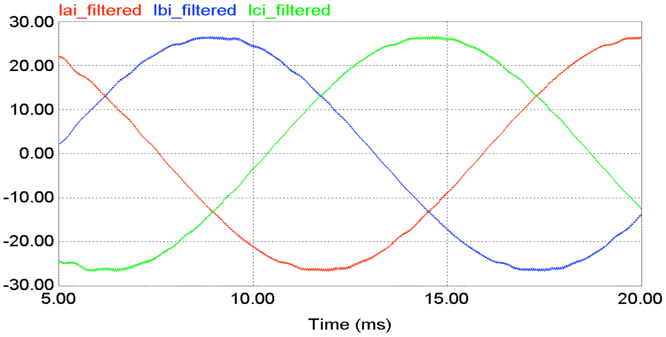


Fig. 7: Input Currents

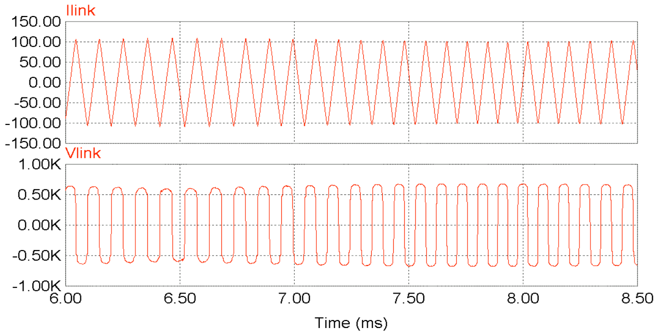


Fig. 8: Link current and voltage

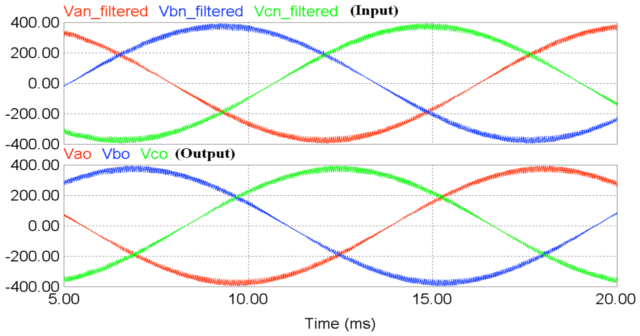


Fig. 9: Input and output voltages phase shifted to demonstrate isolation between input and output

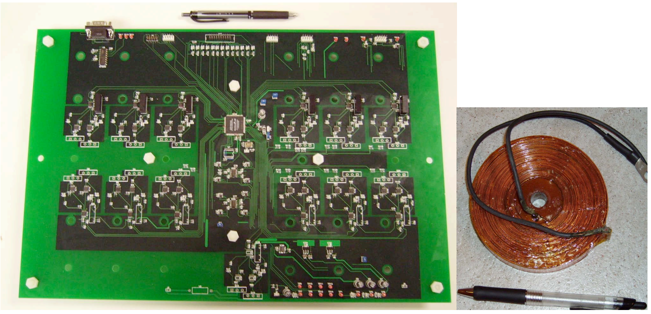


Fig. 10: Circuit board and link inductor of prototype under construction

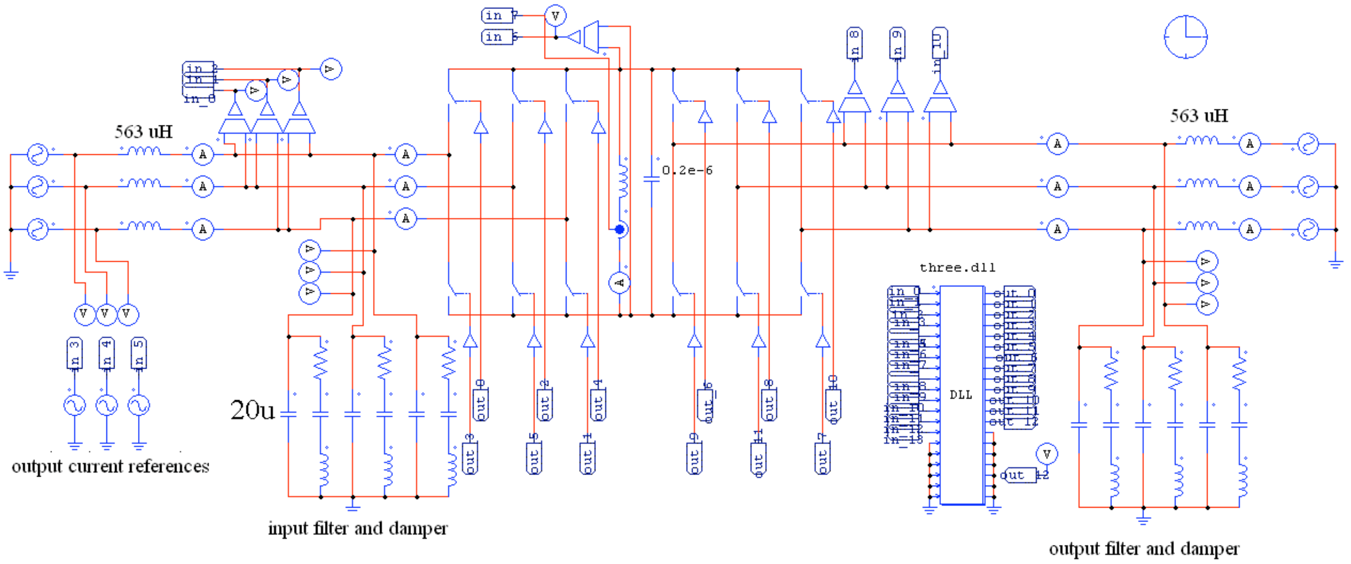


Fig. 11: Schematic used for simulation

IV. CONCLUSION

The Soft Switched AC-Link Buck-Boost Converter may be utilized in a wide variety of applications ranging from low and medium voltage motor drives, to transformer-less solar inverters, large wind power converters, isolated ac-ac and ac-dc bi-directional converters, and many other applications that may benefit from its conversion versatility, soft-switching efficiency, input-output isolation, and high power quality. The topology is expected to offer relatively low cost, low weight, compact and efficient power converters and motor drives.

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