Research Report

96-07

Double Bridge Resonant DC Link Converter with Variable Input and Output Frequency

A. Julian, D. Divan, T. Lipo, F. Nozari, P. Mezs

Wisconsin Power Electronics Center
University of Wisconsin-Madison
Madison WI 53706-1691

Boeing Corporation
PO Box 3707
Seattle WA 98124-2207

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

Double Bridge Resonant DC Link Converter with Variable Input and Output Frequency

A. Julian, D. Divan, T. Lipo
University of Wisconsin, Madison
1415 Johnson Drive
Madison, WI 53712

F. Nozari, P. Mezs
Boeing Aircraft Company
Seattle, WA

Abstract - A bi-directional resonant DC link (RDCL) converter is presented for use as a variable frequency to variable frequency (VF-VF) sinusoidal three phase power converter for aerospace applications. Three phase sinusoidal input up to 750 Hz and sinusoidal output up to 400 Hz is achieved using second order filters on the input and output of the converter. The results demonstrate active damping of the input and output resonance conditions. Input and output conducted current emissions, which contribute to inductively coupled EMI, are shown to be low. High efficiency, high power density, small DC bus capacitance and unity input power factor are some of the attributes of this converter topology.

1. INTRODUCTION

The aircraft industry is moving towards a more electrically operated aircraft. Hydraulic lines will be replaced with electric power distribution, and will perform actuator functions using a mixture of electro-mechanical and electro-hydraulic power conversion. Power converters will be used extensively to interface the aircraft's distribution bus to application specific loads.

It has been proposed that the aircraft distribution bus be a variable frequency bus which is connected directly to the aircraft generator or ground power supply. The frequency could vary from 50 to 1000 Hz. Many of the load functions also require bi-directional power flow. Given the proliferation of electronic loads on the aircraft bus, it is also clear that the input stages of these converters will need to have low harmonic distortion. A final important specification concerns the aircraft's susceptibility to electromagnetic interference (EMI). Conventional hard switching power converters are significant generators of narrow band EMI over a large frequency range which is difficult to suppress and adequate EMI containment becomes critical in assessing their suitability for this application. An alternate approach, using soft switching principles, is seen to generate significantly lower EMI, making it much easier to filter the remaining EMI.

The last decade has seen a proliferation of soft switching converters which have been proposed for various applications, such as motor drives, active filters and UPS systems [1]. The resonant dc link inverter was one of the first zero voltage switching inverters proposed, and features desirable properties for such an application. In particular, the topology chosen, i.e. the passively clamped resonant dc link inverter, has the highest link frequency for best spectral response, and the lowest dv/dt's for the lowest EMI. A bi-directional form of the converter was proposed in [2], and is chosen here as the topology of choice.

The objective of this paper is to describe the development of a soft switching bi-directional converter (BDC) to realize a low EMI converter for aerospace applications. It is shown that the softer transition of the resonant DC link (RDCL) converter generates broad band EMI over a narrower frequency range. The measured inductively coupled current is presented for comparison with relevant standards. In addition, the RDCL inverter has high efficiency, good dynamic response and is capable of high power density. This paper is intended to demonstrate, in hardware, the favorable operating characteristics of the RDCL inverter.

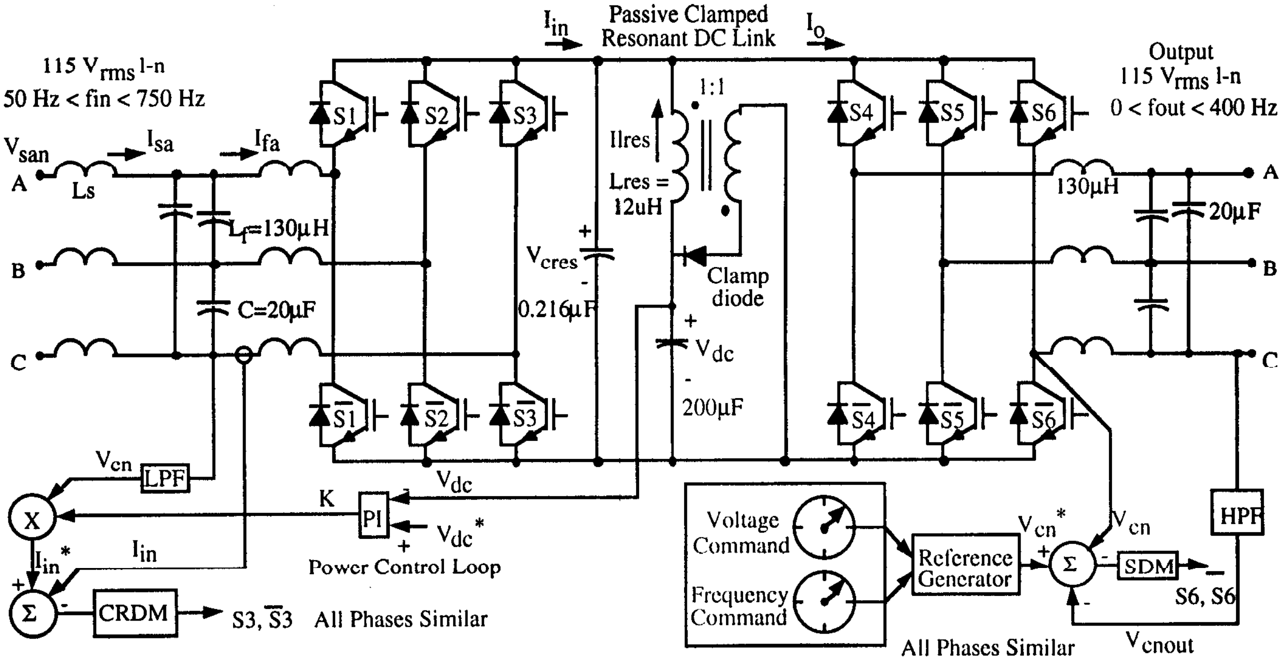
2. POWER CIRCUIT

Fig. 1 presents the converter topology and all of the control loops necessary to implement the entire power conversion system. This converter is an excellent demonstration of the integration of many new power conversion and control ideas into one system. This project demonstrates soft switching, active damping, passive filtering, coaxial transformer technology, pulse density modulation, bidirectional power flow and DC bus capacitance reduction all integrated into one system and shows that these concepts are very complementary. The fact that these ideas could be integrated together to achieve the desired sinusoidal power conversion received much skeptisism in the beginning.

The circuit used is the BDC shown in Fig. 1. The output stage consists of a resonant dc link inverter, with an LC filter on the output for generating the sinusoidal voltage required. The input stage is an active rectifier connected to the same resonant dc link, allowing all twelve devices to operate under zero voltage switching conditions. An input LC filter is also used to reduce the input current total harmonic distortion (THD). The overall ratings of the converter built are given below:

Input Rectifier:	
Voltage Rating:	205 V l-l rms
Frequency Range:	60 to 750 Hz

Power Rating:	20 kVA
Output Inverter:	
Voltage Rating:	205 V l-l rms
Frequency Range:	0 to 400 Hz
Power Rating:	20 kVA
System Efficiency:	93 % at 10 kVA
Power Density:	0.5 kVA/lb



-Resonant inductor is magnetizing inductance of coaxial transformer.
-Coaxial transformer provides overvoltage protection for IGBTs.
-Resonant frequency of converter is 100 kHz.

Fig. 1 Converter Topology

The double bridge RDCL converter is comprised of two converters connected through a resonant dc link as shown in Fig. 1. The output inverter is an active three phase inverter. The high frequency content of the inverter pole voltage is filtered by a second order filter, realizing sinusoidal output waveforms across the 20 μF capacitors of the filter. Additionally, the capacitor voltages are fed back to the voltage regulator through a high pass filter (HPF) to actively dampen oscillations between the output capacitor and an inductive load [3]. Sigma delta modulation (SDM) [4,5] is used to control the output pole voltages. This modulation strategy of a 100 kHz resonant link yields a wide bandwidth of control for active damping, allowing the filter size to be reduced. Fig. 2 shows the voltage gain of the converter output with and without active damping. The large gain represents the point where resonance can occur. It can be seen that the resonant condition is completely eliminated with the use of active damping.

The absence of the active damping control loop for an induction motor load can be seen in Figs. 3 and 4. Fig. 3 shows the voltage and current in one phase of an induction machine at 225 Hz with active damping working. Fig. 4 shows the same operating point after the active damping has been disabled. The resonant frequency which appears in Fig. 4 has the potential to exceed the bandwidth of the converter.making it uncontrollable This is especially true for a low inductance electrical machine. The RDCL extends the bandwidth of the converter through soft switching, expanding the useful frequency range of the active damping control loop. The commanded voltage and frequency are controlled by the operator. Figs. 5 and 6 show the time domain voltage and current wave forms for the output of the

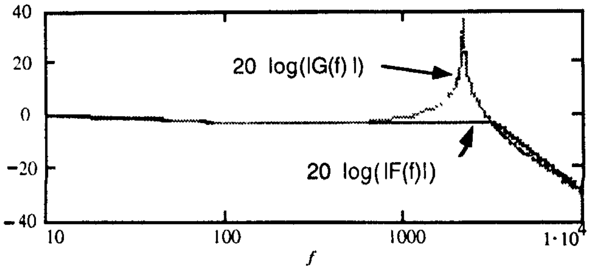


Fig. 2: Output Voltage Gain vs. Frequency with (F) and without (G) Active Damping

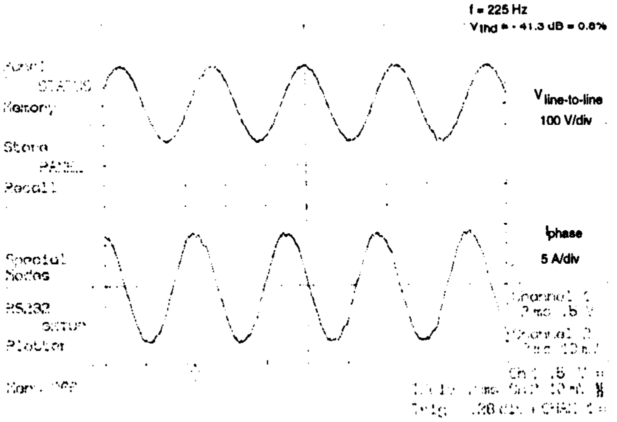


Fig. 3: Induction Motor Voltage and Current at 225 Hz with Active Damping in Operation

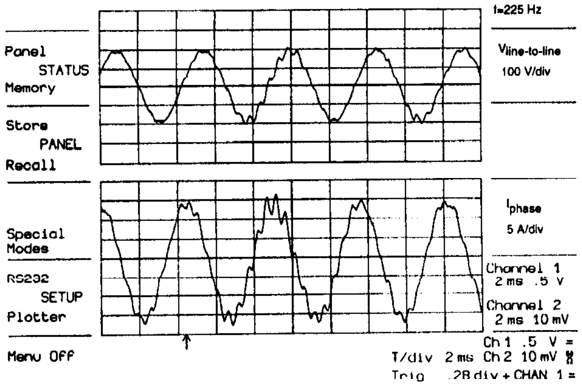


Fig. 4: Induction Motor Voltage and Current at 225 Hz with Active Damping Disabled

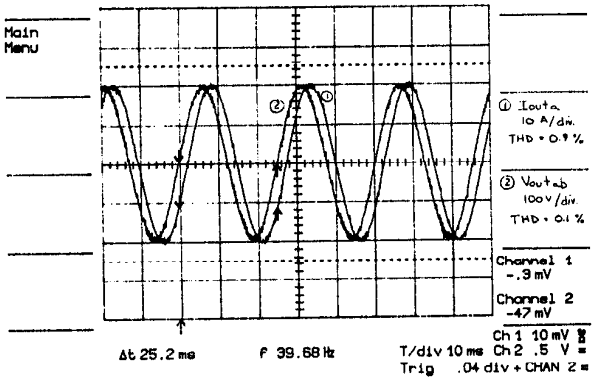


Fig. 5: Output Voltage and Current at 40 Hz

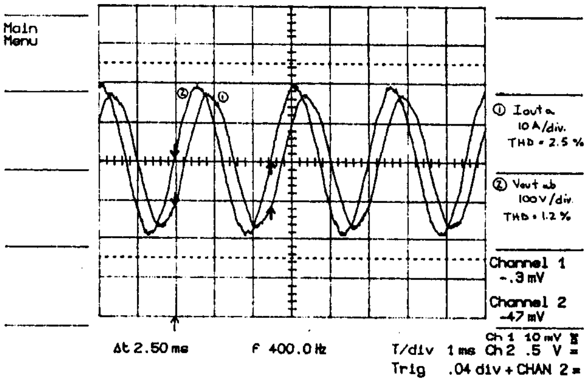


Fig. 6: Output Voltage and Current at 400 Hz

converter at different operating frequencies (40 and 400 Hz) demonstrating that sinusoidal voltage operation has been obtained over a wide frequency range. Over the first twenty harmonics of the output fundamental voltage the THD is one tenth of one percent at 40 Hz. The THD increases to 1.2 % at 400 Hz yielding sinusoidal output.

In order to achieve bi-directional power flow an active rectifier is used to interface the RDCL with the source. The active rectifier draws sinusoidal currents at unity power factor from a three phase source through a second order filter (Fig. 1). Current regulated delta modulation (CRDM) [3] of the 130 μH inductor current of the rectifier filter is used to control the rectifier input currents. Fig. 7 shows the source current and voltage at 60 Hz. The THD of the source voltage is 3.4 %. The THD of the source current is 5.9 %. Measurements for Fig. 7 were made with the output power at 5 kW. The converter was tested up to an input frequency of 750 Hz in the lab.

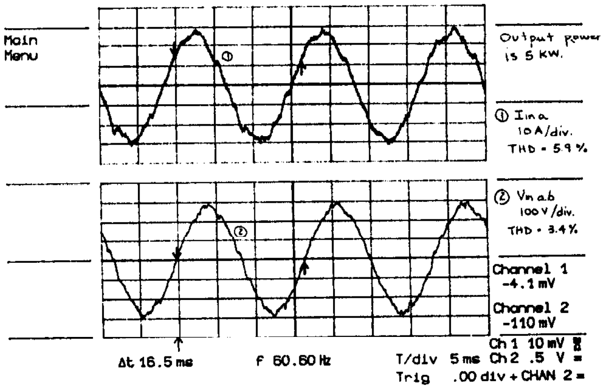


Fig. 7: Input Voltage and Current at 60 Hz and 5 kW

The input filter capacitor has the potential to resonate with the source inductance. This resonance condition is potentially a real problem that will require active damping to control however the input power control loop inherently provides active damping to the rectifier. The damped second order behavior of the input current regulator as it is implemented is a very useful property of the power control loop. Fig. 8 is a simplified model of the rectifier power control loop. Eq. 1 expresses the capacitor voltage gain due to the source voltage excitation. The power level of the converter, which is proportional to K, is seen to impact the active damping of the rectifier (Eq. 2). The inherent active damping of the input side of the converter is an attractive feature of this control scheme.

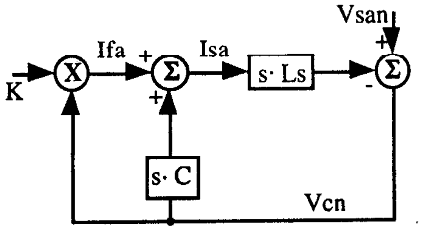


Fig. 8 Block Diagram of Rectifier Control Loop

$$\frac{V_{cn}}{V_{san}} = \frac{1}{L_s \cdot C} \cdot \frac{1}{s^2 + s \cdot \frac{K}{C} + \frac{1}{L_s \cdot C}} \tag{1}$$

$$3 \cdot V_{cnrms}{}^2 \cdot K = P_{in} \tag{2}$$

A. Resonant DC Link

Power balance between the input and output of the converter is realized by regulating the DC bus voltage using a PI regulator as illustrated in Fig. 1. The DC bus voltage between the two converters is controlled by measuring the DC bus error and feeding it through a PI compensator to establish the amplitude of the input reference current, K, shown in Fig. 1. Multiplication of K times the capacitor line to neutral voltage provides a unity power factor reference wave form for the input current regulator.

The DC output of the PI regulator is modulated by the filter capacitor voltage to provide the reference current for the rectifier. Reducing the gain of the PI regulator would attenuate undesirable spectral content from the DC bus that appears in the current reference, reducing input current distortion. However, reducing the PI gain would effect dynamic performance and increase DC bus ripple. This is especially important because the DC bus capacitance is very small (200 µF). As shown in [6] reducing the PI gain can be compensated by feeding the load power forward to maintain dynamic performance levels while reducing unwanted source distortion. Feeding the load power forward improves the step response of the converter. The load current feed forward loop was not implemented in this converter.

The link provides a sinusoidal voltage oscillation at 100 kHz across all switch modules. Resonance occurs between the magnetizing inductance of the coaxial transformer (12 µh) and the 0.216 µF resonant capacitor (Fig. 1), allowing soft switching to occur and dramatically reducing the dV/dt seen at the poles of the converter. The resonant link voltage is the essential aspect of the resonant link which:

- Reduces EMI emissions
- Increases the efficiency by reducing switching losses
- Allows for higher switching frequencies to increase converter bandwidth

The design of magnetic components in resonant converters can have an enormous impact on the performance of the converter. Selection of core material and conductor geometry for inductors and transformers is a topic of ongoing research at the WEMPEC labs. Much attention is being focused on minimizing the losses in magnetic designs. For this converter molypermalloy powder cores (MPP) were used to simplify the magnetics design problem. Research completed since this project began to point to other magnetic materials for minimizing losses [7]. The coaxial transformer used in this converter is the integration of two magnetic components. Firstly, when the coaxial transformer diode, shown in Fig. 1, is not conducting the secondary winding is an open circuit and the primary winding looks like an inductor with a value equal to its magnetizing inductance. This magnetizing inductance is the resonant inductor. When the diode is on, the secondary sees a voltage source, V_{dc}, clamping the primary winding to this voltage and preventing an over voltage on the switches.

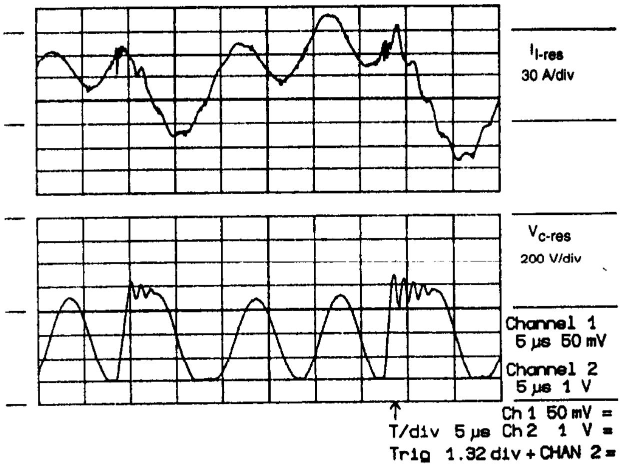


Fig. 9: RDCL Voltage and Current Waveforms

The coaxial geometry is a critical technolgy to minimize the leakage inductance of the transformer, limiting the voltage overshoot during turn-on of the clamp diode. Fig. 9 shows the resonant voltage, $V_{c\text{-res}}$, and the resonant current, $I_{l\text{-res}}$. The voltage overshoot of the resonant bus seen in Fig. 9 can be best understood by looking at the time domain equation for the resonant voltage. Referring to Fig. 1, the resonant DC link voltage can be approximated by [2]:

REFERENCES

1. G. Venkataramanan, D.M. Divan, "Improved Performance Voltage and Current Regulators Using Discrete Pulse Modulation", PESC 92 Conference Records, pp. 601-606.

2. D.M. Divan, "The Resonant DC Link Converter - A New Concept in Static Power Conversion", IEEE-IAS Annual Conference Records, 1986, pp. 648-656.

3. A. Nabae, H. Nakano, Y. Okamura, "A Novel Control Strategy of the Inverter with Sinusoidal Voltage and Current Outputs", PESC 94 Conference Records, pp. 154-159.

4. P.K. Sood and T.A. Lipo, "Power Conversion Distribution System Using a Resonant High-Frequency AC Link", IEEE Trans. on Industry Applications, vol. 24, Mar/Apr. 1988, pp. 288-300.

5. G. Venkataramanan, D. Divan, T.M. Jahns, "Discrete Pulse Modulation Strategies for High-Frequency Inverter Systems", PESC 89 Conference Records, pp. 1013-1020.

6. P. Caldeira, "High Frequency Series Resonant DC Link Power Conversion System", Ph.D. Thesis, University of Wisconsin, 1990.

7. N.H. Kutkut, D.W. Novotny, D.M. Divan, E. Yeow "Analysis of Winding Losses in High Frequency Foil Wound Inductors", IEEE IAS Annual Meeting, 1995, pp. 859-867.

8. D.R.J. White, Electromagnetic Interference and Compatibility, Vol. 2, (book) Don White Consultants, Inc., 1976.