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Compact AC-Link Converter: AC–DC Power Conditioning for Directed Energy Applications

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A novel concept that utilizes an AC-Link^{TM} topology is presented for ac–dc power conditioning. It is applicable for charging pulse-forming networks, dc loads with highly regulated voltage requirements, or other pulsed applications. The power conditioner interfaces with any ac generator and produces less than 1% harmonics, therefore permitting the generator to operate at full rated power, minimizing heating and eliminating the low-frequency transformers necessary for isolation or voltage transformation. The AC-Link^{TM} power conditioner provides full galvanic isolation between the generator and the load, and no transformer is required for a dc load with voltage requirements similar to the ac supply voltage. For higher dc voltage applications, the power conditioner can be configured as an electronic transformer. This system includes a single-phase, high-frequency transformer that is operated in the 20-kHz range. This high-frequency operation reduces the transformer weight, volume, and losses to a minimum, yielding an overall compact power conditioning system. The inverter is scalable to any power level using present-day power electric components. The preliminary design of a 5-MW, 95-kV klystron power supply will be used as an illustration.

KEYWORDS: High voltage, Low harmonic distortion, Power converter, Solid state

1. Introduction

AC-Link^{TM} is a new inverter topology applicable for direct ac–ac power conversion without the requirement of a dc link. The input or output can also be simplified to dc as an input and/or dc on the output. Normally the system is operated when the input and output voltages are comparable; however, the system can also be combined with a high-frequency transformer such that the reconstructed or rectified output may be stepped up or stepped down. With the transformer operated at the inverter frequency, the transformer weight and volume is significantly reduced.

Unlike the pulse width modulator (PWM), AC-Link^{TM} is a natural "soft switching" inverter topology, therefore not encountering the "hard switched" losses. In addition, AC-Link^{TM} does not require opening switches, therefore allowing the use of the more efficient thyristors that scale to higher power, voltage, and current levels instead of using insulated gate bipolar transistors (IGBTs). However, the Science Application International

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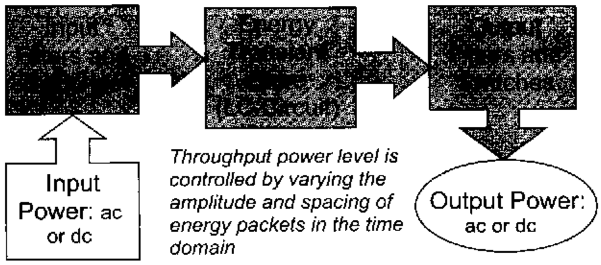

Fig. 1. Basic AC-Link™ configuration.

Corporation (SAIC) has also used IGBTs for operating up to 20 kHz to reduce the passive components, such as capacitors, inductors, and the transformer. In the ac–ac applications, the input and output current is nearly harmonic free with a total harmonic distortion (THD) as low as 1% with a dV/dt of less than 10 V/μs. This performance permits the AC-Link™ to draw power from high-voltage generators or to supply power to motors at a high voltage levels without compromising the machine winding insulation. No multilevel inverter topology is required, and no additional galvanic isolation is needed, thus eliminating the weight and volume of low-frequency transformers.

This paper addresses the AC-Link™ inverter as an interface between the power source and a number of potential directed energy weapons (DEW) loads, with the focus on reducing the weight and volume of the complete interface system. This paper identifies the following generic DEW requirements:

a) Direct ac–dc power conversion, with full galvanic isolation.
b) AC-XtrDC (ac–dc with transformation), in which the output voltage requirement is significantly higher than the supply voltage and supplies a highly regulated dc voltage or current.
c) AC-XtrDC operation for charging a capacitor bank such as a pulse-forming network.
d) AC–DC or AC-XtrDC with an additional dc port, in which the generator supplies the average power and the combination of the generator and the dc storage system provides the peak load power for a repetitively pulsed load.

2. AC-Link™ Technology

AC-Link™ is new inverter topology applicable for direct ac–ac power converter with a basic configuration as shown in Fig. 1. The inverter charges off the input power with a frequency of many times that of the input line frequency, drawing charges from each of the input phases, proportionally to the line voltage. This yields a unity input power factor. In the second step of the AC-Link™ cycle, this charge is dumped into all three output phases, to reconstruct an ac output with the required frequency, voltage, and phase. The dc input or dc output is just a subset of the ac–ac operation.

A limited number of publications are available on the AC-Link™ technology. The best reference is U.S. patent 6,118,678, issued September 12, 2000.[2] Others are Refs. 1 and 3–7.

The AC-Link™ technology is being investigated by SAIC for the U.S. Navy for electric ship propulsion and power conditioning. SAIC also built a high-power density power supply for the Air Force Active Denial Technology. The results are included in an additional paper provided for the conference proceedings.[6] Several studies were sponsored by the Royal Navy

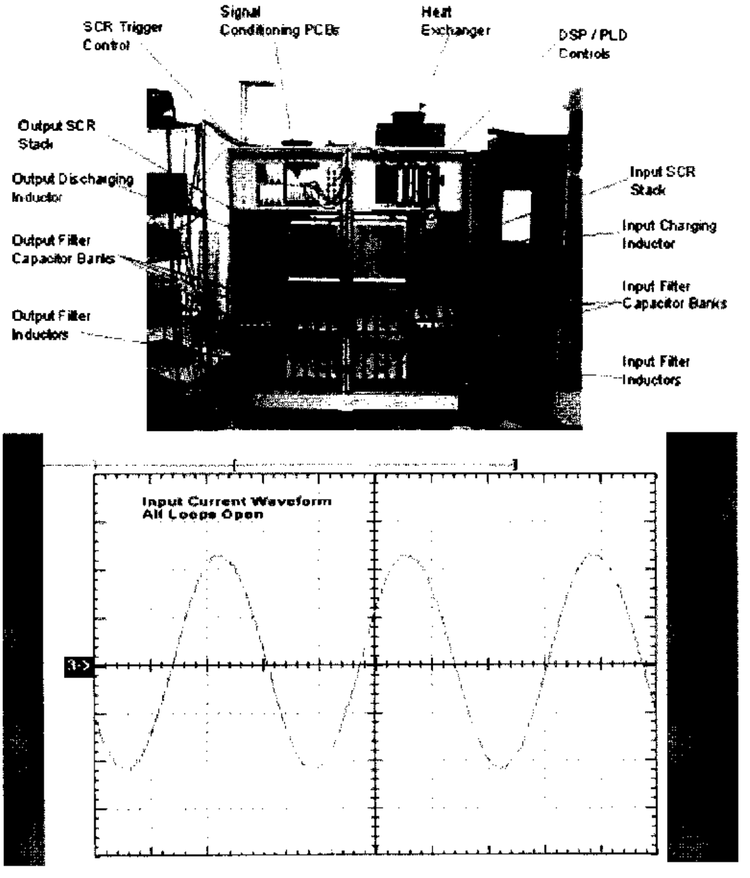

Fig. 2. 250-kW AC-Link^{TM} inverter with input current waveform.

for ship propulsion and power conditioning, for superconductive generators, and for a low-weight power supply for an airborne microwave system. In the commercial area, NewVAR LLC tested a 100-kilo-volt-ampere-reactive (kVAR) active VAR compensator. The Electric Power Research Institute (EPRI) independently tested a Princeton Power Systems (PPS)–constructed motor drive to substantiate the AC-Link^{TM} claims, resulting in low-dV/dt tests with 500 ft of power cable between the inverter and the motor load. A picture of the first AC-Link^{TM} system, a 250-kW, 480-V ac motor drive, is shown in Fig. 2 with the input current waveform. The output current is identical, both with less than 1.5% THD and a dV/dt of less than 5 V/μs.

3. Technical Concepts

Figure 3 shows a single-module ac–dc AC-Link^{TM} inverter configured as an interface between a three-phase power source and the dc load, such as a diode laser. The generator and load voltage is matched to obtain efficiency and minimum weight and volume. For 480-V ac input, a load voltage of about 550 V dc is ideal. The generator frequency can be anything, and high-speed generators are recommended to minimize total system weight and volume. In addition, the inverter switches are shown as thyristors; however, other switches

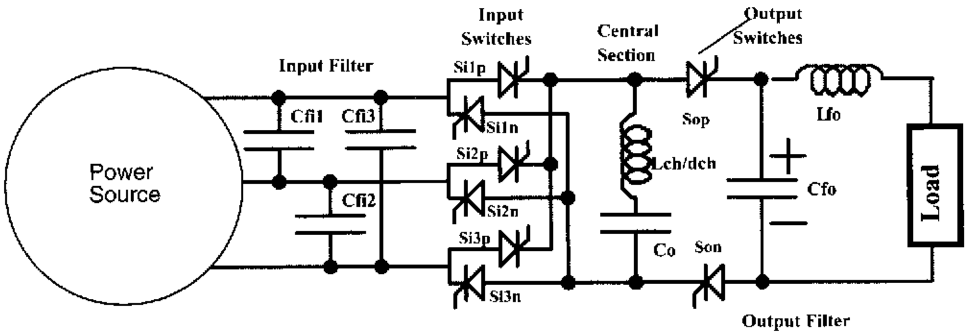

Fig. 3. Basic AC-Link™ ac–dc converter for regulated dc load requirement.

such as IGBTs may be used for switching frequencies in the range of 20 kHz for weight and size reduction.

The power drawn from the generator is nearly harmonic-free, as shown in Fig. 2, which permits the use of superconductive generators, since minimum harmonic rotor heating occurs. The low harmonics also requires no generator de-rating, since the typical 50% heating from six-pulse rectification does not occur.

The current drawn from the generator never can exceed the normal load current; therefore the generator windings do not have to be designed for the typical 8–10× fault current. These two important features permit an integrated generator, inverter, and load design with a significant reduction of overall system weight.

The system draws power from all three phases per pulse using a resonant charge process to store momentarily energy in the central capacitor "Co." The charging and discharging period is defined by the Co capacitor and "Lch/dch" inductor. During the charging process, the load is isolated from Co with the two output switches. As soon as the charging process is complete, the input switches recover, and the discharge starts with the Co energy transferred to the output. During that time, the input switches provide the isolation between the load and the power source. Any load terminal may be grounded with the power source.

The energy throughput is regulated by the combination of the number of pulses per second and the energy per pulse that is being drawn from the input. The energy per pulse is controlled by the "inversion control" process, a key operation of the AC-Link™ inverter. Four input switches with three input steps are used for every charge cycle, while three output switches with two steps are used for the ac output reconstruction. For dc reconstruction, only a single resonant discharge cycle is used. For an isolated dc output, two switches are required, while only one output switch is needed for a floating load. If no isolation is needed, only one output switch is used.

Most DEW loads require a higher dc output than a generator can practically produce. For that requirement, an AC-Link™ electronic transformer is used.

The AC-Link™ AC-XtrDC electronic transformer is a modification of the basic ac–ac technology with the integration of a high-frequency transformer as part of the basic AC-Link™ operation. The input voltage can be either step-up or step-down over a large range with the proper transformer turn-ratio selection. The output can then be reconstructed as either three-phase ac with the required frequency, regulated voltage, and phase. For dc requirements, the output section of the transformer secondary is simply rectified, using a diode rectification section with the voltage regulated from the transformer primary.

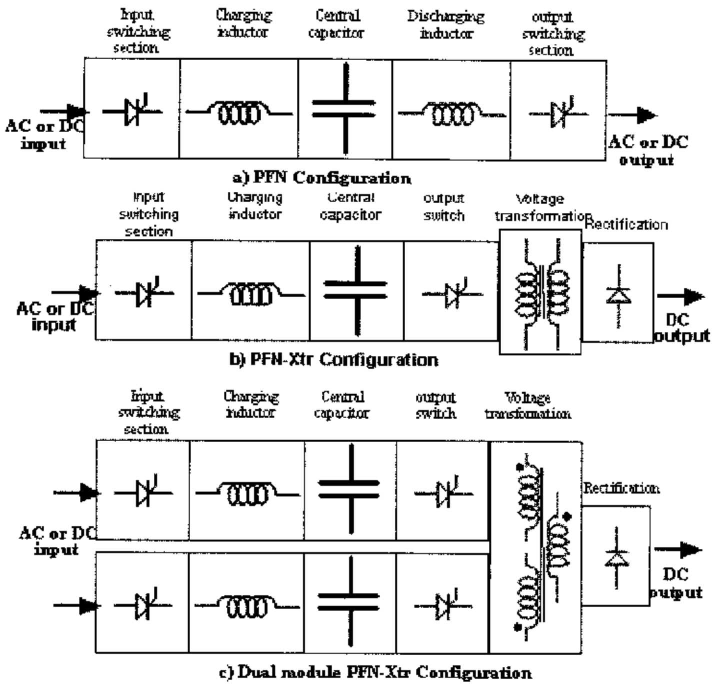

Fig. 4. Schematic AC-Link^{TM} AC-XtrDC converter concept.

A typical ac–dc converter is shown in Fig. 4a with both charging and discharging inductors. For the AC-XtrDC shown in Fig. 4b, the charging inductor is replaced by the leakage inductance of the single-phase transformer. With the correct leakage inductance, the central capacitor energy resonates through the transformer, where it is rectified on the secondary. The discharge pulse is a simple half-sine-wave-current output per discharge cycle. To use the core of the transformer more effectively, two AC-Link^{TM} modules are used with one transformer. The parallel operation is time interleaved, with one module charging while the other module is discharging. The functions are reversed for the next cycle, producing a full-sine-wave output. The output is simply rectified with a full-wave bridge, and the configuration is schematically shown in Fig. 4c.

Since the transformer is operated at the inverter frequency, its size is dictated by the inverter frequency and power level. For instance, the 20-kHz transformer for the 250-kW active denial system weighs only 26 lb. This weight reduction is the key to the AC-XtrDC power supply. The same concept can be used to configure a low-weight AC-XtrAC transformer with the standard ac reconstruction on the transformer secondary.

The regulation of the AC-XtrDC is identical to that of an ac–dc inverter with the output regulated to a selected voltage and current. The regulation is controlled by the inverter frequency and energy per pulse method.

In summary, a single-phase transformer in the AC-Link^{TM} AC-XtrDC system performs two functions. First it provides the transformer turns ratio for the voltage step-up or step-down to yield the desired output voltage range, while the leakage inductance provides the desired inverter frequency. For that configuration, the leakage inductance performs a useful function and is not a negative factor. It can be shown that the same transformer has 5–10 times the power through capacity with an AC-Link^{TM} as with a PWM.

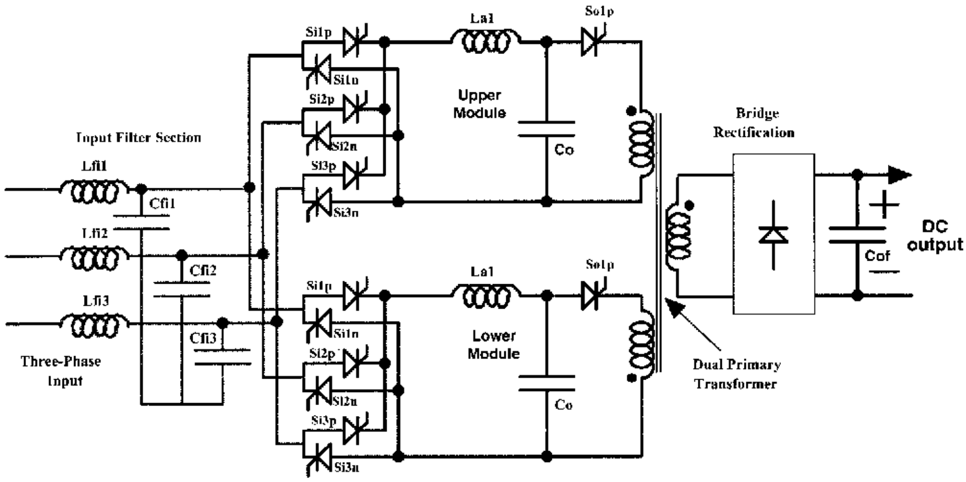

Fig. 5. Dual AC-Link^{TM} module with transformed and regulated dc output.

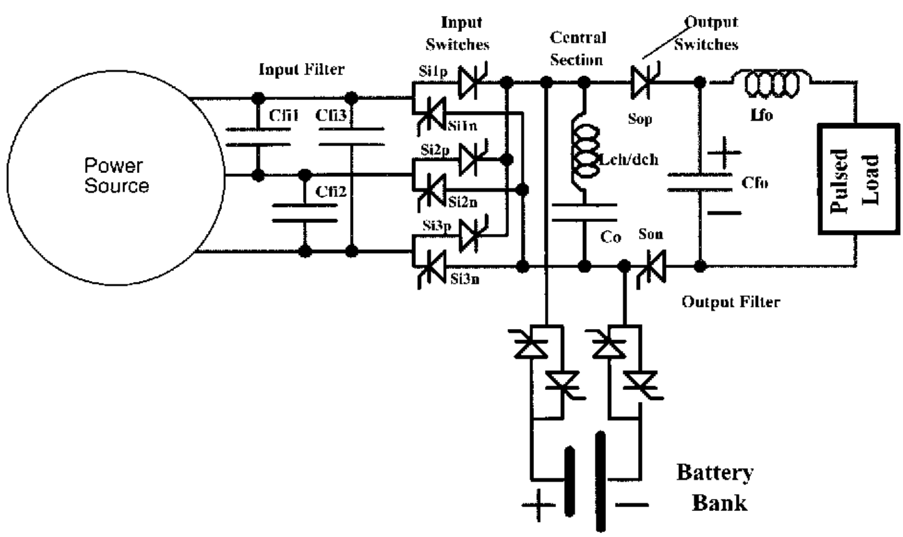

Fig. 6. Dual output port inverter with energy storage.

Figure 5 shows the AC-XtrDC power supply electric schematics with all of its components. For a megawatt system, the transformer leakage inductance permits operation up to the 5–10-kHz range. Thyristor operation is limited to about 4 kHz. For a lower power system, such as the active denial power supply, the transformer technology will permit operation in the 20–30-kHz range, with IGBT switches.

The dc output may be a regulated continuous wave, pulsed, or used to charge a capacitor bank. Most generators cannot support a pulsed load with fast power turn-on and turnoff. For a repetitively pulsed operation the AC-Link^{TM} can be configured as a multiport as shown in Fig. 6. This system draws constant power from the generator and stores that power in a battery or capacitor bank during the load off period. During the power-on time, this multiport inverter delivers that power to the load from one discharge cycle to the next.

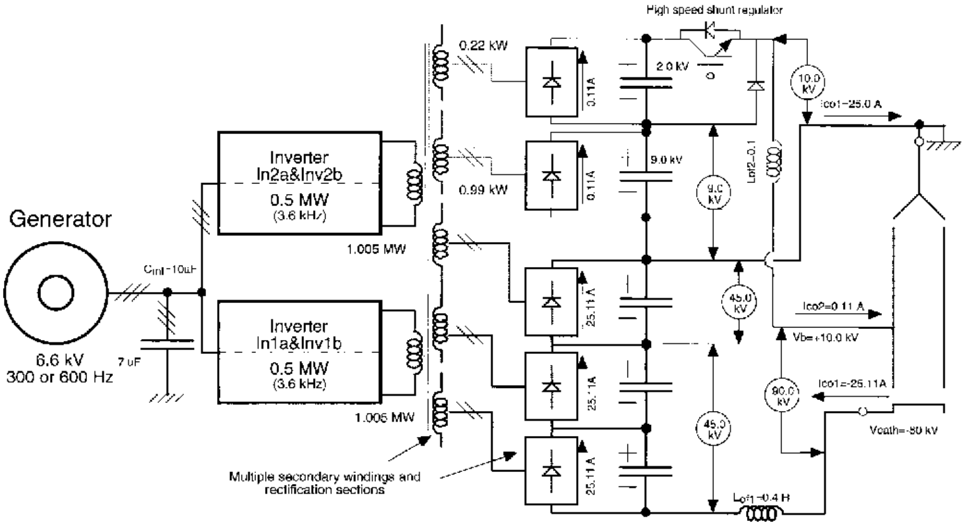

Fig. 7. Two megawatt regulated power supplies for an airborne microwave tube.

Additional dc–dc inverters, not shown, provide the additional pulse load. The multiport inverter in Fig. 6 is shown as an ac–dc/dc inverter with an output voltage comparable to that of the ac input voltage. The same system can be configured with a transformer output for high-voltage pulsed dc operation.

The system is relatively flexible, since multiple parallel inverters may be used in an interleaved way. For example, for a 1,000-kW, 40-kV peak power requirement, with a pulse duration of 50 ms and a duty cycle of 25%, one 250-kW AC-DC/XtrDC in conjunction with three 250-kW DC-XtrDC inverters is used. The multiport would draw 250 kW continuous, delivering the generator power either to the pulsed dc load or to the dc storage. The other three inverters are idle 75% of the time and provide only 750 kW during the 50-ms pulse, together with the multiport output, for the total requirements of 1,000 kW. With each inverter operating at a frequency of 20 kHz, the output ripple frequency is 320 kHz with interleaved operation.

Figure 7 shows a configuration of a 2-MW, low-weight, regulated airborne power supply for a −90-kV microwave tube. The system uses four AC-Link™ modules to supply the microwave tube. Two of the voltages are regulated on the primary with the configuration shown, and a shunt regulator is used to provide a regulation of a fraction of 1%.

With the inverter operating at high frequency, the transformer weight and volume is reduced to about 21 kW/kg. The four AC Link™ modules draw power directly from a 6.6-kV generator, with a THD of less than 1% and a dV/dt of less than 10 V/μs. A similar study was performed for a 5-MW airborne power supply.

4. Summary

This paper gives a short overview of the AC-Link™ topology applied to several versions of DEW power supply configurations. As can be seen, the AC-Link™ system is highly flexible and adaptable for several configurations. Most important, it provides the highest power density of any available technology.

AC-Link™ technology has been under development for about six years and is reliable. A U.S. patent, 6,118,678, was issued on September 12, 2000,[2] and SAIC developed a 250-kW, 480-V ac–ac system under Office of Naval Research sponsorship. The same agency sponsored the design of a 5-MW 4,160 ac line voltage multiport design.

The first integration of the AC-Link™ inverter with a high-frequency transformer was recently demonstrated with a DC-XtrDC, 250-kW active denial power supply for the Air Force with a 350-V dc input and regulated dc output in the 30–50-kV range. Several studies were performed, one for the Royal Navy, for ship propulsion and power conditioning systems. In another study, the AC-Link™ system was adopted for a high-speed, high-power superconductive generator power conditioning system.

In the commercial area, NewVAR LLC has tested a laboratory version of a 100-kVAR VAR compensator, and PPS has 30–300-hp variable speed drives commercially available. One of their drives was tested by the independent agency EPRI.[7] In addition, PPS has developed a small wind turbine and a solar power grid-tied inverter meeting standards UL-1741, IEEE-1547, and IEEE 555-1992.

In conclusion, the AC-Link™ technology has been demonstrated in multiple applications, and a number of flexible configurations are available for high-power, low-weight, and high-power-density DEW applications.

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Dr. Rudolf (Rudy) Limpaecher received his Ph.D. from UCLA in the field of plasma physics and worked for 22 years in the directed energy technology group at the AVCO Everett Research Laboratory/Textron. His areas of expertise included large pulsed CO_2 lasers, E-beam initiated pulsed chemical lasers, Air Breathing Electric Laser ("ABEL"), as well a large EMERAL laser. These systems required repetitively pulsed power systems up to 1.6 MV. These repetitively pulsed power systems required constant attention, and Dr. Limpaecher became a power conditioning expert. Rudy is now with SAIC, and this paper is a result of this technical exposure that is named AC-Link™. Dr. Limpaecher is the inventor (patented) of the AC-Link™ technology, which has numerous applications for large military systems, industrial power conditioning, and electric transmission and distribution applications.

Mr. Rigo Rodriguez received his B.S. in electrical engineering from the University of Bridgeport and has been working for the past 23 years designing, testing, and fabricating pulsed power/power electronics systems for radar modulators, laser power supplies, and particle accelerators. He is currently the Electric Power Systems Technology Battleview Laboratory Manager for SAIC and is tasked with the development of the AC-Link technology as well as other pulsed power system topologies.

Bill Siegel: Bio not available at the time of publication.