Resonant Link Regional Electrical Grid Power Transfer Converters

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Current Power Transfer Between Regional Grids

Today, transferring power between regional grids is both costly and limited in performance. It typically requires the rectification of AC to DC, followed by reconstruction from DC back to AC, with asynchronous AC power injected into the receiving grid.

A newly developed and patented **Resonant Link Converter (RLC)** enables direct AC-to-AC power transfer between asynchronous grids at the required frequency and phase—**without the need for an intermediate DC stage**. Additionally, AC voltage transformation can be achieved as part of the process.

Power flow through the converter is **regulated, reversible within milliseconds**, and can be stopped entirely by halting the triggering of the converter switches.

Soft-Switching Resonant Link Technology

The Resonant Link Converter employs **soft-switching technology**, eliminating switching losses and allowing the use of high-voltage switches (e.g., 6.5 kV IGBTs) operating at 5–10 kHz. This high switching frequency **reduces the size and cost of passive components** and lowers harmonic ripple to **less than 1%**.

Operation of the Resonant Link Converter (RLC)

The electrical schematic of the RLC is shown in Figure 1. It operates with a **100% duty cycle** and provides **full galvanic isolation** between the two grids. The converter is also **bidirectional**.

The high-frequency transformer operates at approximately **6 kHz**, allowing for a **core cross-section of only 1% of a standard 60 Hz transformer**, with **over 99% reduction in core weight**. Due to the reduced size, **high efficiency, nanocrystalline core materials** are typically used in the transformer and the two charging inductors (Lo).

To prevent magnetic core saturation, **two converter sections** are used on the left side. While one section charges, the other discharges through the transformer during each half cycle, ensuring **magnetic flux reversal** and supporting both **voltage transformation and galvanic isolation**.

With an initially zero input current, **switch turn-on losses are eliminated**. At the end of each pulse, when the resonant current drops to zero, **turn-off losses are also avoided**. This enables high-frequency operation with high-voltage switches, including **6.5 kV IGBTs, GTOs**, and future higher-voltage devices.

Each switch consists of an **IGBT in series with a diode**. On the output side, **back-to-back 6.5 kV IGBT modules** are used. For systems operating at **11 kV AC or higher**, series-connected switches are required.

As shown in Figure 1, the converter maintains **galvanic isolation between input and output grids**. In the event of a component failure, the control system immediately halts switch triggering. **Power flow stops in under 1 millisecond**, and fault current is limited to **less than 120% of the operational current**.

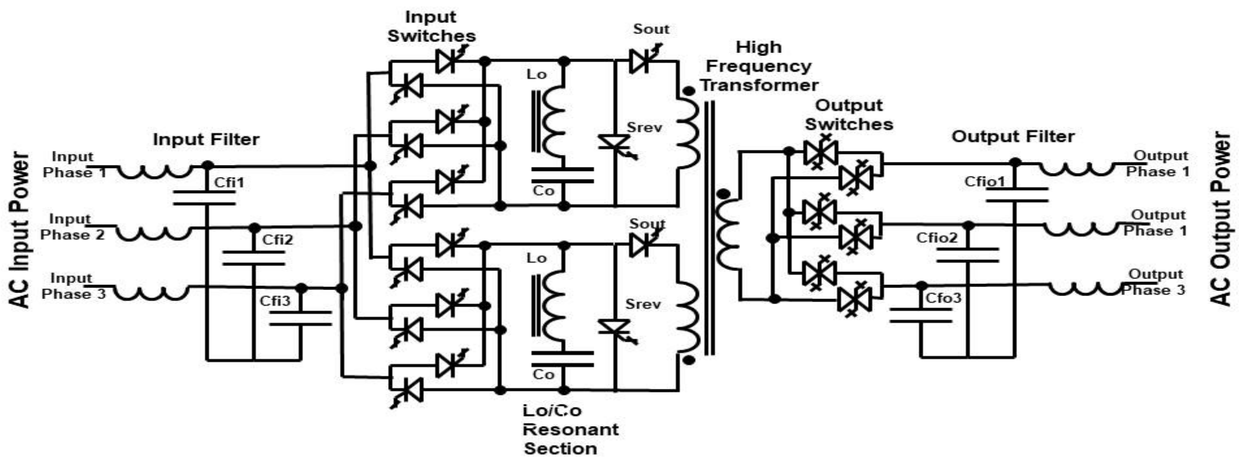

Figure 1 Basic circuit of an AC-to-AC converter with voltage transformation with output voltage, phase, and VAR regulation

Overall and Electrical Architecture

Figure 1 shows the Resonant Link Converter (RLC) circuit operating at a 100% duty cycle. The circuit includes a high-frequency transformer with two windings on the left side and one winding on the right side. Alternating charge injection into the two left-side windings reverses the magnetic flux with each charge transfer. The converter supports bidirectional power flow—either from left to right or right to left.

During each charge transfer pulse, one "Co" capacitor is charged while the other is discharged through the appropriate resonant inductor, the output switch "Sout," and the transformer.

For every charge pulse, current is drawn from each input phase in proportion to its voltage, resulting in a unity power factor. The charging of the "Co" capacitor begins between the "primary" and "secondary" phases. Once a sufficient charge is drawn from the "secondary," the "tertiary" switch is triggered. If the "tertiary" voltage is higher, by back biasing the "secondary" switch, it is forced off. The charge cycle is completed between the "primary" and "tertiary" switches. As the current returns to zero, all switches become back-biased and turn off, completing the charging process for the first "Co" capacitor.

The discharging of the first "Co" capacitor follows, initiated by triggering the output switch "Sout" into the transformer winding. This generates a current pulse on the transformer's secondary side. Three output switches are selected to transfer this pulse into the three output phases. Initially, the discharge flows between the "output primary" and "output secondary." Once enough charge is transferred to the "output secondary," the "output tertiary" switch is triggered, forcing the "output secondary" switch off. The discharge then continues between the "output primary" and "output tertiary" phases and completes as the current reaches zero. At that point, the charging cycle for the first "Co" capacitor can begin again.

While the first "Co" capacitor discharges, the second "Co" capacitor is simultaneously charged. Its subsequent discharge uses the second primary transformer winding, reversing the transformer core's magnetic flux. The timing of the "tertiary" switch controls the reactive (VAR) components. If the "tertiary" input switch is triggered such that the charge drawn from each phase is proportional to its voltage, the input power factor remains unity. Delayed triggering increases the charge from the "secondary" phase, producing a leading VAR component. Conversely, a shorter "secondary" charge period results in a lagging VAR component. The same principles apply to the discharge phase. As a result, the converter offers control over power flow direction, real power, and both input and output VARs.

The reversal switch "Srev" operates before the start of the charge cycles to reverse any residual voltage on the "Co" capacitor from the previous discharge. The timing of this switch determines the energy per pulse and, together with the pulse repetition rate, sets the converter’s average power.

For 60 Hz operation, the converter may operate at 5,400 pulses per second, equating to 90 pulses per input cycle—one every 4 electrical degrees. Since the input waveform repeats every 120 degrees, trigger timing must be calculated for 30 pulses. Due to 60-degree timing repetition, a total of 15 trigger timing values are needed.

Typically, timing is precomputed and stored in an FPGA lookup table, with multiple pages selected based on the desired real power and VAR levels. A CPU measures the value of each pulse and applies minor adjustments to the active timing table. Additionally, the CPU monitors each sub-pulse's amplitude to detect any component failure. If a fault is detected, the system halts pulse triggering and shuts down current flow within one millisecond. It then enters a component precheck sequence and resumes operation once the fault is cleared.

Installation of the Asynchronous Resonant Link AC to AC converter

Figure 2 shows the North American grid map and its interconnections. There is only one high-voltage DC long-distance interconnection between the Quebec Interconnection and the Eastern (New England) grid. All other interconnections consist of fewer, shorter connections that are spaced along the interconnection boundaries.

We propose deploying a larger number of medium-sized, bidirectional, asynchronous AC-to-AC converters along the boundaries between all grid regions.

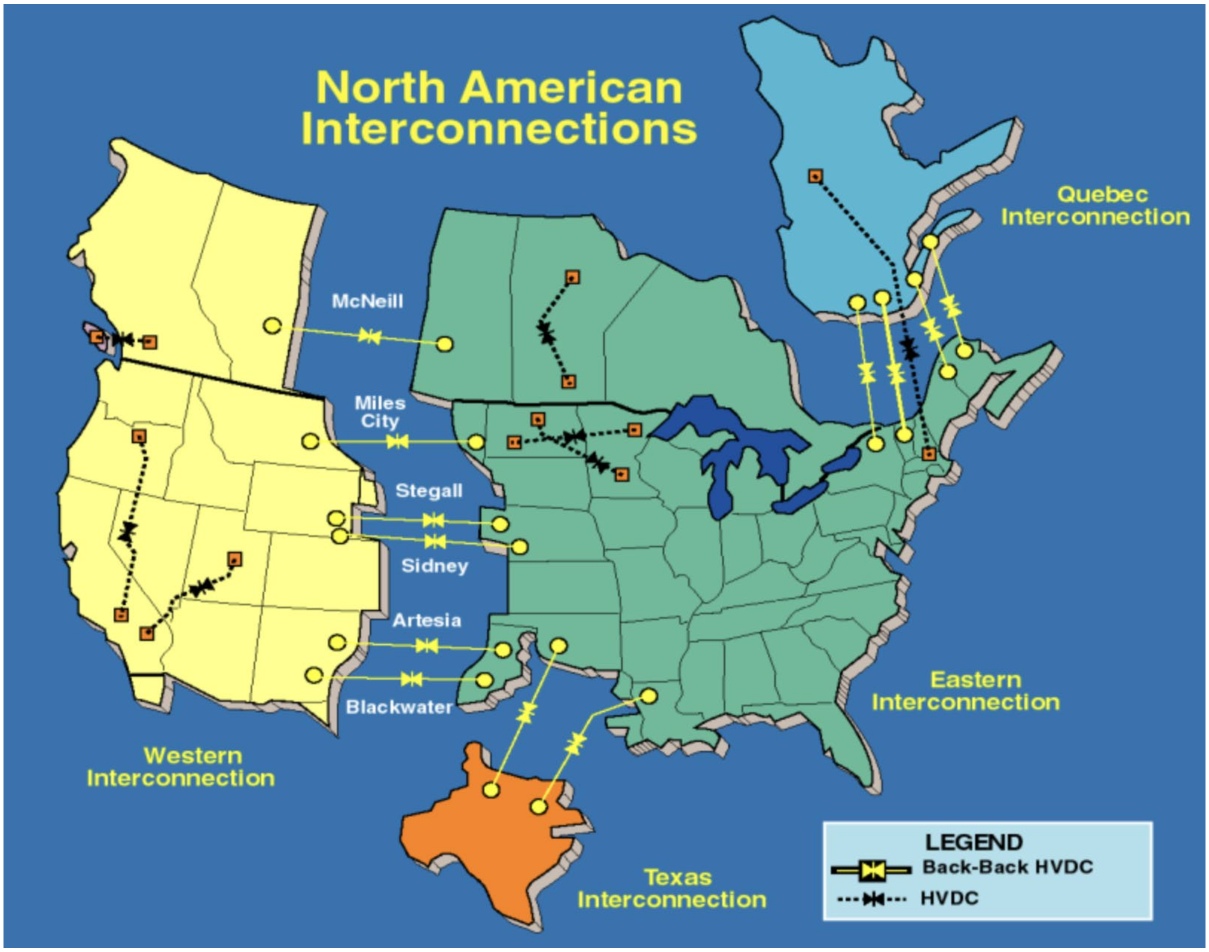

Figure 2 North American Grid Map and existing Interconnection (including Canada)

This approach would effectively interconnect all asynchronous North American grid regions, allowing power sharing among all North American power sources. We propose using medium-voltage AC connections (11 kV to 35 kV). Each AC-to-AC converter can be installed in an existing grid substation, with a short AC line connecting it to the power line of another asynchronous grid. Thanks to the internal AC-to-AC Link transformer, the input and output voltages do not need to be the same.

The Resonant Link AC converter offers higher efficiency than a traditional 60 Hz regulated transformer operating at an average load factor of 40%. This is due to the absence of switching losses and the significant reduction of transformer core losses caused by magnetic flux magnification.

We utilize much smaller nanocrystalline cores, whose core losses are negligible and proportional to the transferred power.

At higher converter frequencies, the components are smaller, resulting in a high power density of 2 to 4 MVA/m^3. These converter components are immersed in transformer oil for cooling. The heat rejection requirement is approximately 2% of the converter's instantaneous power, or about 20 kW per megawatt.

We use standard 6.5 kV-rated IGBTs, enabling the construction of asynchronous converters in the 10 to 20 MVA range. For higher power levels, converters can be easily paralleled.

Power flow and direction can be precisely controlled. At a switching frequency of 5.6 kHz, the input and output ripple are 9.2 kHz, requiring only small input and output filters to reduce harmonic content to below 1%. As a result, the power transferred between grids is practically free of harmonics. With sufficient converter installations along grid boundaries, all North American grids—from Texas to Quebec and from the West Coast to the East Coast—can be interconnected to form a single large grid.

The rationale for maintaining multiple asynchronous grids is to improve overall grid stability. While synchronous grids are influenced by geography, they are more critically limited by size. At high power levels, synchronous grids can experience subharmonic oscillations severe enough to cause mechanical stress, including twisting of generator shafts.

DC links between asynchronous grids enable power transfer without significantly contributing to subharmonic oscillations. The Resonant Link converter serves a similar role. Its ability to precisely control power flow supports grid stability by actively managing real power across the full range of potential subharmonic frequencies. Additionally, its capability to control reactive power (VAR) further enhances grid stability.

Additional VAR Control

While the real input and output power remains equal—simply passing through the converter—the unused capacity of the Resonant Link AC to AC converter can be used to draw controlled reactive power (VAR) from each end of the converter independently. This ability to support the power factor is increasingly important with the growing integration of renewable energy sources such as solar and wind. Standard PWM converters typically inject only real power into the grid, so additional VAR generation is highly beneficial. The combined real and reactive power is limited by the peak KVA rating of the Resonant Link converter, which can continuously operate at a 100% load factor.

Some References and Selective Application

Reference [1] describes the original AC Link technology, which operated without voltage transformation. This technology was primarily used for applications such as 480 V AC variable-speed motor drives. It was especially suited for converter systems that required low harmonic distortion and long power cables, as the absence of standing waves minimized cable-related issues. We typically used 2 kV SCRs, operating at a switching frequency of 2160 Hz. However, most customers favored PWM drives, as they prioritized cost and familiarity over reduced harmonics.

For higher voltage and higher frequency applications, SCRs proved impractical. As a result, we transitioned to using commercial IGBT modules capable of operating at much higher switching frequencies. These were implemented with soft-switching Resonant Link Converters, which eliminate both turn-on and turn-off switching losses due to the resonant current reaching zero at each switching event.

The first implementation of the Resonant Link Converter with transformation capability was in a high-voltage DC-DC converter. This system had an input of 300 V DC and delivered a regulated output of 50 kV DC. It was developed for the U.S. Air Force's “Active Denial System” as part of a 300kW power supply for a Gyrotron. The total available volume for this system was only 182 liters, yielding a transformer power density of 1.6 MW/m^3. To meet both size and output ripple requirements, a transformation switching frequency of 20 kHz was selected.

The high-voltage Resonant Link Converter with transformation was patented in 2014 [2]. This transformation capability can be applied across multiple topologies, including high-voltage DC-DC, AC-DC, DC-AC, and AC-AC conversions. For higher power applications, the optimal switching frequency typically falls in the 5–10 kHz range. We propose using this technology for Grid Power Transformer Converters in asynchronous AC-to-AC applications. Its soft-switching nature, with no switching losses, enables the use of 6.5 kV IGBT modules. Furthermore, the same control and instrumentation boards used in lower-voltage systems can be reused. The use of nanocrystalline transformer core materials and compact high-frequency components allows for high efficiency and excellent power density.

Below are selected publications from SAIC, Princeton Power and Resonant Link Technology :

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[7] Limpaecher, R., Rodriguez, R. J., Fikse, T., Ashton, R., Holveck, M., Limpaecher, E. ”Advanced Power Converters For Electric Ship Propulsion, Shipboard Power Distribution, and Electric Weapon System”, High speed/High Performance Ship and Craft Symposium, July 19-20. 2005, Everett, WA

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[11] AC-Link™ Converter Topology for High Voltage Directed Energy Applications, Rigo Rodriguez, Bill Drumheller, George Hutchins, Ephi Rubin, Steve Gagne, Rudy Limpaecher Science Application International Corporation Erik Limpaecher, Casey Jacobson Princeton Power Systems Jim O’Loughlin AFRL- DEHA ,ADT-DEPS paper Marge 3, 2006

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“Clean, Innovative DC Power for Marine and Offshore Applications via AC Link Technology”. Evans, IC, Limpaecher R. White Paper November 2009.

White paper, “Comparison of PWM VFDs versus Resonant Link Converters for Oilfield ESP Duty”.   Evans IC, R Limpaecher, Resonant Link Technology Limited. 21st May 2021.

White paper, “Resonant Link Technology - Powering Platforms from Fixed and Floating Offshore Wind”, Evans IC, R Limpaecher, Resonant Link Technology Limited. 24th May 2022.

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