Powering Floating & Fixed Wind.
Resonant Link Technology - The 21st Century Alternative

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Figure 1 : Example of floating wind turbines

Introduction

Freeing up offshore wind power from conventional bottom-fixed designs has been a dream for many years. Now it is a reality and opens a world of new opportunities for renewal and sustainable power sources (Figure 1).

To date, on offshore wind farms, conventional methods of electrical power transmission have been utilised to bring the power from the wind turbine generator to the shore. Depending on the distance from the shore, this entails AC or DC power transmission. Both AC and DC based conventional power transmission have innate disadvantages for these applications, however, from 50 km and above the DC transmission is only practical option.

Figure 2(c) illustrates an alternative offshore DC power conversion topology powering floating and other wind farms. Figures 2(a) and Figure 2(b) are the traditional configurations, limited by the currently available converter and transformation technology.

For both of voltage source converters (VSC) utilised in Figures 2(a) and 2(b) below have an overall electrical efficiency below 94.5%. This low efficiency results in significant and expensive energy losses over the project equipment cost of 20-25 years.

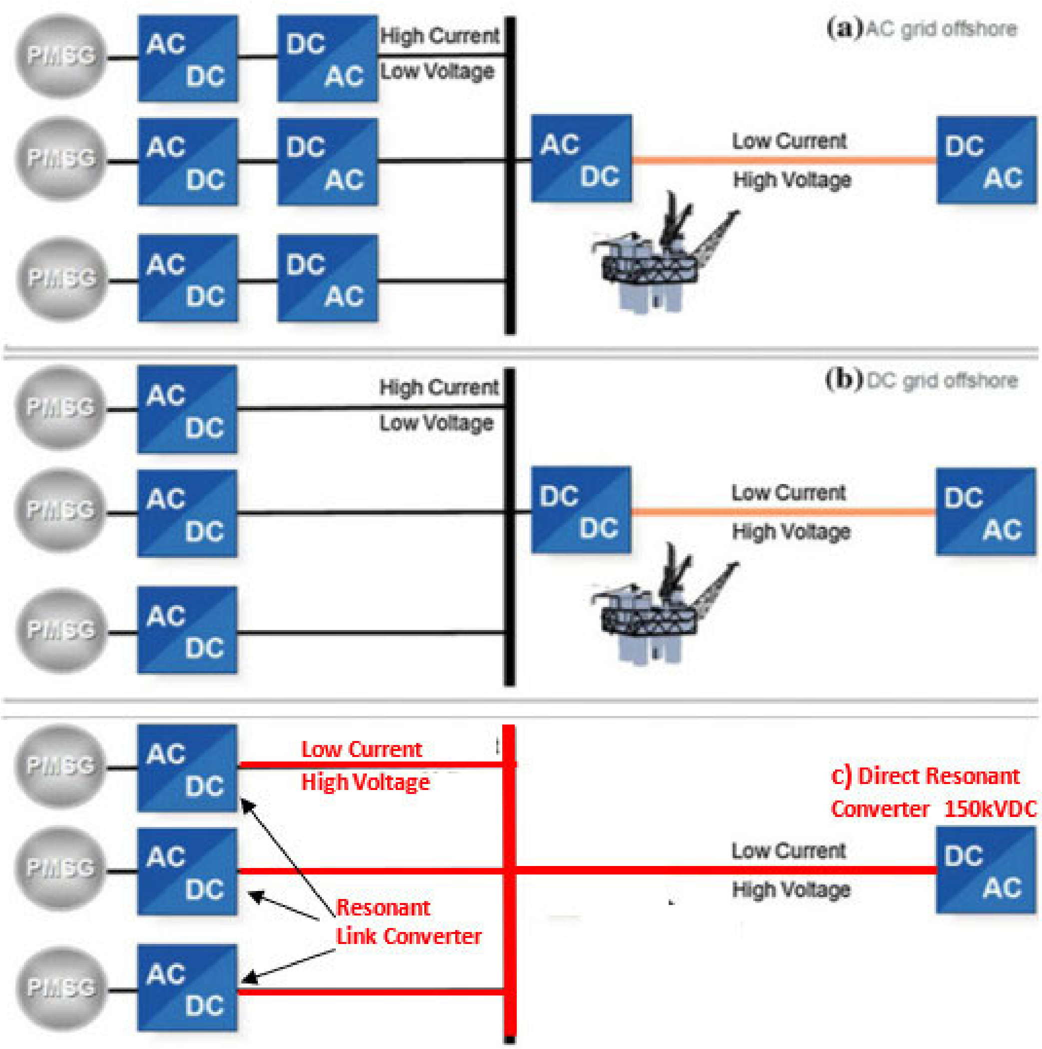

Figure 2 : Three HVDC alternatives for powering floating wind farms.
<u>Note – Figs 2(a) and 2(b) power transformers not shown</u> !

Wind powered turbine generators typically have an AC output voltage of 690V at 50 or 60Hz frequency. It is acknowledged that offshore wind farms in excess of 40-50kM from the point of power transfer (platform or shore) require DC voltage instead of AC voltage. Furthermore, large windfarms with typically, 100 wind turbines, will be spread out over an area of about 10km by 10km. This distance requires larger and more expensive AC power cables for the 2(a) approach or high DC current approach for 2(b) configuration. In addition, a number of power converters, transformers, VAR controllers and other equipment are required for Figures 2(a) and 2(b), add both complexity, equipment cost plus expensive cable and other power losses for wind farms over a projected lifetime of 20-25 years.

The Resonant Link technology option, seen as Figure 2(c), has one power stage, 690VAC to a high DC voltage conversion (+/- 150kVDC). The high voltage DC voltage cables are routed directly to the DC power collection point via small diameter cables prior to transmitting the total DC power to shore via larger diameter DC cables. The same DC power transmission may be also used to power oil or gas platforms. With Resonant Link technology, no further transformation or power conversion is required for DC power transmission to platforms and/or the shore via plus and minus DC power cables . There is only one stage AC to high voltage DC conversion process as shown in Figure (2c) above, thus reducing the overall installation cost significantly and minimising expensive losses due to the Resonant converter operation. In addition, since the transmission voltage to the platform(s) and/or the shore is 150kVDC voltage, the Ohmic cable losses are significantly reduced thereby minimising the cable cost due to the reduced copper conductor requirement.

Resonant Link Converter Topology – An Overview

Figure 3 below illustrates the patented Resonant Link converter circuit topology for an AC converter with step up and rectification to high voltage DC. The key feature is that the resonant converter is a ***soft switching technology***, therefore without current turn-on or turn-off losses. This eliminates all switching losses due to the solid-state switches (i.e. SCRs, GTOs, IGBTs et al). The lack of switching losses permit high power converter operation up to 20kHz and to reduce key component physical size compared to that required for conventional converter topologies as shown in Figures 2(a) and 2(b).

Resonant Link does not require expensive short-circuit/overcurrent protective devices for the DC voltage; the controlling software detects any short or overcurrent and switches off the power devices within 10ms.

The schematic in Figure 3 below illustrates the circuit topology together with voltage waveforms, applicable to wind power generators. The HVDC output voltage (+/- 150kVDC) is available for direct transmission to platforms and/or the shore or via the collector.

Resonant Link technology utilises SOFT SWITCHING converters which have no switching losses; only conduction losses. The elimination of switching losses increases efficiency to between 98.5% to 99% over the complete power range. This compares very favourably indeed with voltage source converters (VSCs), thus reducing the operational costs significantly in favour of Resonant Link technology.

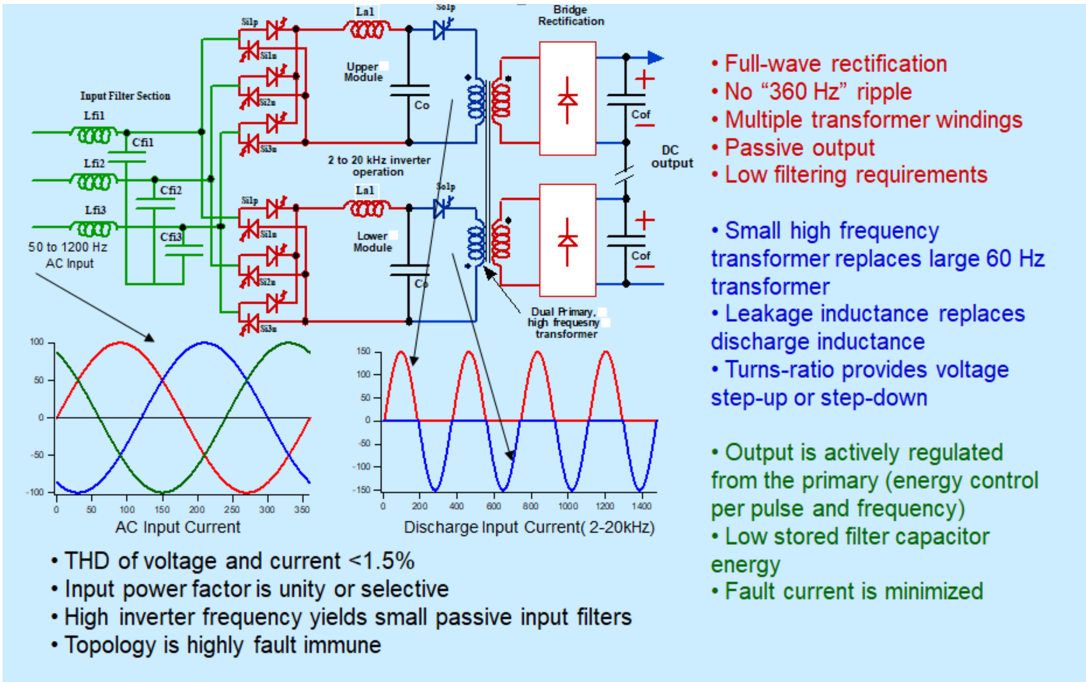

Figure 3 : Resonant Link AC to HV DC converter
(690VAC to +150KVDC or -150kVDC, depending on polarity)

The cross-sectional area of the nanocrystalline transformer magnetic cores utilised in Resonant Link converters are inversely proportional to the switching frequency. With a switching frequency is 6.0-7.2kHz at high power, high voltage levels (150kVDC), the transformer magnetic core cross-section is less than 1% of that of a 50 or 60Hz transformer. This translates into a 99% reduction of the core weight and loss reduction of both the transformer core and associated transformer windings.

The core weight is insignificant due to the use of nanocrystalline core materials; therefore, the remaining passive components are also reduced in size. The converter has a power density of the order of 3MW/m^3 thus permitting the Resonant Link converter to be installed directly in the nacelle.

Resonant Link Converter for Two Generator Types

Wind power generators are generally of two types. One uses a permanent magnet design. This requires no field excitation. The other type, the induction generator, required field excitation which is achieved via reactive VAR control.

The permanent magnet generator (Figure 4) produces frequency and voltage output proportional to the generator rpm. The nominal AC output of 690VAC can be directly used by the AC to DC step-up stage to provide a regulated DC output of plus and minus 150KVDC to combine with the power feed from other generators in the wind farm.

There is also the option, of rectifying the 690VAC, as shown in Figure 4, to yield a nominal DC voltage of 900VDC. In this configuration, a 900VDC to 150kVDC, DC-DC converter (i.e. essentially an active transformer) is in operation. The output voltage is regulated to 150kVDC with variable input control of DC voltage and rectification ripple.

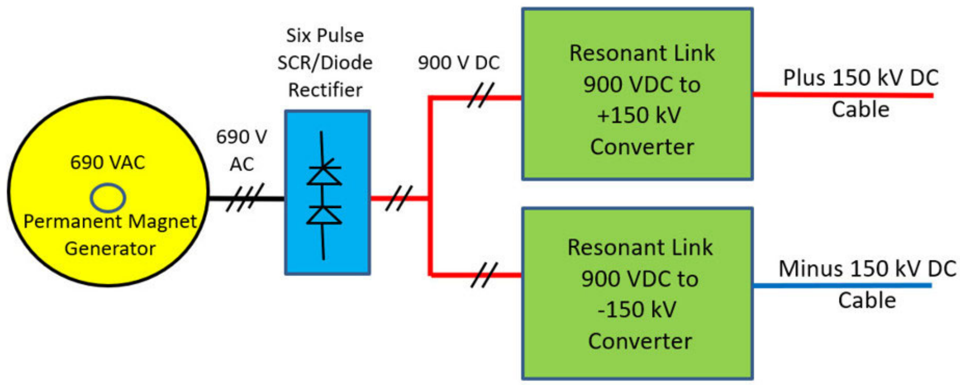

Figure 4 : Resonant Link topology for 690VAC permanent magnetic generators

Alternatively, the Resonant Link converter can be connected to 690VAC (Figure 5) output of the induction generators, where its being steps-up from the 690VAC voltage and rectifies to 150kVDC. The converter draws real power and controlled VAR which provides reactive power control for generator field excitation. A self-excited induction generator requires about 70% of reactive power (or VAR) for full rated power output. This translates into a requirement of about 6.0MVAR of reactive power and therefore a large capacitor bank has to be installed for generator self-excitation. The Resonant Link converter eliminates any additional VAR excitation requirement.

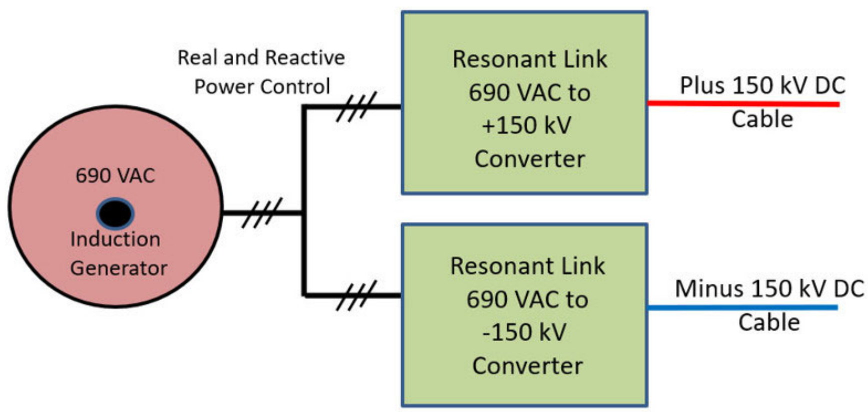

Figure 5 : Resonant Link topology for 690VAC induction generators

The schematic of Figure 6 below, illustrates a 690VAC-150kVDC Resonant Link converter module based on 690VAC input and 150kVDC output. The rating of each plus and minus module is 2.5MW, any number of each can be paralleled up to obtain the rated generator output power. The modules can utilize the 690VAC generator output, 900VDC or other generator output voltages and frequencies.

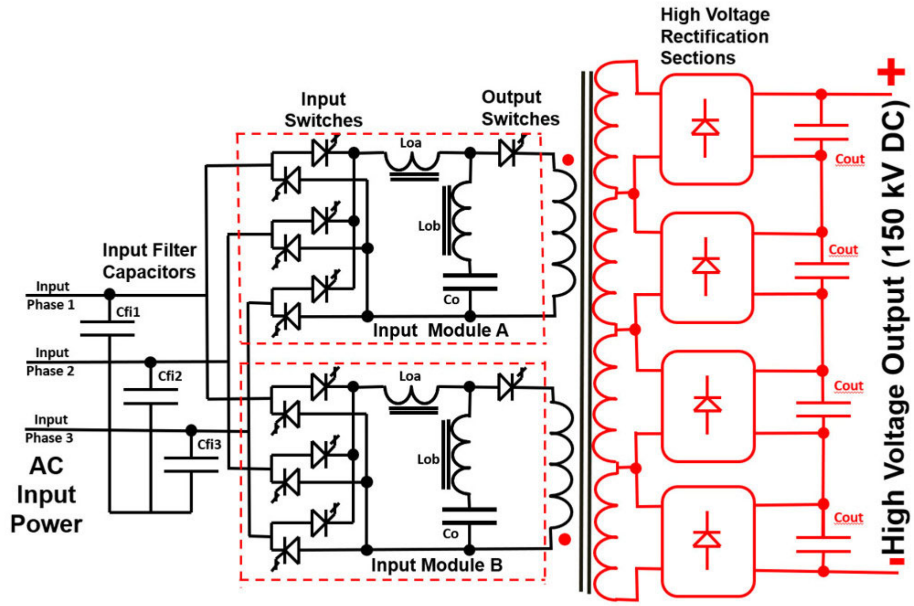

Figure 6 : Typical 2.5MW, 690VAC to 150kVDC Resonant Link modules (individually plus and minus 150kVDC), are paralleled to match the generator power output

Resonant Link to Power for Floating Wind Applications

The capital requirement for the AC to DC Resonant Converter is relatively low, since the 2.5 MW converters, shown in Figure 3, are small and a test-site with 2.5MW power capabilities and 690VAC can be easily installed and configured.

Unlike other high voltage DC transmission, a large and expensive AC to high voltage DC converters is not necessary. The operation 690VAC to 150kVDC transformation via IGBTs and drivers are readily available. Figure 7 below shows a typical power device as utilised in Resonant Link converters.

Figure 7 : Commercial IGBT 2400 A, 1700V IGBT as utilized in Resonant Link converters

These are the only active switching components required and no IGBTs nor diodes are required to be switched or connected in series as must be utilised in VCS converters.

It is important to note that Resonant Link converter is a patented **Current Transfer Converter** which transfers a selected amount of energy (or charge) and transfers that energy pulse to the high voltage DC output. The charges per pulse are proportional to the theoretical sinusoidal current per phase, for a unity power factor input. Resonant Link also can control the energy to draw a real and reactive charge pulse per phase to provide a reactive current for the induction generator field excitation.

DC Cable Requirements

The generator output of 690VAC is directly converted to 150kVDC by the Resonant Link converter. In this HV configuration, all the remaining power conversion and transformation associated with conventional technologies are eliminated and the cable power losses are significantly reduced.

Crosslinked polypropylene DC cables have been developed up to 500kV. 150kV cables are also used for the ABB Cross Sound Cable Project in the USA with similar current of 1175A (Figure 8). This cable has all the protection armour and has a 30mm diameter copper core. Depending on the current requirement, the copper diameter is changed, while the insulation and armour remains the same.

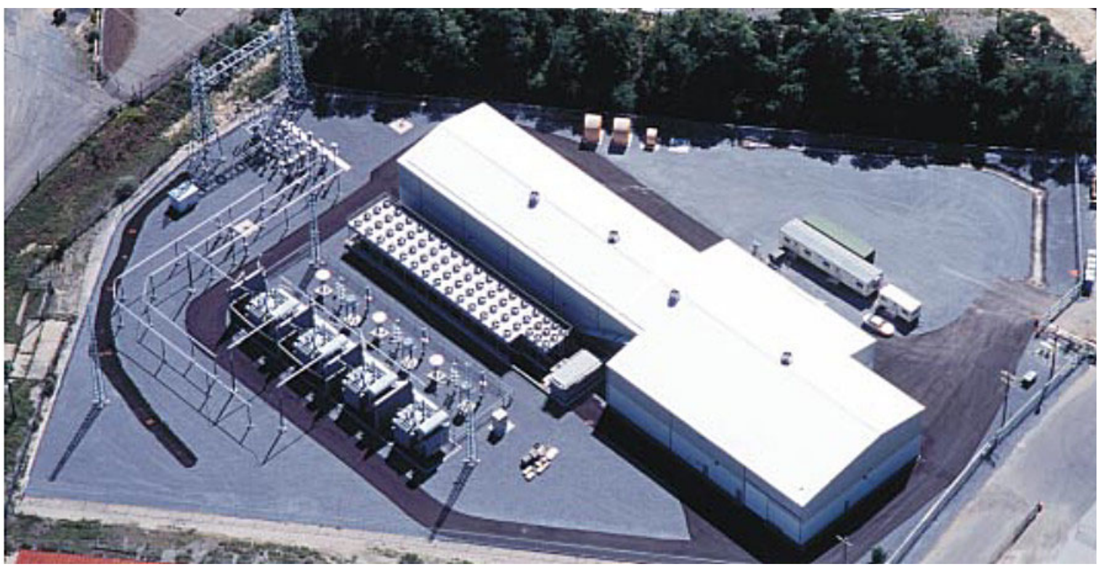

Figure 8 : ABB. 150kVDC 330MW Cross-Sound Converter Station Cable Project in the US

Shore Power Converter

Once the plus and minus 150kVDC power reaches the shore (or platform), a second set of Resonant Link converters will invert the DC voltage back to three phase AC at the appropriate voltage and high inverter switching frequency (6 kHz) with less than 1% to 2% total harmonic current distortion (THDi). Unlike with a voltage source converter the Resonant Link converter can also provide **controlled** reactive power to support the reactive requirement of the AC grid. The controlling reactive power injection has a minimum bandwidth of about a 200Hz, much higher than the approximate 6Hz needed for subharmonic grid instability suppression.

The Resonant Link converter is much simpler, smaller in size, and reconstructing the 50Hz AC wave at 6kHz (or 7.2 Hz for a 60Hz grid) and practically requires no external harmonic filtering. In addition, the Resonant Link converter requires no additional AC power source for line commutation. As mentioned above the Resonant Link DC to AC converter provides a controlled reactive power output.

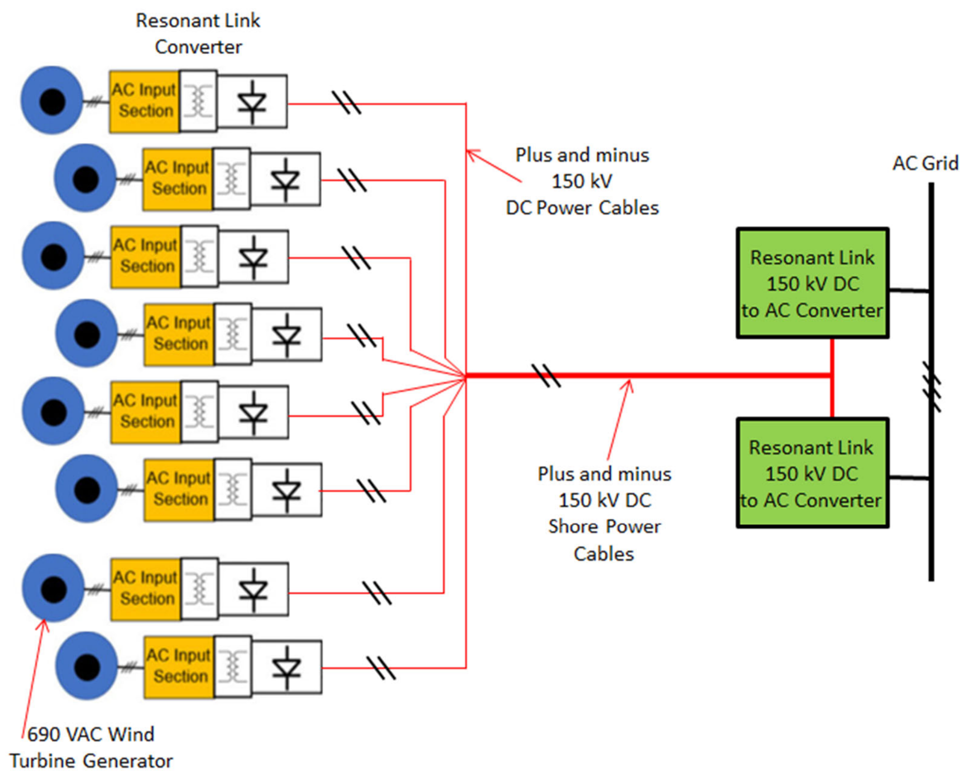

Figure 9 : Resonant Link Wind Power Generator to 150 kV DC cable transmission to shore DC to three phase AC power conversion

Figure 9 above illustrates the complete configuration using the Resonant Link 690VAC wind power conversion from the 690 V AC wind power generators to plus and minus 150kVDC. Followed up with a 100km plus and minus 150kV power cable to shore DC cables. This is followed with a Resonant Link DC to AC power inversion. It is important to note that HVDC to AC voltage inversion, require high voltage switches such as IGBT, GTOs, or SCRs. These devices have high switching losses when utilised for voltage source converters and can seriously impact the converter efficiencies. The soft switching Resonant Link converter has no such switching losses.

To illustrate this, Figure 10 demonstrates the power throughout versus switching frequency for PWM voltage source converters and Resonant Link converters. The test data is based on IGBT manufacturers data sheet for IGBT with an operating voltage of 1.7 kV, 3.3 kV and 6.5 kV. The manufacturer lists the turn-on and turn-off losses per pulse. The heat resistance between the IGBT chip junctions and the cold-plate temperature that is assumed to be 50 deg C for all of the IGBT.

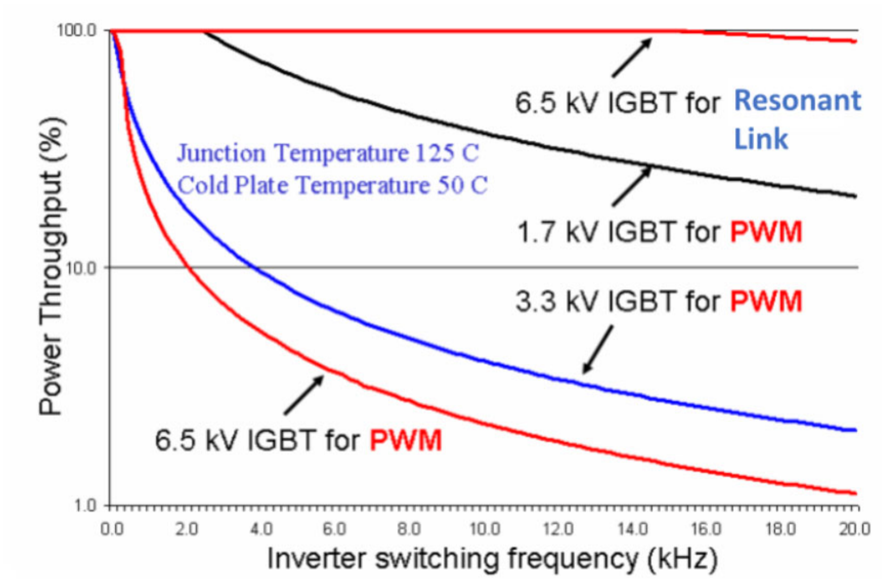

Figure 10 : Power throughput versus switching frequency of i) IGBT hard-switched PWM converters and ii) soft-switched switched Resonant Link converters.
Note the vertical axis is logarithmic.

At zero switching frequency the IGBT only has conduction losses at maximum power throughput and the curve is normalized at zero switching. However, as the switching frequency increases, the switching losses also increase almost linearly. The conduction losses and power throughput must decrease by the switching loss amount since the total thermal losses has to stay constant. These calculations were computed over a switching frequency from zero to 20 kHz. Considering the 1.7kV IGBT, the power decline was the lowest since the lower voltage switches have reduced switching losses**.** As can be observed, the PWM power throughout reduces very considerably with increased switching frequency, whereas the Resonant Link power throughput continues at a very high level, with only a slight reduction at around 20kHz.

If one considers 6.5kV IGBTs, the losses become much greater with the IGBT throughput power dropping to ten per cent of the power throughput at a switching frequency of about 2.2kHz switching rate. We note that the percentage throughput power is that provided by the curve in Figure 10, while the power switching losses are the value between the curves to the 100 % line.

Transitioning to the 6.5kV soft-switching Resonant Link curve, a converter that turns on when the current is zero and turns off when the current becomes zero again, no addition switching losses occurs until the switching frequency is well over 15kHz. Therefore, the losses remain essentially constant and the power throughput remains at a maximum. This is one reason that we operate the Resonant Link converter at switching frequency between 6 to 12kHz. This minimizes the component size and cost.

From the throughput/switching curves in Figure 10 it can be seen that the 'hard switched' voltage source converter has to operate at the lowest practical frequency to minimise the losses, whilst the soft-switching Resonant Link converter switching operation is not constrained by frequency.

In order to optimise the hard-switching losses, voltage source converters are more suited to IGBTs with lower voltage ratings such as those utilised in Siemens and ABB converters. Both use 1.2kV IGBTs, that requires to utilise five (5) 1.2kV devices in series to obtain the same 'hold-off' requirements, which is also possible with one 6.5kV IGBT. The Resonant Link converter however does not have the same constraints and can operate at higher switching frequencies with one-quarter the number of IGBTs in series required for voltage source converters.

The Resonant Link converter, with the reduced number of IGBTs and smaller passive components, permits much higher power density of, about ~3-4MW/m^3. This power density is much higher than an equivalent hard switched voltage source converter as can be clearly seen in Figure 8 (ABB Cross-Sound Converter Station).

Resonant Link 150kV DC to AC Shore Power Conversion

The voltages of plus and minus 150kVDC requires to be inverted to three-phase AC power before being injected into the AC grid. The Resonant Link circuit is shown in Figure 11. Unlike the three-level HVDC ABB Light voltage source converter switching the full 150kVDC voltage via a large string of 1.2kV IGBTs, the Resonant Link approach is to utilise multiple stacked sub-converters with much lower DC input voltage, each a lesser number of 6.5kV IGBTs.

As illustrated, the 150kVDC input is subdivided with a string of N input capacitors. Each capacitor feeds a plus or minus DC input to a sub-converter with an input voltage of 150kV/N. Each sub-converter inverters the DC power to a three-phase AC output at a switching frequency of 6kHz, with a ripple frequency of 12kHz. With each of the sub-converter output time-interleaved, the reconstructed AC voltage has ripple of N times 6kHz. With six sub-converters the ripple would equate to 72kHz. This requires insignificant filtering on the AC output side compared to that required for voltage source converters.

The schematic in Figure 11 also shows a C-L low-pass output filter. For that ripple frequency the output inductor illustrated can be simply replace by a few turns of the AC interconnect cable. In comparison, the ABB voltage source converters used in the 330MW Cross-Sound Project in the USA (Figure 8) required an AC output harmonic filters of (21st=103 MVAR), (25th= 61MVAR), (41th= 32 MVAR) respectively. The ABB system design has a DC power cable with a DC current of 1175 A. Furthermore, multiple passive harmonic filters and VAR capacitors for reactive power control are both required for all voltage source converters.

The fast switching, interleaved, Resonant Link converter requires almost zero filtering and can in addition provide VAR support for the grid without any additional equipment. In addition, with Resonant Link technology, no evaluation studies are required regarding harmonic stability on the power system, as are mandatory with voltage source converter transmission systems. Nor are any additional equipment, for example STATCOM, required to ensure that stability.

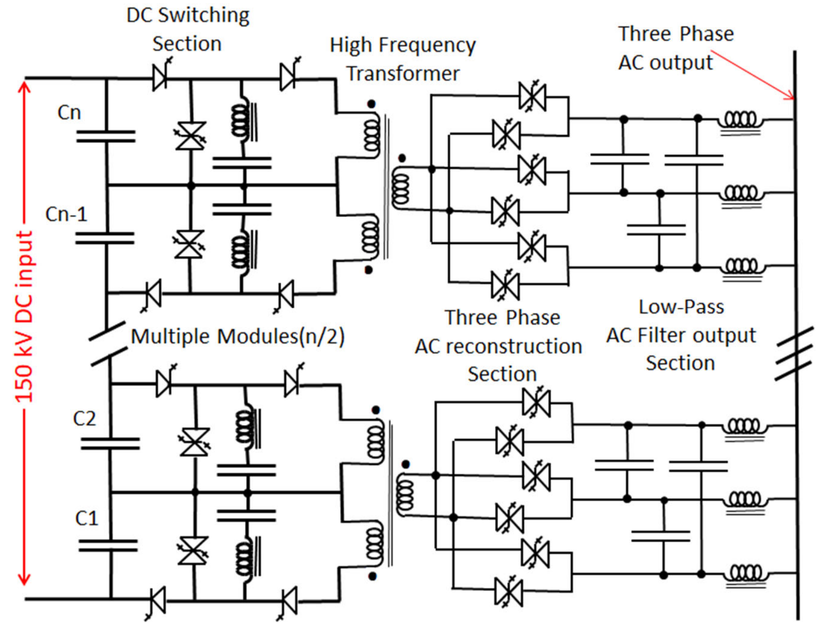

Figure 11 : Resonant Link converter schematics for 150kVDC to three-phase AC reconstruction

The Resonant Link design requires the power throughput of each sub-converter to be the same in order to maintain equal input voltage division. However, if one converter extracts less power, its input voltage will increase but in that situation the Resonant Link system becomes self-stabilising. If one of the sub-converters becomes defective, the voltage division will become uneven, the complete string of sub-converters would be shut down, without a major system fault nor loss of transmission power.

With this configuration, fewer high voltage IGBTs are connected in series. The voltage requirement for passive components is low, and the system is modularised. Also, the high voltage DC side and lower voltage AC side are galvanically isolated through the high-frequency, sub-converter nanocrystalline transformers.

The internal Resonant Link nanocrystalline transformers provides galvanic isolation but also give the flexibility that the DC input voltage **does not** define the AC output voltage as is the case for a DC to AC voltage source converter.

On larger DC input wind power projects, an appropriate number of independent converter strings will be used to converter the higher power outputs to AC. This requires redundancy and independent throughput power control for differing isolated AC circuits.

The Resonant Link 'charge transfer' or controlled current converter capability has the flexibility to reconstruct the AC output for a given voltage and frequency and transforming real power but also can inject controlled reactive current with leading or lagging phase(s). This permits the injection of real and reactive current or VAR into the AC output.

The AC reconstruction occurs on a 'pulse by pulse' basis, with a constant energy per pulse. Each AC phase receives for every energy pulse charge, determined by the phase voltage and phase current. For this circuit output IGBT switches are back-to-back 6.5 kV IGBTs with the necessary number of IGBTs are connected in series to satisfy the voltage hold-off requirements.

AC Power Flow Control

The power flow control of wind turbine output is regulated to generate plus and minus 150kVDC. For full power generator output, each converter is operated at 100% power output with each converter switching at 6kHz.

The onshore DC to AC power control initiates at full power with a switching frequency of 6kHz for each sub-converter. As the plus and minus 150kVDC supply is reduced, the inversion control will inject both real and controlled reactive power into the three-phase AC output terminals. All the sub-converters in the DC string will provide simultaneously the same real and reactive power components to maintain the voltage of all the N filter capacitors. With several inverter strings used, some inverter strings can be idled. Following that, switching frequencies will be reduced to about 2kHz to continue to inject real and reactive power. The real power output can in theory reduces to zero, while the remaining sub-converter can inject controlled reactive power.

Resonant Link Fault Protection

As can be appreciated, effective and rapid overcurrent and short circuit fault protection are absolutely crucial to electrical power systems. From a fault protection perspective, the Resonant Link converters' operational sub-cycles and currents and voltages are continually monitored. The transition from one sub-cycle to the next is only initiated if the current of the previous sub-cycle is zero. If the currents are not zero in the predetermine time, this will indicate a potential component failure or control fault. This will initiate an immediate controlled sub-converter shutdown. The converter control always initiates a self-diagnostic mode, before running up the converter. The inverter shutdown will occur in a fraction of a millisecond and fault current will not have the opportunity to damage any components. The majority of control and fault monitoring on Resonant Link are implemented via FPGA (field-programmable gate array) devices . Fault protection will shut down the converter in less than one millisecond to protect the installation and personnel in order to avoid the dangerous situation which resulted in the serious fire at the ABB 330MW Cross Sound Project in the US during 2014 (Figure 11 below).

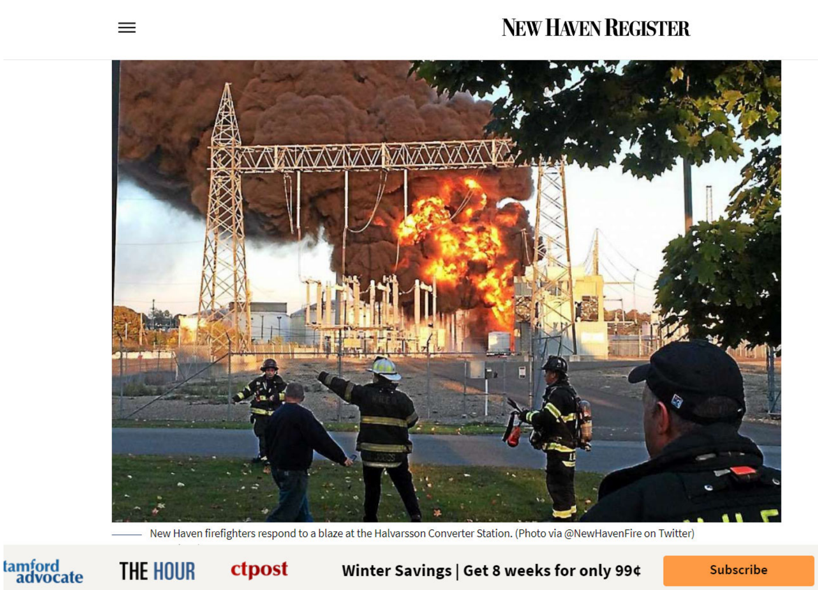

Figure 11 : Result of uncleared fault at ABB's 330MW Cross Sound project in the US

The Resonant Link fault protection also monitors the DC cable output and the AC output terminals voltage and currents. If a load fault is detected the Resonant Link converter will turn off the output in a pre-determined time (<1ms) to limit the fault current. The Resonant converter acts as an 'circuit breaker' for AC and DC faults.

To successfully protect IGBTs, a 10-20ms interruption time is insufficient. The Resonant Link fault interruption time of <1ms compares favourably to the fastest conventional circuit-breakers available (20ms). Electronic DC circuit breakers (~5-8ms) may be successful but they are extremely expensive and not yet fully developed. The <1ms interruption time under fault or overcurrent conditions is inbuild into all Resonant Link converters at no additional cost.

Conclusions

It has been demonstrated in this White Paper that Resonant Link technology is vastly superior to conventional PWM voltage source technology for the powering of bottom-tied and floating wind turbines.

It is more efficient, offers higher reliability, has inbuilt redundancy and requires very significantly less installation space per MW. It does not require conventional transformers for voltage transformation (AC or DC) but utilises high frequency transformers which are a faction of the physical size and weight of comparable conventional transformers.

Resonant Link offers extremely fast short-circuit protection (<1ms), compared to voltage source technology at no additional cost. It does not require expensive harmonics filters or VAR control for successful operation. Most importantly perhaps, Resonant Link technology is significantly more cost effective than voltage source technology for wind power applications (and for a wide range of other applications).

Resonant Link technology is **the** 21st Century, 150kVDC alternative for powering bottom-tied and floating wind applications.

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