Resonant Link Technology - Powering Platforms from Fixed and Floating Offshore Wind

24th May 2022

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Appendices

Appendix One – Report and evaluation of US Navy's (AC Link) main propulsion evaluation drive.

Appendix Two – Brief details of 250kW, 480VAC to 50kVDC heliborne laser power supply.

Appendix Three – White Paper, " Powering Floating & Fixed Wind - The 21st Century Alternative".

Appendix Four – "White Paper, Comparison of PWM VFDs versus Resonant Link Converters for Oilfield ESP Duty. Parts 1 and 2".

1.0. Background

In the 1990s, during the development of the laser weapons for the US Star Wars programme, a specification was issued from the US Department of Défense for powerful, but very compact and very low harmonic, power converters to drive the laser weapons and other equipment. The result was a technology entitled, "Sequential Discharge Rectification" (SDR), this name was changed to "AC Link Technology" in the early 2001. Its inventor was Dr Rudy Limpaecher, a plasma physicist. The patent numbers and associated papers are listed at the rear of this document.

In 1997, SDR was introduced into the Royal Navy by Ian C Evans for "Project Horizon", the Type 45 destroyers for 1000kVDC ring main, from which any AC voltages and frequencies and DC voltages could be supplied. In addition, the requirement was for 2 x 20MW electric main propulsion drives. The Royal Navy was in very much favour but the MOD wanted to go the "traditional route" of PWM main propulsion drives, which at that time the MOD had no experience of. The result was harmonic voltage distortion (THDu) FOUR times the NATO maximum and common mode voltage in kV around the hulls. These problems continue to dog the Type 45s destroyers since their initial launch in 2006. The two new Royal Navy aircraft carriers share the same propulsion system.

In 2002 onwards, the US Navy became interested in this technology for main propulsion drives. A contract was entered into with SAIC, US military contractor and licensee of the technology (who had employed Dr Limpaecher) with the US Navy's Office of Naval Research (ONR) for a 250kW evaluation variable frequency drive (VFD). The conclusions of ONR's assessment report and comments are in Appendix One. However, the Chairman of ONR did not want the technology, even though ONR had given it a ringing endorsement, as it would have diverted the US Navy from the PWM technology route he wanted. To date (2022) the US Navy is still trying to overcome the serious problems with PWM technology on vessels, especially 'common mode voltage' and spending very considerable funding in the process.

In addition, Dr Limpaecher was involved with military aviation licensees, including Boeing and Rolls Royce. Appendix Two illustrates a 250kW heliborne laser power supply (480VAC in – 50kVDC out). The internal nanocrystalline, high frequency transformer weighs 11kg. Other military developments are classified.

From 2005 onwards, the technology was, with the agreement with the US Government, made available for commercial use and NATO use, outside the US Navy. Princeton Power Systems (PPS) developed a range of VFDs to 150kW and used the technology on renewable power systems.

However, what is now called "Resonant Link Technology", is more suited to niche applications such as powering platforms (or to the shore) from offshore fixed and floating wind turbines (see Appendix One for White Paper) and oilfield ESP (electrical submersible pump) VFDs (see Appendix Two for this White Paper), in addition to medium to high power marine main propulsion drives to 30-50MW.

In all applications, the technology's numerous benefits are 'game changing' !

2.0. Resonant Link for fixed and floating wind power systems platforms

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 platform(s) or the shore. Depending on the distance, both AC and DC based conventional power transmission have innate disadvantages for these applications. Above 50 km the DC transmission is the only practical option. However, with the introduction of Resonant Link technology, the performance, physical size and lack of requirement for additional equipment (i.e. harmonic filters, STATCOM and structures to house them), favours the use of technology, even for short distances, once only thought viable for AC systems.

As can be seen in the accompanying presentation, Resonant Link technology has many benefits. However, for this basic description, the salient benefits can be summarised as follows :

Patented soft switching technology -'Soft switching' (i.e. no switching losses) of the devices enables full power throughput up to 20 kHz. Resonant Link technology can convert significantly more power per cu.m. than conventional systems.

Very high-power density (~5.5MW/cu.m.) - Resonant Link converters have ~40-70% less footprint than conventional systems of the same MW rating. This results in more space in the nacelle (all AC-DC converters, including their integral high frequency transformers) are installed inside the nacelle).

Sinusoidal voltages and currents - Input and output THDi (AC) are <1% THDi. THDu is dependent on system impedances and platform non-linear loads (ESP, compressor, AC & DC drilling package and other adjustable speed drives).

High conversion efficiency (~98%) - Due to soft-switching technology, the high efficiency of Resonant Link results in significantly less power losses over the life of the wind turbines/wind farms.

Use of high frequency nanocrystalline transformers - Voltages, AC and DC, can be transformed without conventional transformers by utilizing integral nanocrystalline types, operating at 6-20kHz.

The high frequency transformers are a fraction of the weight and physical size of conventional types, (e.g., weight (IP00) with windings is 100kg/MW). These are an integral part of the AC-DC and DC-AC converters.

No AC or DC short circuit protection required - Resonant Link converters are complete fault-immune operation and provide natural fault current limiting (i.e. zero-current turn-off). No costly and bulky AC and DC protection for short circuit are required . No costly structures are necessary to house them. With Resonant Link, only isolators are required.

Multi-port operation - Multi-port operation yields instantaneous redirection of power flow, plus Resonant Link converters can cater for power to/from local or subsea lithium battery/ supercapacitor-based energy storage systems (HESS/ESS), including for future retrofitting.

3. Overview of Resonant Link technology for offshore wind applications

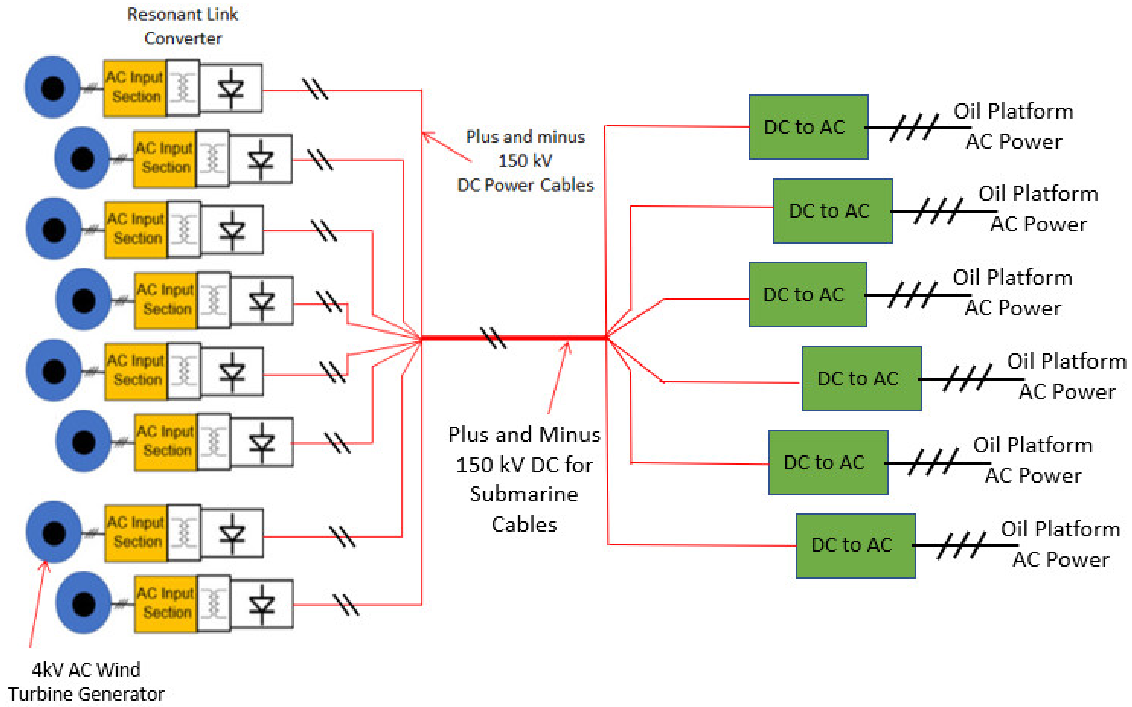

Figure 1 : Wind farm comprising 8 x 15MW turbines connected to multiple offshore platforms through +/-150kVDC submarine cables and Resonant Link DC-AC converters at voltages required by each platform.

Figure 1 above depicts an overview of an installation of eight 15MW wind turbines supplying six discrete platforms. Within each turbine nacelle would be installed a modular Resonant Link AC-DC converter. The number of power modules in each nacelle is dependent on the power rating of the generator. In the example above, there would be 6 x 2.5MW power modules connected in parallel for each 15MW Resonant Link converter system. 4kVAC voltage is shown above as the optimum generator voltage for IGBT ratings, although other AC voltages can be utilised.

The generator AC voltages are transformed via integral high-frequency transformers within each Resonant Link AC-DC module before being rectified to 150kVDC for parallel transmission via submarine cables. On each discrete platform, a modular Resonant Link inverter system will invert the 150kVDC voltage to the appropriate AC voltage and frequency.

With Resonant Link technology, no additional equipment is required, including harmonic filters, VAR control systems, short-circuit AC and DC protection nor the large and expensive structures to house them.

4. Basic description of operation (AC-DC)

A simple dual module, Resonant Link converter in an AC-DC (rectifier) configuration is illustrated in Figure 2. For offshore wind, the AC voltage input may be 690V-4kVAC, 50/60Hz. However, 3kV-4kV is optimum for the rating of the IGBTs or other devices. The input filter section ensures both the input voltages and currents remain sinusoidal.

The Resonant Link technology is 'soft switching'. This means that the commutation of the power devices (i.e. switches) occurs at only zero current, thus eliminating the high switching losses which other technologies have.

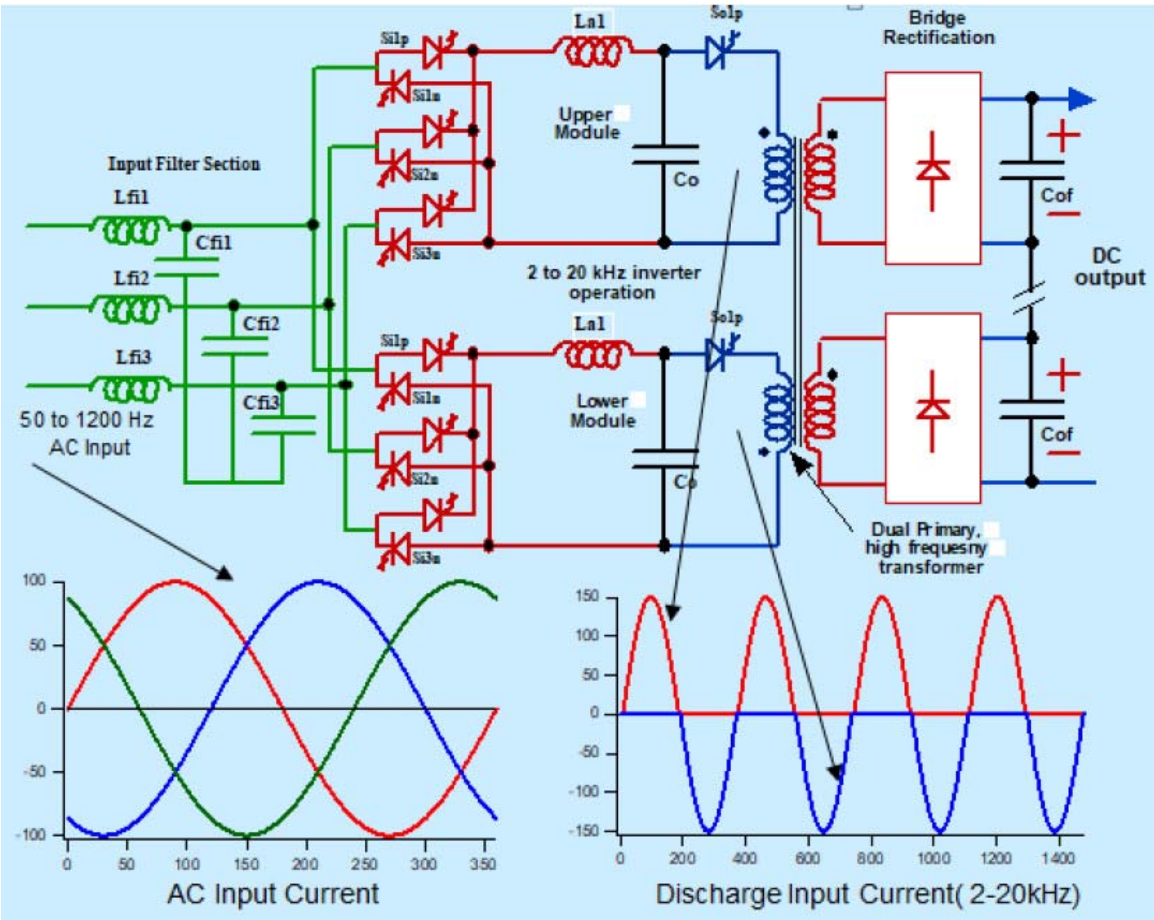

Figure 2 : Dual module AC-DC converter

At the input of each phase there is an inductor, combined with an input capacitor generates a low pass input filter frequency of typically 720Hz. This cut-off filter will draw an input current that has less than a 1% of current harmonics from the supply (<1% THDi). For each charge cycle, a charge would be drawn from each input phase per pulse which is proportional to the input voltage amplitude. This draws a unity displacement power factor, power from the power source, which in the case of offshore wind are the turbine generators. The total input pulse resonantly charges the 'Co' central capacitor through the resonant inductor 'La1'.

The first charge turn-on occurs with a zero current, therefore the IGBTs have no turn-on losses. Similar to the input IGBT back-biased at the end of the charging pulse, the current is again at zero with no turn-off switching losses. The soft switching procedure with no turn-on and turn-off losses also occurs during the discharge processes (Figure 7). There are no switching losses for high voltage IGBTs, such as those rated at 6.5 kV, so these IGBTs can be operated with switching frequencies up to 20kHz. This results in a reduction in all passive components and reduces the number of IGBTs and associated snubbers required to be connected is series, thus reducing weight, volume and cost.

The dual primary winding high frequency transformer illustrated can have a step-up or stepdown voltage ratio, although for offshore wind, a step-up ratio is used to obtain the desired higher voltage levels.

A closer look at the operation of then converters in Figure 2 utilises two Resonant Link modules which draw power from the wind turbine generator and as each module discharges, in sequence, into the high frequency transformer primaries.

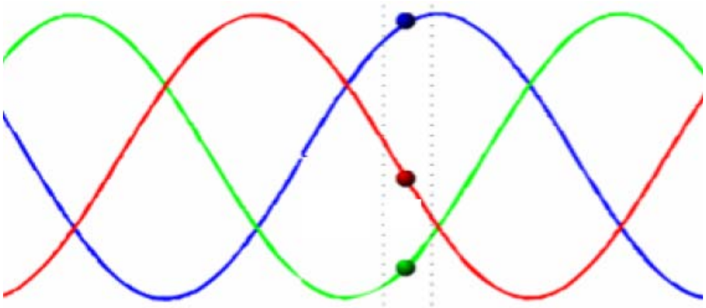

Fig 3: Input AC voltage from turbine at an arbitrary moment

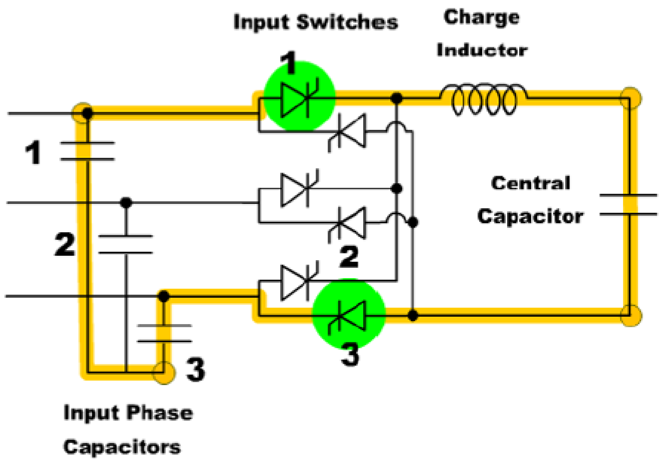

Figure 4 : Initially, the charge is drawn from phases L1 and L3

The central capacitor (Co) is initially charged at the line of dots indicated by Figure 3 by connecting first phase 1 and phase 3 to the input of the Co capacitor with the resonant inductor in series (illustrated by the yellow line in Figure 4). There are no switching losses, so the current is zero is shown in Figure 5. The current increases sinusoidally as shown also in Figure 6 and the current flows through the components shown in Figure 4. As a sufficient charge is drawn from the negative phase 3, the negative switch (or commutation switch) of phase 2 is triggered. Since the input voltage between phase 1 and phase 2 is larger than between phase 1 and phase 3, the negative switch of phase 3 is back-biased and turns off and the Co capacitor is continued to be charged from phase 1 and phase 2. That switching point is also seen in Figure 6 and the currents through the components are shown in Figure 5. As the charging is completed and the charging current become zero, the current of phases 1 and phase 2 become zero and the switches again have no switching losses at the turn-off. After that point the discharge can start. For AC to be transformed into DC operation, the Co capacitor is switched into one of the primary transformer windings.

As the central capacitor ('Co') of the first module is charged from the AC input in two steps (Figures 2 and 6), while the energy stored in the second module central capacitor is discharged. The discharging current and voltage are shown in Figure 7.

Note : Figured 4 and 5 show SCRs, which are limited to around 2.5kHz. Above that, IGBTs and blocking diodes perform the same functions up to 20kHz.

Each central capacitor ("Co")and the transformer leakage inductance form a resonant circuit which produces a 'half-sine wave' on to the transformer secondary for the output. These half-sine waves are pre-determined by the switching frequency, which in turn is based on the design criteria. The transformer secondary current waveforms are then rectified and injected into the output filter capacitor.

When the first cycle is completed, the role of the two modules is reversed and the second module recharges while the first module injects an identical energy (Figure 2) and current pulse into a second primary winding. For the second pulse, the magnetic flux is reversed to produce a second half-sine wave with opposite polarity onto the secondary winding to complete a full sine wave, shown as the 'discharge input current' in Figure 2.

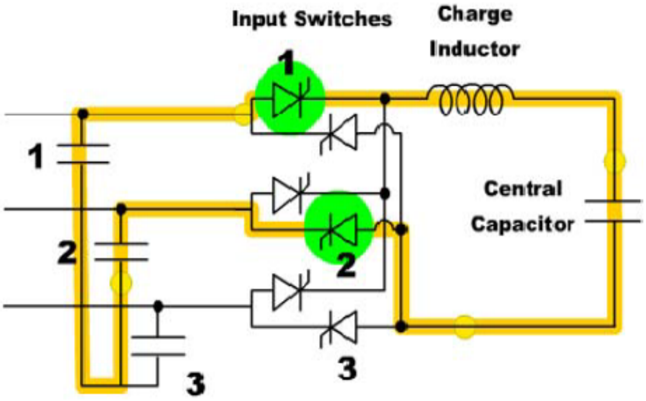

Figure 5 : At predefined calculated moment 'τ' the remaining phases 1-2 starts to conduct

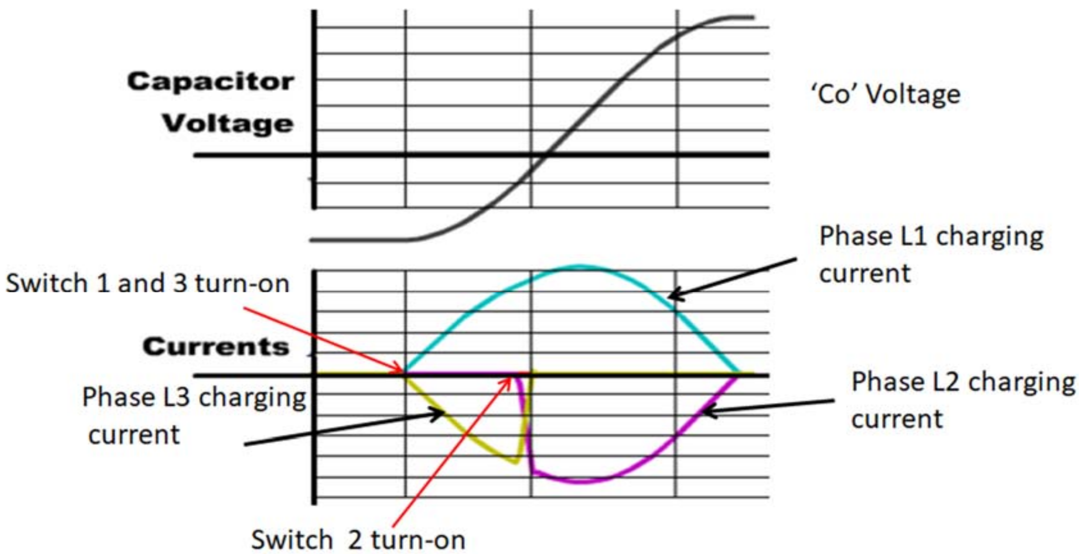

Figure 6 : Charging voltage on Co, Charging Current of Phase L1, l2, and L3, and trigger on all three input phases

After the output current of phase L1 and L2 goes to zero, the IGBTs are back-biased and the charging cycle is complete. The central capacitor 'Co', the high frequency transformer leakage inductance and the DC side capacitor 'Cof' (Figure 2) constitutes the output resonant circuit. The control system maintains the predetermined output reference voltage, or equivalently the output capacitor works as a regulated capacitive voltage source. The discharge cycle is shown overleaf (Figure 7).

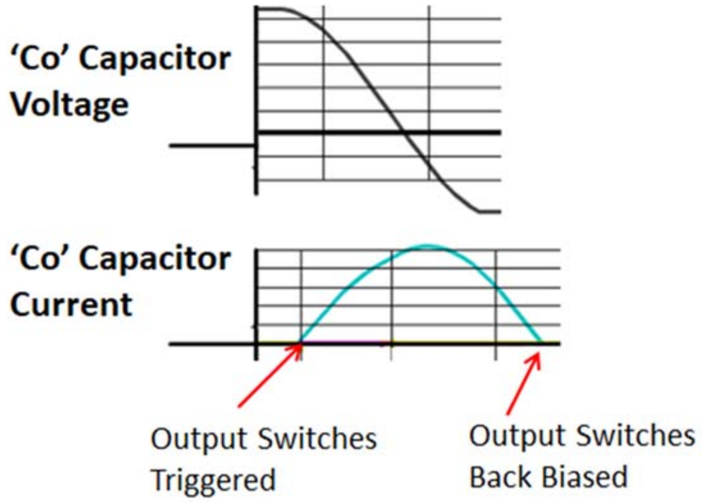

Figure 7 : 'Co' Capacitor voltage and discharge current

The discharge is a simple process. The output switch is So1 is triggered forming a resonant circuit with the 'Co' capacitor and the transformer leakage inductance with a discharging period similar to the charging period. The output of the secondary of the transformer is rectified via conventional diodes to yield a voltage of 150kV DC as shown in Figure 2.

In practical applications, where parallel module may be used, each modules controls only its designated output 150 kV DC voltage. The modules' charging and discharging result in a low ripple that requires no additional filtering.

By operating the converter at a frequency of around 6kHz, for example, not only the current ripple can be effectively filtered, but also the required transformer size is significantly reduced. For example, a 1MVA, IP00, high frequency nanocrystalline transformer with windings weighs around 100kg, a fraction of the weight of as conventional 50Hz or 60Hz transformer (around 2870kg in IP00 format). Indeed, these transformers are so small they are installed within the Resonant Link AC-DC and DC-AC convertors.

Once complete, the 6-10kHz high frequency sine waves of appropriate AC voltage amplitude are rectified with convention diodes to the DC transmission voltage of 150kVDC for offshore wind but for short distances this MVDC voltage can be reduced. For high power applications such as offshore wind, Resonant Link modules are parallel connected, each being 2.5MW or 3.0MW, depending on the switching devices and voltage utilised. For example, a six-module unit would be, 15MW as illustrated in Figure 8 below. **The converters of whatever MW rating would be installed inside the nacelle. No other equipment is required, no short circuit protection, no harmonic filters, nor VAR controllers required !** Depending on what type of generator is used (i.e. induction or permanent magnet), reactive power control can be supplied by the Resonant Link converter.

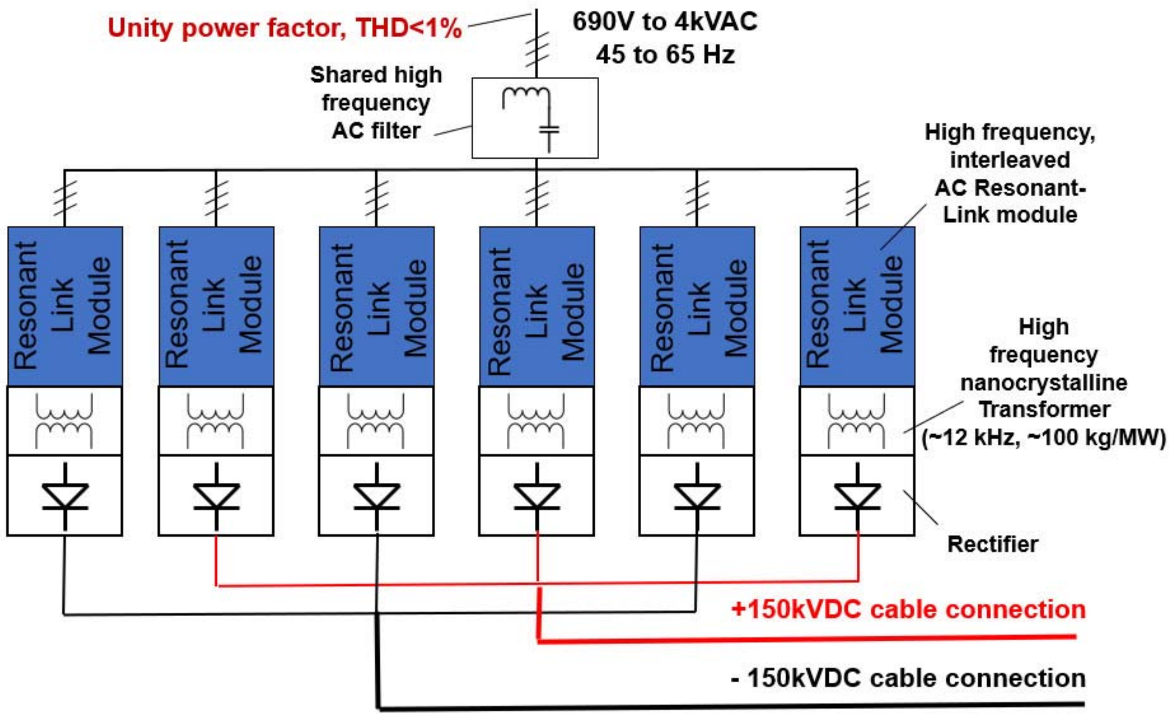

Figure 8 : Example of six (15MW) AC-DC converter

Figure 8 illustrates a 15MW rectifier system based on six 2.5MW modules Note : 3.0MW per module is also possible based on 3kV-4kVAC input and appropriate power devices.

5. 150kVDC export cables

In a conventional system, the DC cables from each turbine in the array must be gathered at a central point, usually a collector/converter platform or offshore substation, where the DC voltage is boosted to 150kVDC (or other DC voltage) for onward transmission to the platform(s). Crucial for conventional system is the requirement is the need for fast DC circuit breakers to limit the short circuit current. These normally form part of the equipment installed on the collector/converter platform. The power transmitted to each platform, the number and rating of the cables is dependent on the power requirements of the platform.

Within each Resonant Link technology AC-DC (150kVDC) converter is inbuilt short-circuit and over current protection for the converter modules themselves and for the export cables. In the event of a fault, the converters cease operating within 200 microseconds, much faster than conventional DC breakers. No additional structures are required for additional equipment.

For applications where there are a small number of dedicated turbines (e.g. 30MW of power transmission to a single platform), the 150kVDC cables can be run directly from each turbine to the platform where the multiple DC cables connect to the Resonant Link inverter (DC-AC). No structures and additional platforms are required. For larger number of turbine installations, where the distances are not significant, point to point connected may be applied or, a subsea collector may also be considered. The latter is possible since the short circuit protection, normally located on offshore substations for conventional DC systems, is already provided on each Resonant Link AC-DC converter module installed within the turbine nacelle.

On each platform, a Resonant Link DC-AC converter would be installed, whose total output is determined by the number of power modules required and is based on power requirement of each discrete platform. The voltage and frequency would also be platform dependent.

6. Inversion of 150kVDC to a platform(s)

On the platform the 150 kV DC power is converted to AC, as illustrated in Figure 9 below, the input of the DC to AC modules are series connected across the 150kVDC (or other HVDC voltage). Each module is configured such that any failure in one module will have no effect on remaining power modules. In addition, each input DC module is 'hot swappable', which means it can be isolated and safely removed and replaced without affecting the operation of the converter system.

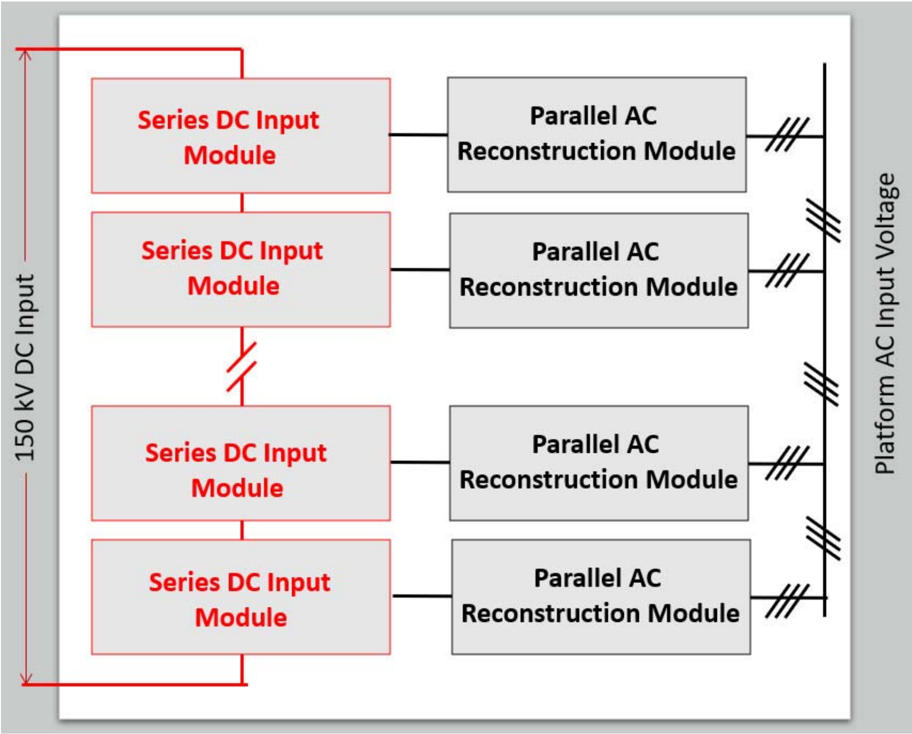

Figure 9: Configuration of DC-AC modules installed on a platform (150kVDC input)

The input 150kVDC bus voltage is proportionally distributed across each module Udc/N (where Udc is the DC voltage and N is the number of power modules). These **N** modules operate synchronously, each one optimized to work with a predefined amount of charge\energy\current (i.e., other voltage levels or power levels can be easily achieved).

In essence, the primary DC filter capacitors, series inductors and central 'Co' capacitors creates the input series resonant circuit, the same central capacitors, same series inductor, with high frequency transformer, and the output filter capacitors create a second. The energy per pulse is injected into the 'Co' capacitor during the 'Co' charging process. The control system distributes the central capacitors charge in such a way, that the output currents have specified frequencies and AC output voltage. The complete process is repeated at a high frequency, of around 6-10 kHz, depending on the power requirements and the devices being utilized. Each pulse is created by combining small amounts of charge taken from each of the modules. When the pulse is passed to the output, it is distributed among the three output phases controlling the amounts of charge controlled by the output IGBT, taken from or distributed into each phase, the current on each of the three inputs and each of the three outputs can be precisely controlled.

A block-diagram and a typical schematic of an inversion module (DC-AC) are shown in Figures 10 and 11 below, each module contains two primary DC filter capacitors Cn and Cn-1 (depending on the number of modules). Two smaller central capacitors energy Co1 and Co2 store precalculated amount of energy per pulse, necessary for one resonant charging/discharging cycle. Essentially, the DC storage capacitors are five times bigger than the central storage capacitors. These capacitors work sequentially to fully magnetize and demagnetize the high frequency transformer. Their charging and discharging cycles are time separated (i.e., Co1 and Co2). Two back-to-back devices adjust/regulate initial voltage value on these central capacitors such that during next charging cycles from the DC-bus primary storage capacitors, those capacitors will contain the amount of charge necessary for the output AC-current reconstruction. At each moment of time, only one IGBT out of four has “on”-state.

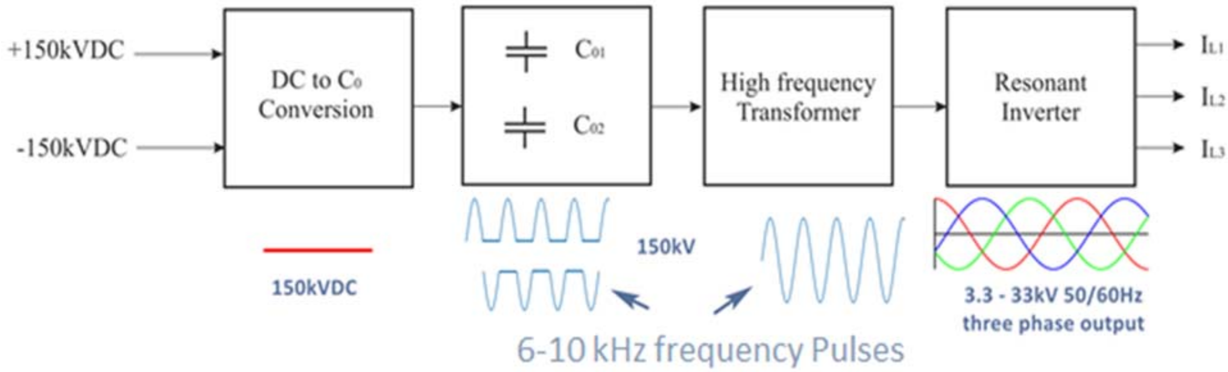

Figure 10 : The output DC-AC converter is similar as the AC-DC converter with the roles reversed.

This transfer is accomplished by again charging up the central capacitor with current from the DC side, then fully discharging the central capacitor into primary of the nanocrystalline transformer. Each charge and discharge process results in positive and negative half cycles of current are passed from the MVDC (150kVDC) input to the high frequency nanocrystalline transformer, where it is stepped down to an appropriate AC voltage level and frequency, which after reconstruction is suitable for platform use, for example (3.3-33kV). A typical schematic of an inversion module (DC-AC) showing components is illustrated in Figure 11 below.

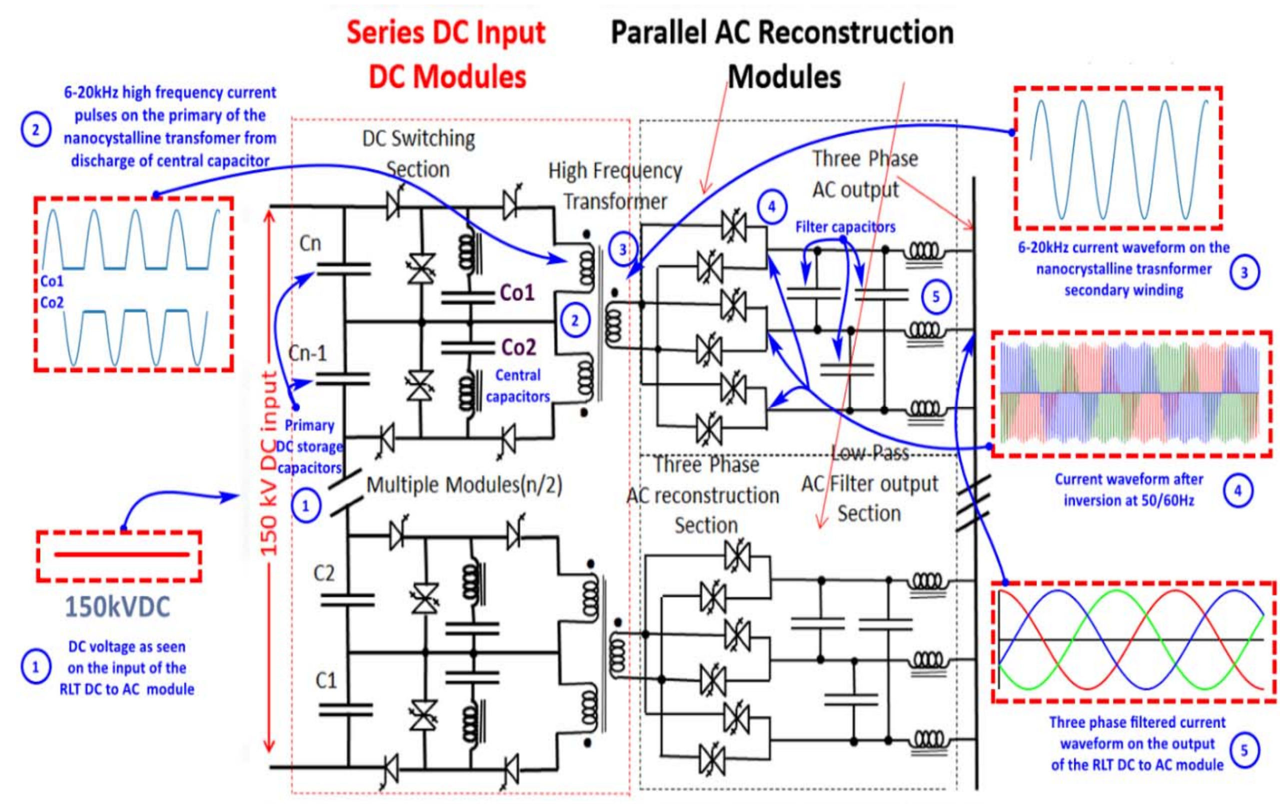

Figure 11 : Basic schematic of DC-AC modules installed on a platform (150kVDC input)

At the Resonant Link converter input (Figure 11), the output current is transferred into each output phase, per pulse. The pulse energy and the converter frequency are controlled to yield the required AC output voltage. Two input modules are utilised on the primary of the nanocrystalline transformer in push-pull operation such that the magnetic flux in the transformer core is reversed. The transformer winding ratio is selected to match the primary voltage to the secondary output ratio.

As the platform AC load is typically reactive, the Resonant Link reconstructed current will have both real and reactive reconstructed components. This eliminates requiring a separate VAR generator source as ‘Statcom’ to provide displacement power factor correction for the equipment onboard the platform.

The authors have tried in the above, to illustrate to the readers, a basic understanding of Resonant Link technology when applied to offshore wind applications; a technology which has many significant advantages over the convention technologies currently being utilised . This reflected on Page 3 and in the Conclusions section on Page 14.

Conclusions

Hopefully, it has been demonstrated that Resonant Link technology is vastly superior to conventional technology for the powering of bottom-tied and floating wind turbines.

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

Resonant Link technology also offers extremely fast short-circuit protection (<1ms – less than 1/20th of a cycle), compared to conventional technology at no additional cost. Neither does it require expensive harmonic 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 has the potential to be **the** 21st Century, the 150kVDC alternative for converting and transmitting bottom- tied and floating wind energy to platforms and beyond.

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