Clean, innovative DC power for marine and offshore applications via AC-Link^{TM} technology

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Executive Summary

This White Paper outlines a relatively new, alternative power conversion technology termed "AC-Link^{TM}. The technology, invented by Dr Rudy Limpaecher, has its roots in the so called 'StarWars Programme' in the USA. To date it has been developed mainly for the US military, including the US Navy, US Army and US Air Force. The technology is now being developed and used for a number of commercial applications.

The salient benefits of AC-Link^{TM} compared to conventional technologies is that it is 'soft switching', has therefore very low EMI emissions and also draws virtually zero harmonic current from the source (i.e. the resultant voltage distortion is very low compared to conventional technologies).

Unlike conventional power converters, AC-Link^{TM} does not require large and expensive conventional transformers in order to step-up or step-down AC voltages. Instead AC-Link^{TM} has, where applicable, an internal high frequency transformer (20kHz operation) which is a fraction of the physical size and weight of conventional types (e.g. a 250kW 480V/40kV AC-Link^{TM} weighs only 11kg/26 lbs). AC-Link^{TM} can transform both AC and DC voltages. Indeed, the capability of a 3:1 step-up or step-down transformer ratio is inherent within the AC-Link^{TM} converter without the requirement of a dedicated high transformer.

Its small comparative footprint/MW, low weight, high performance (i.e. including integral short circuit and overcurrent protection), low harmonic and EMI emissions make AC-Link^{TM} an ideal candidate for applications where space and weight are serious considerations and where generator derived supplies are utilized. In comparison to conventional power conversion technologies, AC-Link^{TM} offers high performance, compact, innovative, cost effective solutions.

This White Paper discusses the significant features and benefits of AC-Link^{TM} technology including considerable savings in equipment, installation and operating costs but concentrates on the provision of 'clean' DC power for marine vessels, offshore drilling rigs and oil production installations which utilize multiple AC variable frequency drives (VFDs) and where 'common DC bus' and 'DC ring main' systems can be implemented. A number of sample applications are illustrated in the White Paper.

The White Paper also advocates AC-Link^{TM} technology for platform-platform, platform-shore and platform-subsea 'point to point' HVDC transmission applications and for subsea distribution, if required (including future subsea pumping stations).

In addition, as presented in the White Paper AC-Link^{TM} can be considered the ideal candidate technology for the new offshore All Electric DC Subsea Wellhead Systems, the development of which is now starting to replace conventional subsea well head control stations (which have hydraulically operated vales, actuators and other equipment) with 'all electrical' equipment. One result is that the heavy and very expensive hydraulic-electrical umbilicals, which cost up to US$ 700,000 per kilometre, can be replaced with smaller, lighter and much less expensive electrical cables.

The application of AC-Link^{TM} clean DC power to the marine and offshore sectors is challenging but exciting technically and commercially and entirely possible.

1.0. Introduction

Historically, the World's first commercial available electricity distribution system was based on DC (i.e. direct current). However, the DC system pioneered by Thomas Edison in the 19th Century was deemed to be uneconomical and impracticable due mainly to the inability to transmit power relatively short distances (i.e. no more than around one mile) at relative low DC voltage levels.

AC (i.e. alternating current) distribution systems, which were also starting to be commercially available at the same time, offered significant advantages compared to DC including the ability to step-up and step-down AC voltage levels via transformers or for bulk transmission over long distances and for local distribution to consumers. The AC induction motor, still the rotating 'workhorse' of industry today, invented in the 19th century revolutionised industry. The advantages of AC compared to DC were so overwhelming that it was largely adopted worldwide as the standard transmission and distribution electrical power system.

However, in the 21st Century the idea of a local, dedicated DC distribution systems (e.g. within a factory, computer server, ship or oil production platform) is now gaining popularity. It is not so surprising given that the majority of industrial and commercial electronic devices indirectly* rely on DC (i.e. the AC voltages have to be rectified into DC voltage for the device) including computers and most associated office equipment (e.g. printers, scanners, fax machines). In addition, AC variable frequency drives (VFDs) for speed control of AC induction motors require an internal DC bus. Many renewable power sources (i.e. wind, tidal, wave and solar) produce DC power which has to be inverted into AC for transmission and distribution. Many continuous process industries such as those involved in the processing of steel, copper, aluminium, hydrogen, zinc, manganese are also indirect users of bulk DC power.

*It should be noted that in order to provide indirect DC power from an AC network transformers, rectifiers and very often harmonic mitigation is required thus increasing purchase costs, reducing efficiencies and increasing running costs and increasing space requirements. In addition, the increased cost of DC switchgear is significant both in terms of costs and of technical challenges.

In each application area the production of harmonic currents (i.e. currents which are multiples of the fundamental frequency) due to the rectification of the AC voltage to DC voltage via conventional technology is now of such serious concerns worldwide such that most countries apply strict limits on the importation of harmonics into the network by consumers.

For the transmission of large amounts of electrical power HVDC (i.e. High Voltage Direct Current transmission) is increasing in popularity worldwide. Using technologies such as AC-Link™ this trend to HVDC is set to accelerate as short transmission distances become more financially viable.

2.0. AC-Link™ technology

This 21st Century, innovative power conversion technology is a product of the so-called US 'StarWars' program of the Reagan years and beyond. It was invented and patented by Dr. Rudy Limpaecher, a plasma-physicist in the 1990s, initially for high power energy laser power supplies.

Until recently, AC-Link™ was almost exclusively used in developments with the US Navy, US Army and US Air Force. Currently, it is both in service with US Navy for general duties and is being further developed as a multi-port converter (see Fig 1) for main propulsion, advanced electric weapon systems and other duties within the US military arms, most of which are classified.

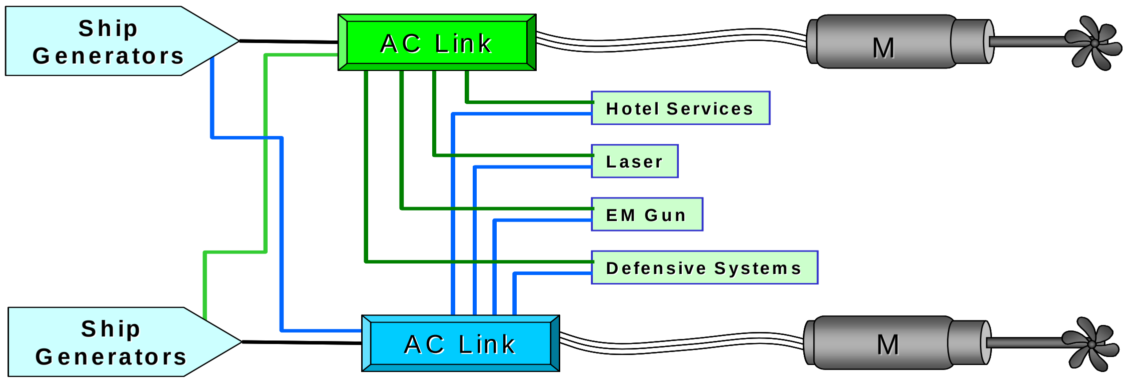


Fig 1 – Basic illustration of a proposed 36MW multi-port AC-Link™ converter system for warship main propulsion, hotel loads, weapon and defensive power supplies

AC-Link™ technology is now available for industrial, commercial and non US Navy NATO applications. It is already been developed commercially to converters for renewable power sources, and AC variable frequency drives and being developed for HVDC transmission systems. Attention is now being directed to direct DC power supplies.

3.0. Comparison - AC-Link™ & conventional power conversion technologies

One of the most important differences between AC-Link™ and conventional technologies, which is described in more detail in later sections of this White Paper, is that AC-Link™ is 'soft switching (i.e. it does not switch current on load and therefore has no switching losses; only conduction losses). In comparison, the vast majority of conventional technologies are 'hard switching' (i.e. have both switching and conduction looses). Therefore AC-Link™ technology is the more efficient.

In addition, the soft switching characteristics permit AC-Link™ based equipment to switch at significantly higher frequencies, especially at MV (i.e. medium voltages), often without the use of series connected devices. This impacts positively on manufacturing costs, reliability, efficiencies and physical size of equipment compared to equipment using conventional power conversion techniques.

However, one of the most striking differences between AC-Link^{TM} technology and conventional power conversions is in the production of harmonics currents. Total harmonic voltage distortion (THDv) is due to the interaction of the harmonic currents with the impedances in the power system and is undoubtedly a significant technical constraint on most power systems, especially on ships and offshore installations, due to for example, variable speed AC and DC drive rectifiers and generator derived power supplies.

The adverse effects of harmonic currents and the subsequent harmonic voltage distortion are widely recognized and do not require reiterating in this document. Excessive voltage distortion (THDv) is a very serious problem. It is not surprising therefore that utilities and other authorities have introduced stringent measures to limit the harmonic distortion in power systems. In the USA and internationally, IEEE 519 (1992) limits the THDv at the PCC (i.e. point of common coupling) to 5%. The United Kingdom harmonic recommendation EA G5/4-1 similarly limits the importation of harmonics by consumers. The majority of marine classification bodies also limit the magnitude of THDv to 5% (Lloyds Register is 8%) in order to minimize any damage or disruption as a result of the harmonic currents produced by variable speed drives and other 'non linear' equipment.

Additional, expensive harmonic mitigation equipment has therefore to be installed in order to reduce harmonic currents to acceptable levels thus increasing the cost of equipment, the space required, the overall efficiency of rectifier fed equipment such as variable speed drives and other non linear equipment. In the region of US$ 3-5 billon is spent each year (Frost & Sullivan, 2005) worldwide on harmonic mitigation by consumers in order to comply with the relevant harmonic recommendations and regulations.

Medium to high power rectification systems, including those pertaining to AC and DC variable speed drives, normally require some form of harmonic mitigation. The additional equipment required to attenuate the harmonic currents to acceptable levels can be of a passive or active (i.e. electronic) design.

The most common forms of harmonic mitigation currently available are :

- Tuned passive L-C (i.e. inductor-capacitor) filters
- Passive multi-limbed reactor/capacitor wide spectrum filters
- Multi-pulse rectifiers (multiple 6 pulse rectifiers with phase shifting)
- Quasi multi-pulse systems (using multiple rectifier loads and phase shifting)
- Active (electronic) filter which act as low impedance source for harmonic currents
- Active front end (AFE) rectifiers (i.e. sinusoidal rectifiers)

Fig 2 depicts a high power (75MW) HVDC transmission rectifier system with both AFE and passive L-C filters.

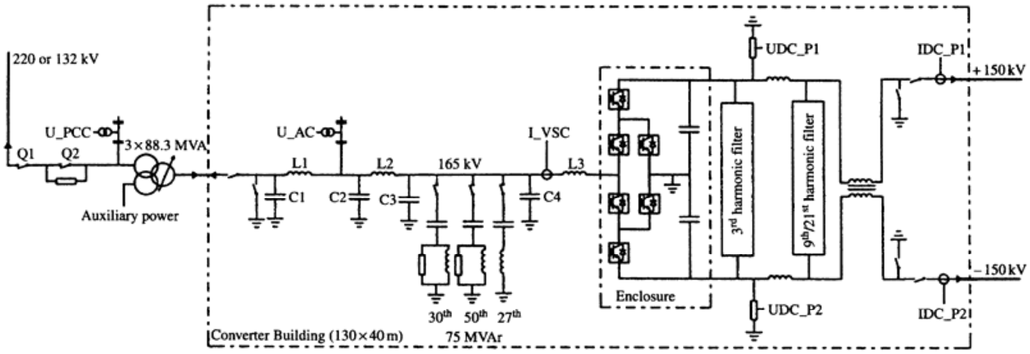


Fig 2 – Example of a high power HVDC transmission rectifier with combination of multiple IGBT AFE front end sinusoidal rectifiers and passive L-C tuned filters

The performance in terms of the reduction in harmonic current and associate THDi (i.e. total harmonic current distortion) varies with the type of mitigation employed. However, the following THDi (i.e. total harmonic current distortion) figures, based on diode rectifiers (the THDi are slightly lower on SCR rectifiers which have inductive loads {e.g. DC drives}), are typical if the type of mitigation is correctly designed and applied :

- 6 pulse diode rectifier on VFD – 85% Ithd if no additional reactance
- 6 pulse diode rectifier on VFD – 38-40% Ithd if 3% AC line reactor installed
- 6 pulse diode rectifier with wide spectrum filter – 5-6% Ithd
- 12 pulse multi-pulse rectifier – 12-15% Ithd depending on transformer type
- 18 pulse multi-pulse rectifier – 5-6% Ithd depending on transformer type
- 24 pulse multi-pulse rectifier – 3-4% Ithd depending on transformer type
- Active filters - <5-8% Ithd depending on design
- Active front ends (AFE) rectifiers - <5-7% Ithd depending on design (<50th only)

The above THDi figures are based on maximum load and ideal voltage supplies. In reality, background voltage distortion and/or imbalance in the supply voltages, which in the case of the equipment with multi-pulse rectifiers, will degrade the performance significantly by forcing the rectifiers to produce ‘uncharacteristic’ harmonic currents. In addition, equipment such AFE rectifiers (i.e. active front end) have significant issues which have to be addressed including production of harmonic currents above the 50th, the exact frequency of which is dependent on the AFE rectifier switching frequency (Fig 3), a ripple on the supply voltage (Fig 4).

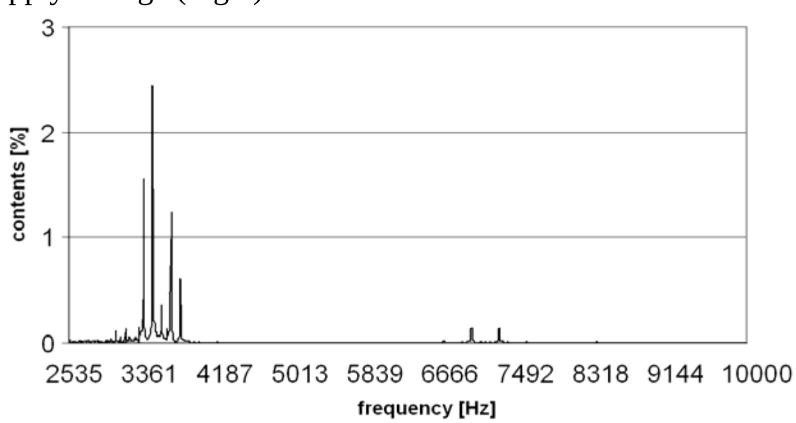


Fig 3 – AFE harmonic current spectrum above 50th harmonic (2kHz) up to 10 kHz.

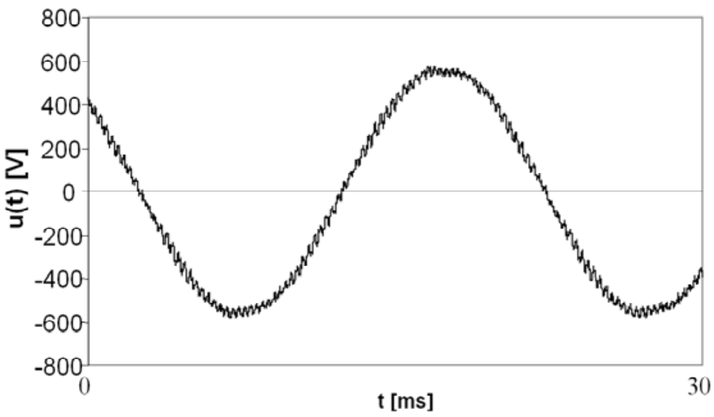


Fig 4 – Voltage ripple on the 400V system voltage when AFE VFD drives are operating

It should be noted that some forms of conventional rectification (e.g. fully controlled SCRs) can reduce the displacement power factor. Depending on the type of system (diode or SCR) additional VAR support via de-tuned capacitors or electronic VAR control may be required adding to the overall cost and reducing the overall system efficiency further.

Power transformers are often important elements in rectifier systems and usually provide three important functions :

- Galvanic isolation between AC input and DC output in order that one leg of the DC voltage can be grounded if required.
- Provides voltage step up or step down to the rectifier.
- If on a multi-pulse rectifier system the secondary windings can be phase shifted in order to obtain a measure of harmonic attenuation.

However, transformers are expensive' heavy and bulky but are necessary for use with conventional power conversion systems.

AC-Link™ is arguably the world's first 'universal' power conversion technology due to the ability to convert DC voltages and/or invert AC voltages steplessly, without conventional transformers and with virtually zero harmonic emissions (<1% THDi). In addition, AC or DC voltages can be stepped up or stepped down within the AC-Link™ without the requirement of conventional power transformers.

4.0. Functional description of AC-Link™

In essence, AC-Link™ draws 'energy packets' at a high frequency from the input to construct the desired output AC waveform or DC voltage. The basic converter (Fig 5) is 'soft switching', has no DC link or 'DC bus' (only a central capacitor) and is considered pseudo-galvanically isolated since the input is never directly connected to the output.

With reference to the warship multi-port configuration illustrated in Fig 1. The converter passes energy packets between multiple sources and loads at various frequencies and voltages (including DC). The energy packets can be redirected between loads in less than a millisecond. The multi-port configuration provides connection points for numerous loads including another AC power source or load (e.g. hotel loads), several types of motor drive loads, DC for industrial process applications.

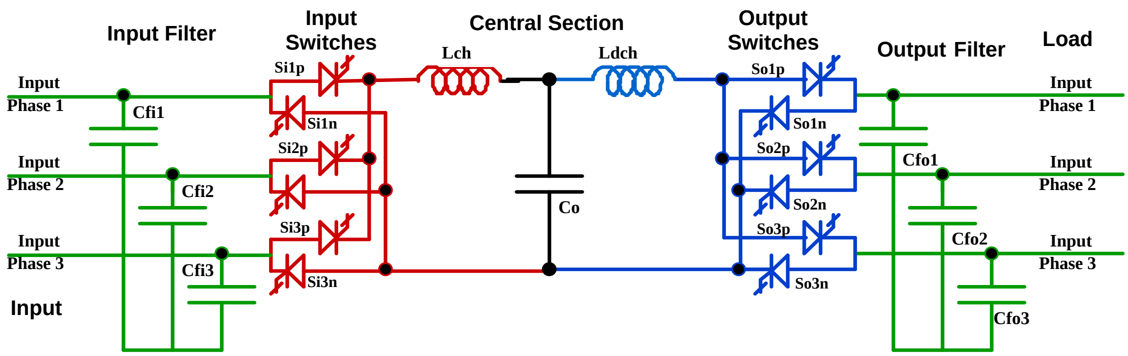


Figure 5 – AC-Link^{TM} converter for AC-AC conversion

As can be seen in Fig 5, the two port AC-Link^{TM} converter has on the left side an AC input section called 'input filter' which resonantly charges the central capacitor "Co" in the central section through the input charging inductor "Lch" at a frequency of between 2kHz to 20 kHz. For the lower frequency operation, typically inverter grade SCRs are utilized, while for the higher frequencies and higher operating voltages, IGBTs or IGCTs are used. For HVDC operation, with the inbuilt voltage transformation, it is proposed to use higher frequency operation in order to reduce weight, physical size and cost of the transformer magnetics.

Once "Co" is charged, it is subsequently discharged through the discharge inductor "Ldch" through the 'output switches', reconstructing an AC waveform with the desired voltage, frequency, and phase.

One key feature of the AC-Link^{TM} AC to DC bus application is best illustrated with the input current comparison of Fig 6. While, the standard 6 pulse rectifier has a measured THDi input of over 32%, the AC-Link^{TM} input current Ithd is below 2%. The latter harmonic level is well within the IEEE 519 and any global harmonic guidelines and does not require any additional harmonic mitigation from passive or active filters. An additional feature of the AC-Link^{TM} converter input is that the input displacement power factor can be adjusted to be both leading or lagging, supporting the overall power factor of the grid supply.

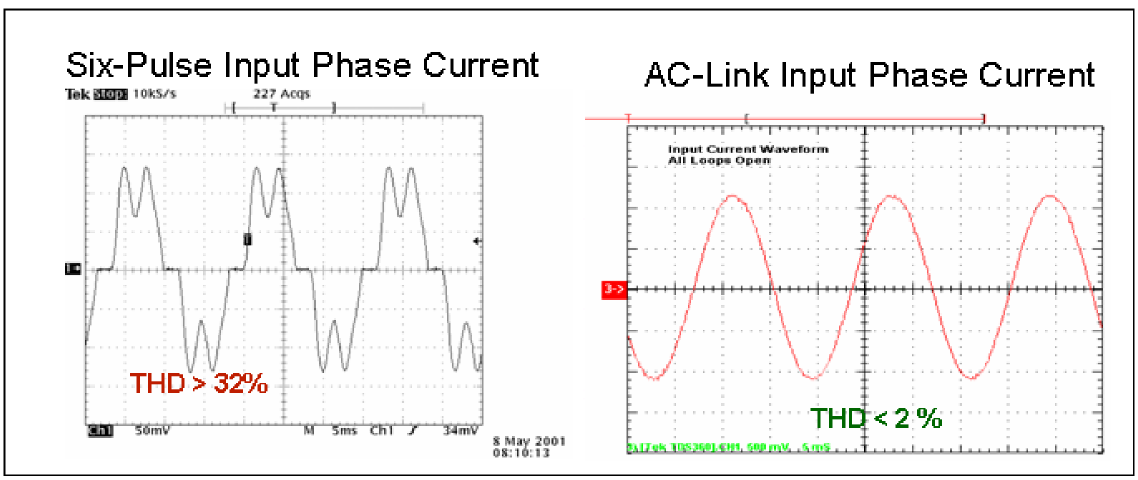


Fig 6 - Input phase current for a standard 6 -pulse rectifier and an AC-Link^{TM} converter

The heating of any IGBT and other solid state switches has the form of:

$$P_{th\max} = A*I + B*I^2 + (C_{ton} + C_{toff})*V_s*I*f_s$$

Note that the first two terms are the conduction losses and the second term consisting of the switch turn-on and switch turn-off losses. These constants, including the maximum switch dissipation are defined by the device characteristics and are typically given or can be computed from device datasheets. For a given power throughput, the first two conduction loss terms remain constant and are only a function of the current or power. The third term defines the switching losses, with the manufacturer typical provides both the turn on and turn-off loss coefficients. These switching losses are proportional to the switch voltage V_s, current, and the switching frequency f_s. For low voltage devices, the switch voltage is low and the switching turn-on time is short and therefore the switching losses are proportionally smaller. However, for a high voltage switch with a higher hold-off requirement, the third term will be dominated at a much lower switching frequency. As the third term increases proportional to the switching frequency, the current and the subsequent throughput power needs to be reduced to retain (for most switches) the junction temperature below a value of, for example, 125 deg C.

A typical electronic power switch throughput is illustrated in Fig. 7 for 6.5 kV IGBTs and compares an AC-Link™ converter and a PWM converter.

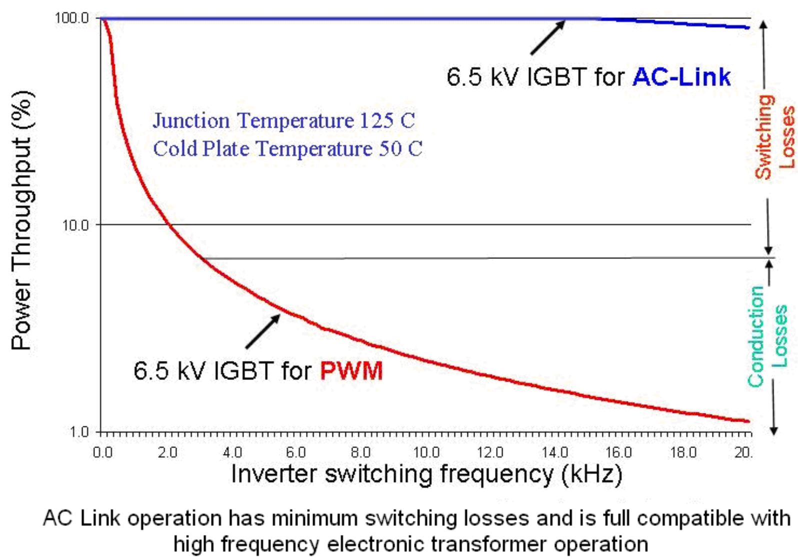


Figure 7 - IGBT throughput power for AC-Link™ operation and PWM operation

At low switching frequencies for both converter types it can be seen that the device has a similar power throughput since all of the losses are conduction losses. If the switching frequency is increased however, the current has to be reduced for the hard switching PWM operation, since the third term becomes an increasingly important consideration. For example, if the switching frequency for the PWM converter is increased to 400Hz (0.4kHz), the switching losses and conduction losses are about equal so the power throughput has to be reduced by about 50% in order to maintain the junction temperature below a maximum 125 deg C. Since the switching losses are the dominant portion of any converter losses, they also reduce the efficiency. As shown on the right side in Fig 7, the conduction losses are proportional to the power throughput given by the values below the performance line, while the relative switching losses are the values above the line.

For any "hard switching" converter topology high frequency operation is not practical, while the "soft switching" AC-Link^{TM} converter can use the 6.5 kV switches up to the switching frequency of 25 kHz with high switching efficiency.

For higher switching frequency, it can be stated that for a medium voltage (MV) PWM inverter 6.5 kV IGBTs cannot be used for most applications as the required switching frequency is significantly higher than 400Hz. To reconstruct a 60 Hz AC waveform, usually requires a minimum of 18 pulses per three phase AC waveform or about 650Hz-800Hz. It therefore follows that in practice, a MV voltage source PWM converter requires five or six series connected 1200 V IGBT for the hold-off of a 6.5 kV device; since lower voltage devices have lower switching losses, and the total switching losses have to be distributed over the five or six junctions.

In comparison, the AC-Link^{TM} switching losses are almost zero due to the natural "soft switching" feature, and the AC-Link^{TM} medium voltage converter can be operated, unlike the PWM converter, with 6.5 kV IGBTs at any switching frequency, up to about 25kHz. In other words, the third term in equation (1) above is nearly zero. This not only reduces the overall component count (in this instant by a factor of five to six) and reduces the physical system size and complexity but also significantly reduces losses. It also permits the use of 'high frequency transformers' (i.e. the transformer core size is inversely proportional to the applied frequency {i.e. inverter switching frequency}). This feature is a key to the AC-Link^{TM} DC transmission converter design.

AC-Link^{TM} is a unique and relatively new power conversion technology which provides both 'clean' (i.e. virtually harmonic free and dv/dt free) input and output voltage and current waveforms. AC-Link^{TM} utilizes proven and reliable components, control circuit design, control techniques and software.

5.0. AC-Link^{TM} benefits and advantages

The benefits that can be derived through use of AC-Link^{TM} are significant and varied but can be summarised as follows :

- Very high power density (~5.5MW/cu.metre) resulting in high power capability from a compact package. Ideal for applications where space is limited (e.g. ships, drilling rigs and oil installations). If used as a AC VFD, an AC Link^{TM} drive is around 10-20% of the size of a conventional PWM converter (in the medium to larger powers).

- High efficiency (~98%) with unity displacement power factor. Lower thermal losses and less running costs compared to conventional technologies. Payback time is reduced. Increased reliability and lifetime of components.

- Direct AC-AC conversion with <1% total current harmonic distortion (THDi). For (AC-DC, DC-AC, or DC-DC conversion are all simpler versions of AC-AC operation). No additional harmonic mitigation is required, resulting in reduced costs and reduced space requirements

- Conventional transformers are eliminated for voltage transformation and/or galvanic isolation requirements. Direct connection to MV supplies is easily achievable. Significant cost, space/weight and running cost reductions are provided.

- Very low EMI footprint. No additional harmonic or EMI filtering required resulting in reduced component weight, losses and overall cost compared to conventional power conversion technologies.

- Soft switching enables inverter operation over 20 kHz and high efficiency operation at medium voltage (IGBT operation). No turn off losses so increased efficiency compared to conventional technologies. Reduced stress of components resulting in increase reliability.

- Voltages, AC and DC, can be transformed without conventional transformers. Small step up and/or step down voltage ratios can be accommodated within converter without use of high frequency transformers (which, in any case is, a fraction of the physical size and weight of a conventional transformer). This results in large reduction is space and weight requirements'. Fig 8 shows an Resonant Link converter with integral high frequency transformer for 250kW DC power system (480V three phase input/50kVDC output). The integral transformer weighed 11kgs/26lbs compared to 1.4-1.6 tons for a conventional type of transformer.

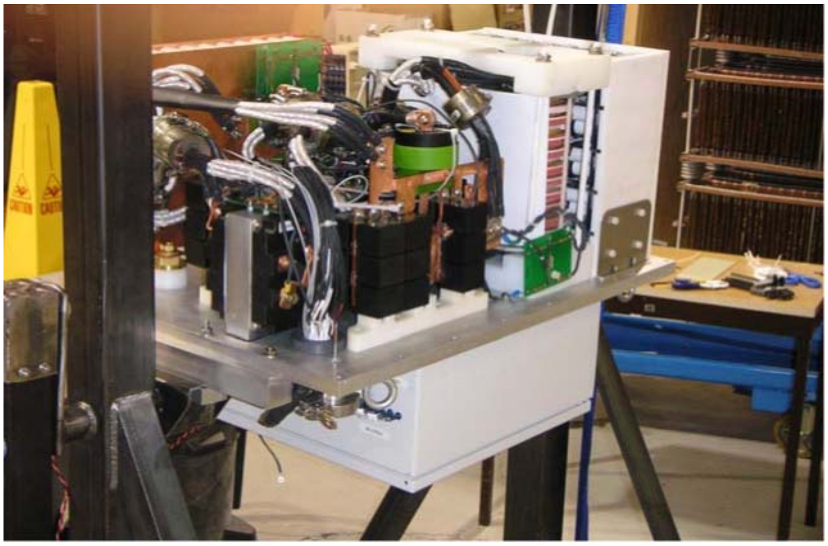


Fig 8 - 250kW Resonant Link^{TM} AC-DC converter for 480VAC-50kVDC. The integral high frequency transformer weighs 11kg.

- An AC-Link^{TM} MV AC VFD converter produces a dv/dt (i.e. rate of rise of voltage) of less than <15 V/uSec (at 4.16kV) thus eliminating insulation failure, bearing erosion and motor cable problems. No output filters required for long cable lengths (such as required on oilfield submersible pumps) and insulated bearings in motors not necessary.

- Multi-port operation yield instantaneous redirection of power flow. Can also be used to link, for example, multiple power sources or control power to/from multiple devices or consumers.

- Scalable to any power level with time-interleaved parallel module operation. By using standard rated power modules (1MW, 5MW for example) connected in paralleled most power and redundancy requirements can be accommodated. 'Hot swap' of power modules possible without loss of supply to consumers.

- Inbuilt short circuit protection. Fault-immune operation, natural fault current limiting (zero-current turn-off, no PWM shoot-through). AC-Link™ is significant faster in operation than any conventional or electronic short circuit protection for both AC or DC operation. No additional short circuit protection is required; this is especially important for DC systems with DC circuit breakers are very large and very expensive.

6. 0. Architecture of AC-Link™ AC-DC conversion

The AC-Link™ AC-AC converter, depicted in Fig 5 can be configured as an active AC to DC rectifier with three phase power input and regulated DC output as shown in Fig 9.

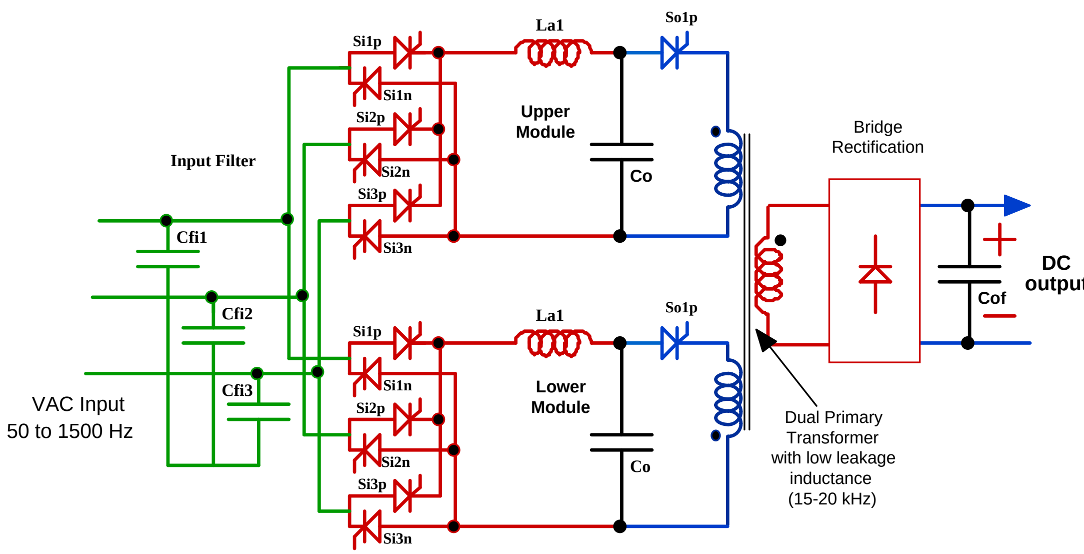


Figure 9 – AC-Link™ high power converter configuration

For the AC Link™ converter of Fig 5 (i.e. AC–AC converter) the inductor 'Ldch' is replaced by the leakage inductance of a high frequency transformer. This unique AC-Link feature uses the transformer as an integrated component of the AC Link™ converter. In addition, since the AC Link™ high voltage switch can be operated at high switching frequencies, this permits the use of a high frequency transformer with a very significant reduction of the transformer core cross section. This architecture therefore eliminates the requirement for large, bulky conventional (i.e. 50Hz or 60Hz) power transformers with a high frequency type with a typical weight of around 45 kg/MW. These features are illustrated in Fig 9 with AC as the input and DC on the output. Since the transformer can be designed for either voltage step-up or voltage step-down it is a universal AC to regulated DC converter architecture.

The output can be regulated from zero to full desired voltage with practically no output ripple; in conventional rectifiers than ripple on the DC voltage is dependent on the pulse number of the rectifier). Since the AC-Link™ system draws controlled energy on a pulse to pulse basis, the ripple current on both the input and output is at the inverter frequency (e.g. 20kHz) and is simply eliminated with small filter capacitors. In addition, since the AC-Link™ converter is "soft switching", a high switching frequency can be efficiently implemented, significantly reducing the cost and size of all passive components. Furthermore, the AC-Link™ requires no galvanic isolation between the AC input and DC output and the architecture permits the DC ground referencing without a dedicated isolation transformer.

The AC-Link^{TM} converter draws input power at unity displacement power factor with THDi of <1%, therefore requires no harmonic filtering and VAR correction. In addition, the output power can be ramped up, eliminating, the high input current inrush current encountered with classical rectification system.

This configuration is also symmetrical so power can flow bi-directionally with an output voltage level that can be boosted to over 150% of the input.

If a high voltage step-up or step-down ratio is required, the discharge inductor "Ldch" shown in Fig 5 (AC-Link^{TM} AC-AC schematic) is replaced with the leakage inductance of a single phase transformer. This implementation permits the configuration with an AC input and high or low voltage DC output. Fig. 9 illustrates a configuration where the leakage inductance of the single phase output replaces the discharging inductors "Ldch" of Fig 3. This generated a positive current pulse on the secondary that is rectified by the bridge rectification circuit.

In Fig. 9 a second AC-Link^{TM} module is connected in parallel with both bridges operating with the same transformer. While the first input module charges, the second module discharges and produces a negative output pulse on the secondary winding of the transformer. With this dual input module configuration the transformer sees a nearly sinusoidal high frequency current output that is rectified and utilizes the core of the transformer effectively.

For MV or HV operation the transformer will have multiple windings. The transformer winding voltage is carefully selected to match the diode or active device (e.g. IGBT) voltage to ensure that no series connected HV devices are required to be switched simultaneously with sub-microsecond timing. A filter capacitor is typically used as shown in Fig. 8 such that it yields a single winding stage voltage. These capacitors represent voltage sources connected in series to form a MV or HV DC voltage string.

Recently, a regulated HV power supply was constructed for the US military to yield 50kVDC output, utilized a twenty (20) winding, high voltage section. This transformer operates with an inverter frequency of 20kHz, resulted in a transformer of 11kg weight for a power output of 250kW and thus a transformer weight density of 44 kg/MW. The total core weight was 5 kg yielding 20 kg/MW for the transformer core. With such a low weight AC-Link^{TM} can afford to use low weight nanocrystaline core material, yielding minimum core losses. The core costs are reducing (with currently nanocrystaline core cost of US$100 per kg) to <$2000/MW.

In summary, AC-Link^{TM} AC-DC converter can be operated at high inverter frequency with readily available 6.5 kV IGBTs and IGCTs since the soft switching topology has virtually zero switching losses. In addition, by using the leakage inductance of a single phase transformer as part of the AC-Link^{TM} circuit topology, a low weight and efficient transformer can be used to eliminate the large 50 or 60Hz three-phase transformer that is required for both medium to high power DC supplies.

Although the schematics illustrate SCRs. IGBTs are commonly used due to high frequency requirements. In the future IGCTs, silicon carbine switches and other advanced devices will be available which will increase the power capability and performance of all AC-Link^{TM} power conversion solutions. It should be noted that for

SiC (i.e. silicon carbide) switches, required for PWM operation, requires an aluminum oxide layer for their functionality. These oxide layers have a limited life over an operating temperature of 160 deg C. This eliminates the key benefit for SiC switches for "hard switched" PWM operation. In comparison, the "soft switched" AC-Link™ inverter can use thyristors, such as SCRs and GTO's that do not required any oxide layers. This implies that a SiC AC-Link™ converter can be constructed today with all the SiC benefits including high junction temperature operation, higher rated voltage switches and lower conduction losses. However, the authors do not claim that a SiC based AC Link™ converter would increase the switching frequency above 25kHz since the passive components are already optimized for operation in the 12kHz-25kHz range and that the silicon switches do not limit the switching frequency. Once the SiC GTOs become available in the required current ratings, only the existing switching section would be replaced with SiC devices. This will yield superior heat rejection and improved converter performance.

7. 0. Motivation for DC power

The present motivation for DC power is not surprising, especially when one considers that increasingly most consumer and industrial electronic equipment requires DC voltage in order to function (e.g. a computer generally requires 12-15VDC; a 400V AC variable frequency drive (VFD) requires around 600VDC to be supplied to its output IGBT inverter stage. Fig 10 illustrates a typical simplified 6 pulse PWM VFD power schematic). At present the DC voltages are provided by rectifying the AC supply conventionally with all the harmonics problems and associated issues thereof.

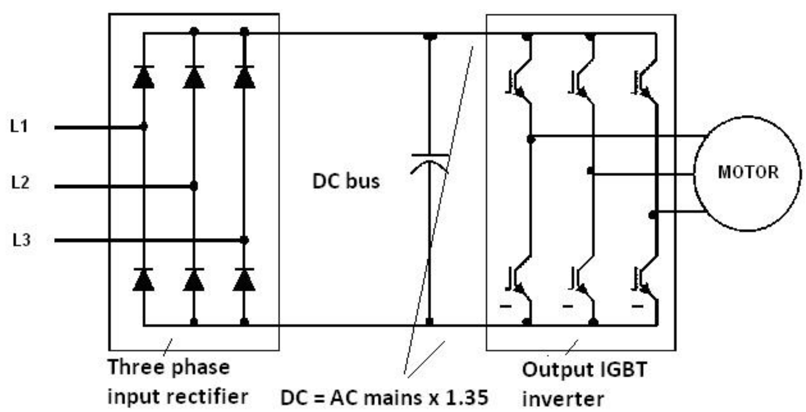


Fig 10 – Typical PWM variable frequency drives showing DC supplied inverter stage

Fig 10 illustrates that, in theory, any PWM VFD IGBT inverter bridge can be supplied independently with the appropriate DC voltage (e.g. a battery or other power source); indeed this is the basis of an AC PWM drive system with a common DC bus.

A large majority of renewable distributed power sources such as tidal generators, fuel cell and photovoltaic cells generate DC power. In addition, bulk power energy storage devices including capacitors, flywheels and batteries store DC power. Chemical process industries such as those involved in copper, zinc (and other metals) and hydrogen production are large consumers of DC power. For these industries the local AC voltage has to be rectified to produce the DC power resulting in harmonics and VAR issues, both of which increase the cost of the installation.

DC power is now commonly used for the bulk transmission of power over long distances, both overland, from shore to island and inter-island. This entails both rectification at the transmitting end of the power line and inversion back into AC at the other end. Harmonics and VAR considerations have to be addressed at both ends of the power line, increasing the space required in addition to both the equipment and operational costs.

On offshore platforms, hydraulically and AC electrically (relatively low kW however) powered subsea systems to control subsea wellhead valves and other equipment have been commonly used until relatively recently. Once the length of subsea cable exceeded a critical length, AC power is difficult to apply, due mainly to the cable capacitance, restricting the maximum cable or umbilical distance. The offshore oil sector requires increasingly longer subsea cable and DC power, due to having no theoretical maximum cable distance, is now being used in preference to AC. Offshore, there now is a significant trend to go to 'All Electric Subsea Systems'; currently oil production platforms run electro-hydraulic umbilical cables from 'topside' (e.g. the platform) to the seabed wellheads and other subsea installations. The large diameter umbilical cables supply power, control and hydraulic oil for subsea wellhead actuators and other equipment. In the future these large umbilical cables will be replaced by electric power cables in order to control and drive electric actuators. Due to the cable distances required from 'topside' to subsea DC power will have to be used. The cost per kilometre of electric cables compared to the present electro-hydraulic umbilicals is dramatically less.

8.0. Short-circuit and, overcurrent and overvoltage protection of downstream DC power system and sub-systems using AC-Link™ technology

DC power interruption is a major problem entailing the use of large and expensive protective device such as DC circuit breaker. This is due to the fact that the DC voltage does not go through zero, which is the case for AC power which does provides a natural zero crossover to open the circuit. The problems associated with interrupting DC power are overcome with the AC-Link™ system as the converter operates at a high internal frequencies. The DC output section can be assumed to be a simple two pulse rectifier with high frequency AC input supplied from the secondary of the high frequency transformer. If a DC short circuit develops on the output of the converter, the control and fault diagnostics system will detect the short circuit fault and 'quench' (i.e. turn off the power being supplied to it) by turning off the high frequency transformer though inhibiting the primary winding voltage. When operating the converter at 10kHz, the transformer power flow will be inhibited in less than 50uS; if operating at 20kHz in less than 25uS.

The power transfer per pulse is a defined energy package. The energy package for a converter frequency of 10kHz and for a 1MW converter, for example, is 500 joules per pulse. To reduce the DC output ripple, the filter capacitor size is selected to store a total energy of three inverter pulses or 1,500 joules for the 1MW converter. This is the total energy that can be dumped into the short circuit current fault. Since this energy comes from the filter capacitor, the rectifier and the high frequency transformer does not see the short circuit fault current. The remainder of the AC-Link™ converter, including the primary power source, sees no fault current so there is no possibility of damage to the converter due to a DC side short circuit.

As previously stated the AC-Link^{TM} universal power conversion system has a powerful built-in fault current limitation with almost instantaneous DC side protection in the case of a short circuit and that no additional fault protection devices are required. Should a DC side short circuit occur, the DC converter will shut down and the mechanical load disconnect switch can be opened under no load condition. As soon as the fault is cleared, normal operation supplying the remaining DC loads can continue.

Since the short circuit current is also limited by the low pass output filter inductor, the AC-Link^{TM} disconnect switch may consist of a standard SCR (i.e. thyristor). Using this configuration the converter down time can be minimised and the mechanical disconnect switch can be potentially eliminated.

For a common ring main with a number of DC loads or VFD IGBT inverter drive loads, a dedicated DC filter for each drive can be used. Each VFD drive and its bus filter capacitor can be isolated with a symmetric SCR. This will limit the short circuit current for the IGBT bridge circuit during a VSD fault. With a fault signal from the drive to the DC bus, the common DC bus can be instantaneously shut down to unlatch the SCR and isolate the faulty drive. Normal operation can continue with the common DC bus power up again. For downstream DC distribution panels and individual DC loads the options of isolating DC faults using standard DC fusing or conventional DC breakers.

9.0. AC-Link^{TM} converter modularity for medium to high power DC systems

For medium to high power (i.e. 5MW up to 50MW+) DC power requirements a number paralleled AC-Link^{TM} converters, utilizing a time interleaving configuration. Depending on the required DC power level, the AC voltage level and/or redundancy requirements, the modular converter rating used would range from 1MW, 5MW up to 10MW. Fig 11 illustrates the parallel module arrangement based on a common DC bus system for VFD IGBT bridges.

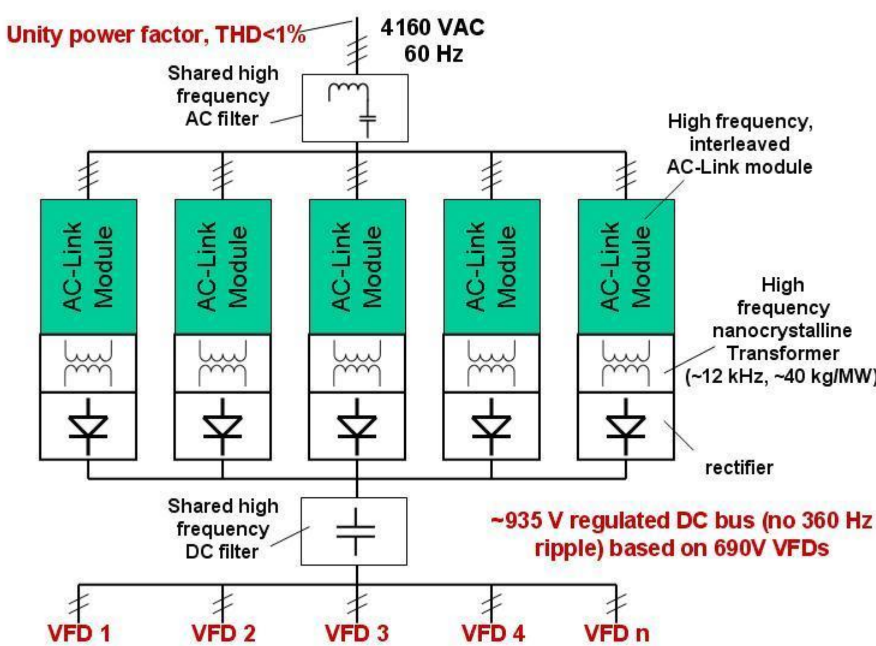


Fig 11 – AC-Link^{TM} multi-module, AC-DC active transformer system with >3MW/cu.m density for marine/ offshore drive systems with PWM IGBT output bridges DC voltage is based on AC (690V) x 1.35 but can be full regulated and adjusted.

The AC-Link^{TM} modular design has a number of advantages. Firstly, the development costs of a few single rating modules (e.g. 1MW and 5MW which can be paralleled up for large systems) is much lower in cost. In addition, single lower power modules can be extensively tested, prior to a complete, higher power system going through final assembly and testing. Secondly, as a module is essentially a 'building block', a single spare module can be kept on hand on site for replacement if a failure occurs and does not have to wait 3-4 months as usually required for a conventional transformer, for example. Each module has the capability to produce an output of up to 150 % of the nominal voltage. A defective module can be shut down in the event of a failure with the remaining modules retaining the capability of still being able to produce the required DC output voltage and current. The main AC-Link^{TM} DC voltage section does not have to be disconnected since the individual short circuit protection (e.g. SCRs or fuses) in the discrete DC supplies to each load will operate and disconnect the faulted circuit. Similarly, if one of the bridge diodes is shorted, no disconnection is required. The system can still function up to rated voltage and rated power.

Similarly, on the input side, should one of the AC section components fail or be damaged, turning off its power device triggering providing isolation. The operation of the remaining modules may continue without a disconnect or loss of power. However, usually a disconnect switch would be used to open under no input fault current. Since the AC-Link^{TM} fault detection can turn off within one cycle if a fault occurs, the converter will shut immediately off all solid state devices and then open disconnect switches safely.

If further redundancy is required, additional AC-Link^{TM} modules can be inserted into the DC voltage chain for standby in event of failure. This permits the system to operate at full throughput power at all times, since that standby module can be switched instantaneously, while a faulty one is turned off. It is often the case that the operation of duty/standby units are cycled regularly to ensure even operation of the converters.

10.0 AC-Link^{TM} high frequency transformer – a critical component

The high frequency AC-Link^{TM} transformer and its leakage inductance is a critical component. The transformer has two critical functions; i) it has to be designed for the usual voltage and transformation and also ii) as a specified transformer leakage inductance.

The transformer technology is well established and powerful design tools are available to design and assist in the building the high frequency transformers. A number of high frequency AC-Link^{TM} transformers with different power levels, voltages, and converter frequencies have been designed, manufactured and tested. The high frequency transformer uses a small nonocrystalline core, with typically # 32 AWG Litz wires. Two types of high frequency transformer designs are available, a liquid dielectric cooled transformer and a transformer with a solid dielectric coil structure. The high frequency transformer selection is dependent on the application criteria.

Fig 12 illustrates the typical construction of a 20kHz transformer winding. An amorphous nanocrystalline core was selected to minimize losses. Each primary coil was wound using eight turns of bifilar Litz wires to yield a Q of over one hundred. One of the primary windings was reverse-wound to simplify the electrical interconnections to the power circuit. Each transformer leg contains two primary coils. The secondary winding is split into twenty (20) individual coils with seventy turns each and constructed also using Litz wire. Ten coils each are then placed on each of the transformer legs. The total transformer weight for 250kW operation for 480V to 50kVDC was 11kg/26 lbs.

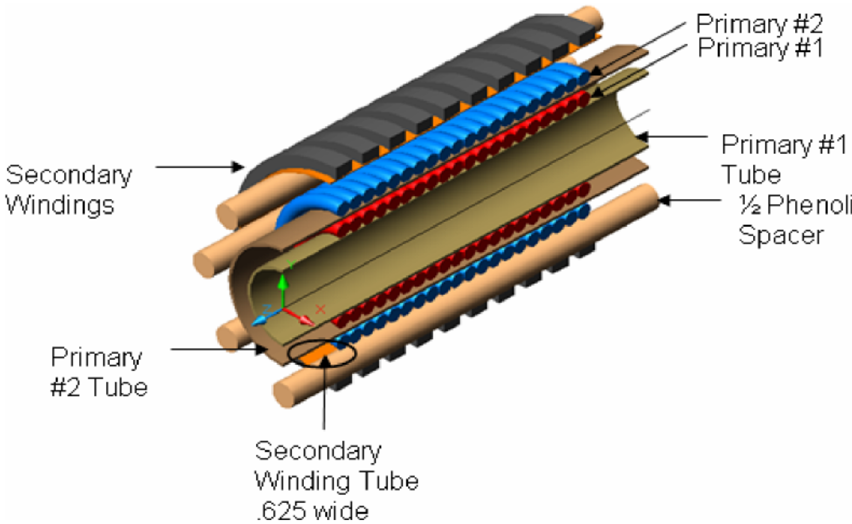


Fig 12 - Cross section construction of a typical high frequency output transformer

The testing of the high frequency transformer, after fabrication, follows similar procedure to a conventional power transformer and consists of checking the turns-ratio, leakage inductance and voltage isolation. Thermal measurements of both the windings and the core are typically made during extended full power testing to confirm that the thermal management design is correct.

Since the transformer is an integrated circuit component of the AC-Link^{TM} converter, the transformer size and power level is defined by the AC-Link^{TM} converter power. The converter power level in turn is defined by the solid state switch current rating. For high power application, any number of converters can be paralleled up using time interleaving techniques, to yield the required total peak power level. An additional converter can be added for redundancy, if required. Each one of these converters will have their dedicated high frequency transformer. The transformer weight is of the order of 44 kg/MW for an inverter larger than 250 kW and a fraction of the weight of conventional transformers.

For any power level, the converter power quantification is via the selection of the IGBT power level. This quantization permits the construction of standardised modules and any number of these modules can be run in parallel for the required application.

11.0. Marine and Offshore EMC Issues

In order to achieve a successful installation of variable speed drives onboard ship or offshore there are two serious issues which have to addressed. The first issue, harmonics, was briefly mentioned in Section 3 of this paper together with the salient methods used to reduce the magnitude of the harmonic currents. Suffice to say any type of mitigation increases the costs, the space requirements and the overall efficiency of the drive installation.

The second issue is often not afforded the serious consideration it deserves. This issue is that of EMC (i.e. electromagnetically compatibility); the ability of equipment to operate in its given environment without affecting (emissions) other equipment, OR being affected (susceptibility) by other equipment, due to electromagnetic emissions, both conducted and emitted (i.e. through the air). In Europe there has been an EU EMC Directive in place for almost 15 years making it an offence to ‘offer to market’ any equipment which does not comply with the limits set out in the Directive and accompanying standards. Many other countries have adopted the EU Directive as their basis for national EMC limits. The FCC in the US has emission standards for equipment but none, as far as the authors are aware, on susceptibility.

‘EMC’ covers electromagnetic phenomena over a very wide range of frequencies. The European EU Directive limits the frequency range from 0Hz (DC) to 400GHz. However, although the majority of EMC standards are based on the requirements of radio communication systems there are serious problems to be found in much lower frequencies due to variable speed drives, especially AC VFDs if the installation is not correct from the EMC standpoint.

Conventional variable speed drives, irrespective of type, are potentially powerful sources of electro-magnetic noise. This is of course due to the rapid ‘hard’ switching of voltage and current. SCRs, such as those used in DC drives switch relatively slowly, consequently limiting their emission spectrum to around 1MHz. However, VFDs which use IGBTs emit frequencies up to around 50MHz with the most problematic emissions usually in the range 10kHz-10MHz although problems can occur VFD switching frequencies.

Within European Union countries it is a legal requirement to use with drives and other equipment specially designed EMC filters or similar devices, usually designed for attenuation in the range for 150kHz- 30MHz. The drive(s) or system must also be installed in strict compliance with the drive manufacturer’s EMC recommendations with respect to type of cable, cable routing, enclosure layout and design, earthing (i.e. grounding) and bonding in order to minimise the emissions of EMI (electromagnetic interference). However, EMI problems often occur below 150kHz so special additional filters and techniques are often required.

The majority of ships and offshore installations, including MODUs (i.e. mobile offshore drilling units) have what is termed “IT networks” (i.e. isolated neutrals – that is, the generator neutrals are not connected to earth {ground}). In these networks the use of standard EMC filters is more difficult as the filter capacitors have to be connected to ground and are destroyed if a ground fault appears on the system.

‘Floating EMC filters’ can be used but this often causes safety concerns and successful implementation can be difficult, requiring considerable EMC expertise and experience. Isolation transformers with electrostatic shielding (phase shift types for higher power drives) can be effective but are large and expensive. In some cases, some capacitance to earth can be used to provide some, if inelegant, attenuation.

In the absence of a conductive paths such as apparent in marine and offshore IT network power systems, the VFD common mode (CM) voltages and currents, which are extraneous voltages and current which flow between the phases and ground, also flow through the stray capacitances to grounded metalwork, such as the windings' capacitances to the iron in transformers and generators as illustrated in Fig 13 below.

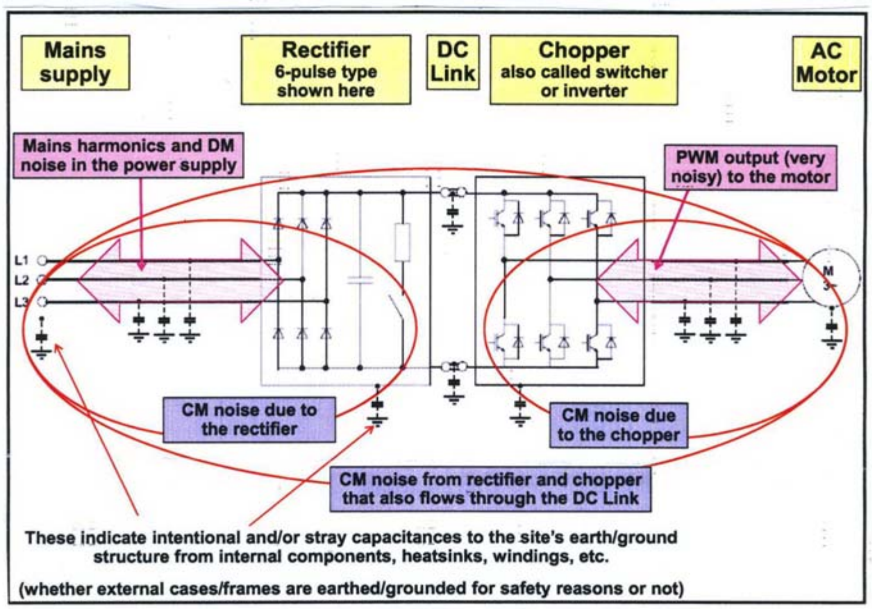


Fig 13 – Common mode noise paths for VFDs on installations with IT networks (Cherry Clough)

The higher the frequency, the lower the impedance of the stray capacitances, which means that the usual VFD switching ‘noise’, mostly consisting of very brief transient 'spikes' at the switching instants, can pass through them very easily.

The common mode noise currents actually flow through insulation, through the air and then of course through the metal structure of the hull and any item of electrical equipment fixed to it. Installing EMC filters and/or isolating transformers at the input essentially provides a shorter path for the common mode currents in order that they do not flow as many items of equipment, sparing their control systems the noise exposure and subsequent EMC problems which may result.

The 50Hz/60Hz supply voltages also induce ground currents in the iron, however, they are differential (DM) mode and balanced and thus usually relatively benign.

An example of ‘common mode noise’, usually the most common EMC problem found onboard ship and offshore installations, is described below.

This installation was a drilling rig whose equipment was rendered dangerous when any of the large (~800-900kW each) AC VFDs were assigned (i.e. holding the motor at zero speed) or operating. An example of the phase and ground voltages is illustrated in Fig 14. Fig 15a and Fig 15b illustrate typical conducted phase to ground voltages with the large drilling package (DP) VFDs OFF and ON respectively.

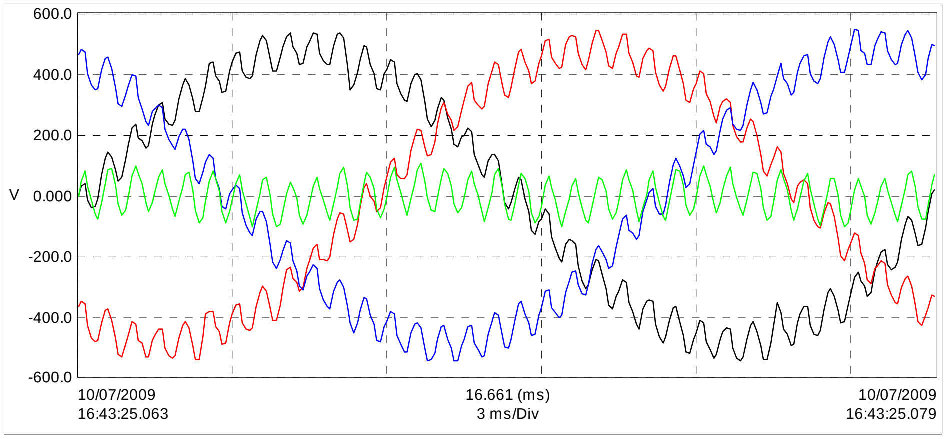


Fig 14 – Phase and ground voltages when any drilling package VFD IGBT bridge(s) operating. The ground rms voltage is green trace.

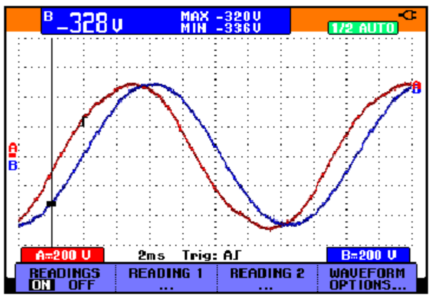


Fig 15a

Phase – ground voltage – DP VFD(s) OFF

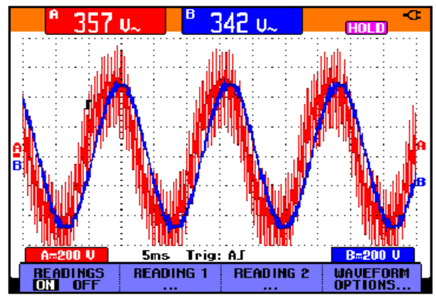


Fig 15b

Phase – ground voltage – DP VFD(s) ON

On investigation it was established that the conducted common mode voltage had, with reference to Fig 16, two separate components; triplen harmonics (i.e. odd multiples of three; mainly 3rd but also 9, 15….) which circulated between the rectifier(s) (discrete per drive or multiple for common DC bus systems) and the supply (which was benign) and a more problematic 2kHz due to the switching frequency of the large VFDs. The latter common mode voltage was observed to reach 207Vrms depending on the number of Drilling Package VFDs running. The two separate component of the common mode voltage can be seen in Fig 17.

It should be obvious that both the nature and level of conducted common mode noise was unacceptable from both an operational and safety standpoint and therefore required urgent attention.

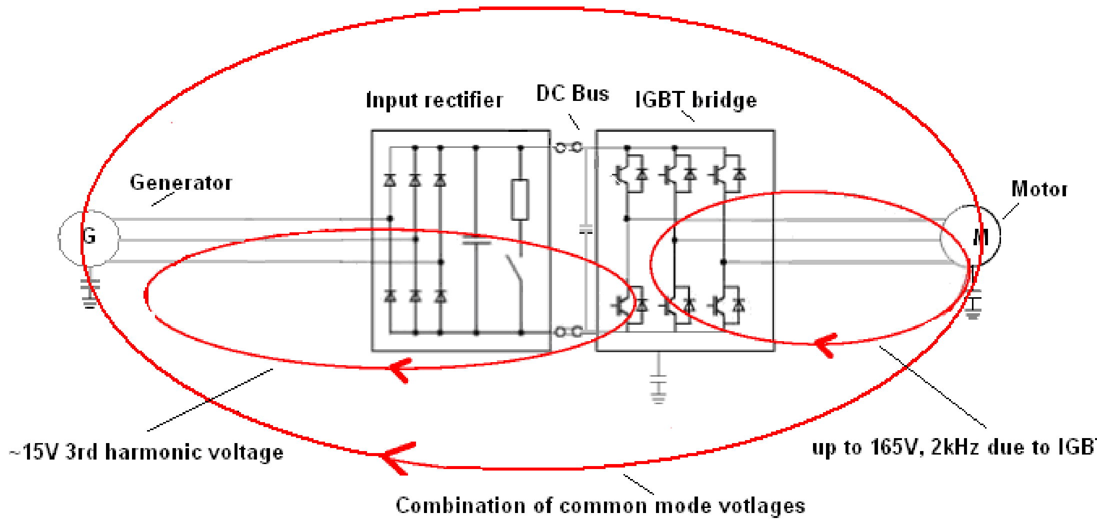


Fig 16 – Common mode voltage/current paths on a drilling rig DP VFD installation

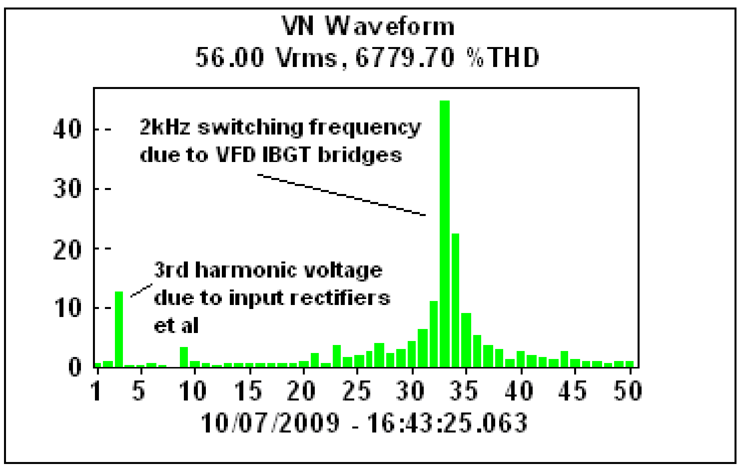


Fig 17 –Phase V1 to ground voltage harmonic spectrum clearly detailing both the 3^rd^ harmonic voltage rectifier/DC bus voltage and 2.0kHz switching frequency of the DP VFD IGBT bridges.

The reason as to why the EMC common mode noise on this installation was so high was it seems down to almost a complete disregard (or ignorance) by the shipyard and others into what was required to minimise EMI emissions, compounded by a lack of supervision by the drive manufacturer. No measures taken to mitigate the EMI such as installing floating EMC filters or isolation transformers. The grounding/bonding for the drives and motors were particularly poor; very often, screened cables were not terminated or terminated incorrectly.

However, although the above may be an extreme case, it does serve to reinforce the fact that EMC is an important issue which requires to the taken seriously. Many EMC problems often go unnoticed or are not investigated.

Minimising EMC problems due to conventional drive technology is possible when it is given priority, is an integral part of the installation design and the equipment is installed and cabled in full compliance with EMC standards and recommendations.

11.1. AC-Link^{TM} technology and EMC

With AC-Link^{TM} active transformer based DC power systems, such as common DC bus or DC ring systems where conventional VFD PWM IGBT bridges can be utilized, the common mode noise and other EMC issues are addressed within the AC-Link^{TM} converter.

AC-Link^{TM} is a soft switching technology and produce negligible EMC emissions. Therefore the switching of the AC-Link^{TM} converters is benign from an EMC standpoint and does not have to be considered further.

It is the nature of EMI that any emissions will try to find a path back to the source. For VFDs conducted emissions it is the same; the conducted emissions from the IGBT output bridge will attempt to travel back via motor cable, motor carcass and ground (i.e. the hull if a ship or offshore installation) to the input rectifier and DC bus. The purpose of any EMC filter or isolation transformer is simply to divert the 'noise' away from the rectifier this preventing the creation of a 'loop'.

AC-Link^{TM} active transformers can provide the required 'EMC filter' function internally via the 20kHz, galvanically isolated, high frequency transformer and a special grounded shield which is be inserted between the high voltage primary and secondary winding (or winding primary and secondary windings if a 1:1 ratio transformer). A version of a 13.8kV dual module AC-Link^{TM} active transformer/rectifier with one rectified DC bus output is shown in Fig 18. The voltage is regulated at the higher voltage side and the high frequency transformer is operated at the inverter frequency (20kHz). The transformer core is very small compared with conventional transformers (i.e. which operate at 50Hz or 60Hz) due to the core cross sectional area reducing in inverse proportion to the inverter frequency. A beneficial consequence of this is that the parasitic capacitance between the primary and secondary windings is significantly reduced. By inserting a small grounded screen between the high voltage primary and low voltage secondary, the high voltage primary and low voltage are completely electrostatically isolated. This prevents common mode (and differential mode) currents from circulating irrespective as to whether a single secondary rectification section or a multiple rectification section, high frequency transformer is utilised. The latter, for example can be implemented for simultaneous operation of both LV and MV VFDs. In addition, multiple DC bus arrangements, each having a discrete, shielded secondary transformer winding and rectification section, also provides attenuation of the common mode current circulating between VFDs.

Since the transformer leakage inductance serves as the resonant discharge inductance of the AC-Link^{TM} converter, the isolated and shielded transformation approach can be used for any voltage level. This permits the utilisation of lower voltage generator(s) power sources with a complete electrostatic isolation without the standard 300Hz or 360 Hz ripple on the DC output. Since the inverter operates again at high frequency, the transformer cost is low, while providing full galvanic isolation for any frequency power source. Again, a number of isolated DC output sources can be generated with multiple transformer winding.

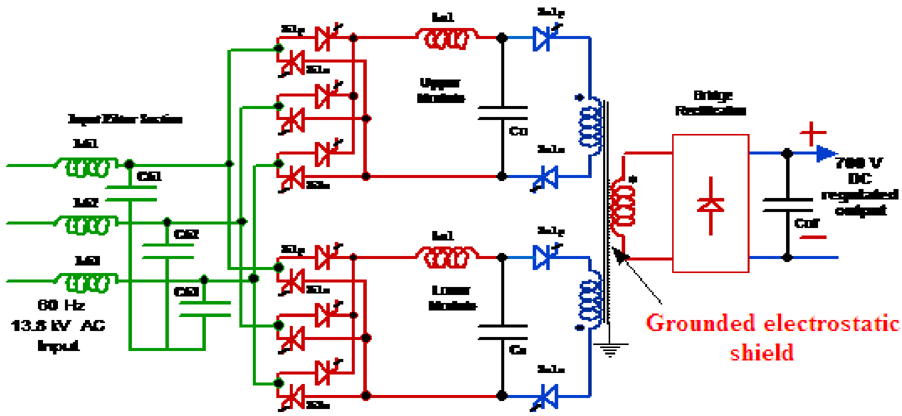


Fig 18 –Dual module AC-Link rectifier/transformer/regulator with electrostatic shield for EMI attenuation

12.0. Use of AC variable frequency drives (VFDs) onboard ship and offshore

This section is included in order that the reader may become fully aware of the growth of electric variable speed drives, particularly AC variable frequency drives (VFD), onboard ship and in offshore installations and thereby should be in a better position to consider the potential for AC-Link™ Clean DC power systems.

12.1. Marine vessels

The last decade has been an exciting one for full electric propulsion with over 3% of marine vessels over 500 tons, some 1500, ships, operating with it. Electric propulsion provides significant benefits for vessels including increased cargo carrying capabilities, lower running costs, less maintenance, reduced manpower, greater redundancy, lower emissions and improved manoeuvrability (with podded or azimuth type propulsors).

The market for marine electric propulsion motors and drives (mainly AC PWM VFDs) is estimated to grow from US$ 1.2m today to between US$ 6-8 billion by the year 2014. Additional growth can be attributed to VFD controlled thrusters and ancillary drives.

Many new classes of ship including ferries, cruise ships, FSPOs (i.e. 'floating storage production offloading vessels'), dynamically positioned drill ships, cable and pipe layers, shuttle tankers, dredgers, ice-breakers and offshore supply vessels (Fig 19) have all benefited from advances in power electronics, electro-magnetics (including superconducting and permanent magnet motors) and innovative hydro-dynamic and propulsion designs. Fig 20 shows a dredger with two VFD driven 6MW pump-sets.

The harmonic voltage distortion (THDv) on marine vessels is of increasing concern. This is due to a significant increase in the use of variable speed drive use, particularly AC VFD drives, onboard ships All classification bodies have rules for the maximum permitted total harmonic voltage distortion (THDv), typically 5% although Lloyds Register stipulate 8%. This results in considerably increased costs and increased physical space requirement on vessels where already space is a premium.

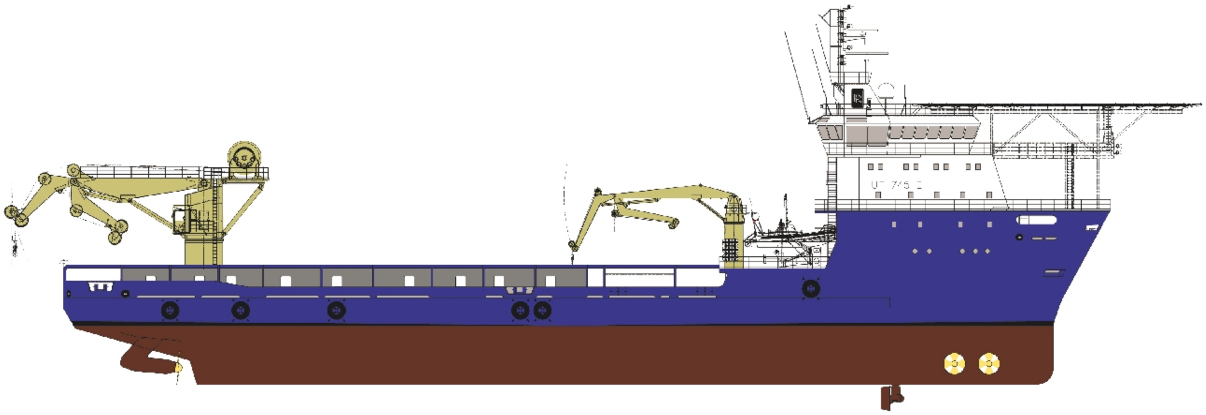


Fig 19 – Offshore supply vessel with electric propulsion

Fig 20 – Installation of 2 off 6MW dredge pumps, both VFD controlled (Bakker-Sliedrecht)

All future NATO major warships will have full electric propulsion with the UK's Type 45 'Daring' class destroyers, each having two 20MW AC PWM variable speed drive propulsion systems, each having passive MV harmonic filters and EMC output filters, being the world's first 'electric warships' (Fig 21). The US Navy Zumwalt Class destroyers will be the US Navy's first electric warships.

Fig 21 – UK Type 45 destroyers with 2 x 20MW PWM VFDs for propulsion (Navy News)

Fig 22 – Selection of low power, low voltage, modular VFDs chassis units (ABB)

The vast majority of AC drives used in commercial vessels and in warships are of the AC PWM type. The majority of these are of the 'standalone' type (i.e. a complete product comprising input rectifier, DC bus capacitors and output IGBT inverter) as depicted in Fig 22 above; these VFDs are low power, modular in construction and require installing in suitable enclosures before use onboard ship.

Fig 23 illustrates a standalone, high power, medium voltage VFD which has a containerised enclosure, and in this case, water cooled for the power semiconductors. Standalone VFDs can be found onboard ship in the range 0.18kW to 20MW.

Fig 23 – Standalone 9MVA MV PWM VFD for dredger pump application (Bakker Sliedrecht)

On most vessels space is at an absolute premium. Often switchboards, large VFDs, other variable speed drives, associated ancillary items such as harmonic filters and other equipment have to be designed around the available space; this can be quite challenging for the shipyards and equipment suppliers. In addition, the variable speed drives and associated equipment has to be installed in strict accordance with EMC recommendations if common mode noise and EMI emissions are to be reduced to acceptable levels.

Over the recent years however, the number of marine installations comprising of a number of VFD IGBT inverter stages, each controlling a dedicated motor, connected to a common DC bus has increased. Unsurprisingly, these are termed 'common DC bus' systems. This configuration reduces the cost and the required space compared to that required for multiple 'standalone' drives. Fig 24 illustrates a common DC bus system comprising two rectifiers, a capacitive DC bus (i.e. storage unit) and eight independently controlled IGBT PWM VFDs inverters (which are the final output stage of a standalone VFD).

Note that this particular system uses two 6 pulse rectifiers, one of each side of the bus tie. The primary windings of both transformers are phase shifted with respect to each other therefore a quasi 12 pulse system with respect to the harmonics will be formed if the bus tie is closed (i.e. to ensure balanced loading on each side).

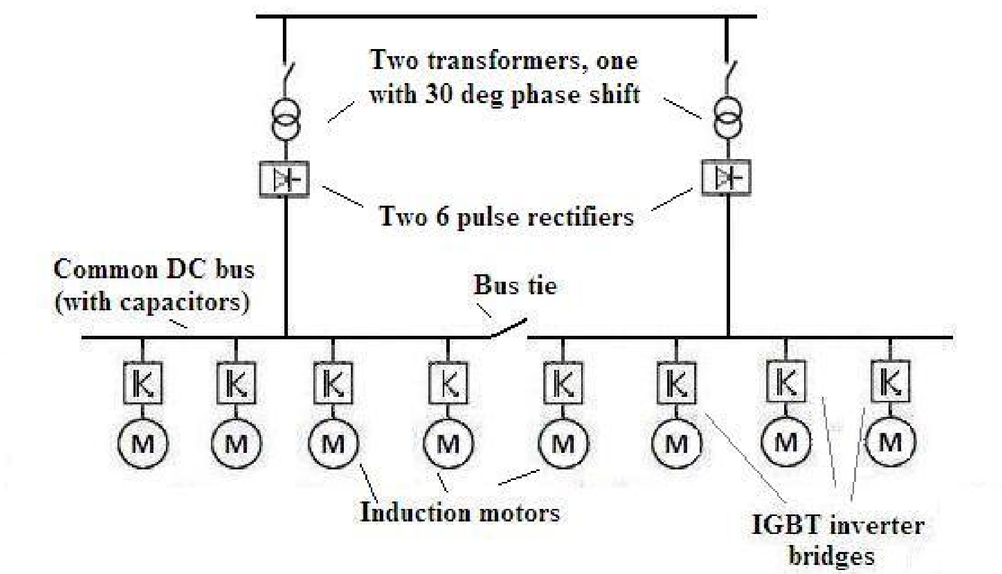


Fig 24 – Common DC bus system with quasi 12 pulse harmonic mitigation

Fig 25 illustrates the typical layout of an enclosure containing the input rectifiers and output IGBT inverters for a common DC bus system similar to that depicted in Fig 24.

The advantages of common DC bus systems are such that their application onboard ship will undoubtedly increase significantly in the future. For larger systems and for electrical propulsion and advanced power system designs, the DC ring main concept will undoubtedly also gain in popularity. These common DC bus and DC ring main power systems are, as will be appreciated in a later section of this White Paper, ideal for operation with AC-Link™ AC-DC active transformers.

Fig 25 – Typical common DC bus system with PWM IGBT output modules fed from a common rectifier and DC capacitor based bus (Control Techniques)

12.2. Drilling rigs and offshore installations

There are a number of types of drilling rig (often called a 'MODU' – mobile offshore drilling unit). These include 'jack-ups' (Fig 26), 'drillships', drilling barges and 'semi-submersibles', the most recent designs (Fig 27) are dynamically positioned (i.e. they do not anchor but hover over the 'hole'; the position maintained by thrusters and GPS control). In addition, some offshore oil platforms also have drilling packages onboard for exploration and other duties.

Fig 26 – Jack-up drilling rig with legs fully extended upwards

Fig 27 –Modern, dynamically positioned semi-submersible drilling rig

Irrespective of the type, all drillings rigs have a 'drilling package' comprising draw-works, mud pumps and a top-drive. From the earliest days of offshore oil exploration until the early to mid to late 1990s DC SCR drives were used almost exclusively for this duty. Indeed, some owners still insist on DC drilling packages for new vessels. Over the last 10 years however AC PWM drives (VFDs) and, on occasion, hydraulic drives, have largely replaced DC drives on new installations.

There are a large number of older rigs still operating with DC drilling package drives but most new builds comprise either multiple, standalone AC VFDs or a AC VFD based 'common DC bus' systems (where the VFD output modules share a common DC power source). Drilling packages usually have a total installed power range of around 4000kW-9000kW (6,000HP-12,000HP). AC VFD drilling packages are often implemented via the common DC bus systems but standalone VFDs are also commonly installed.

Older self-propelled semi-submersible rigs usually have DC drives for main propulsion of around 1.5MW-2.5MW (2000HP/3300HP) and have anchor windlasses, up to eight in number, of powers in the region of 600kW-800kW (800HP-1100HP). Modern semi-submersible rigs are usually 'dynamically positioned' with up to eight thrusters, each rated between 3200kW-4500kW (4300HP-6000HP). A typical schematic diagram is illustrated in Fig 35 (Section 13.1.2.)

The majority of drilling rigs have VFDs for shakers, pumps, fans and other applications. On rigs which have DC drilling packages this can result in an adverse interaction between the DC drives and VFDs due to line notching and any subsequent voltage spikes resulting in damage and destruction to the VFD DC bus capacitors.

However, as is the case with marine vessels, one of the main electrical issues confronting all drilling rigs is still that of harmonic voltage distortion due to conventional 'hard switching' power conversion technology. The cost of harmonic mitigation is relatively high and, in addition, there will be the additional space required for installation on vessels and installations where space is usually very restricted.

As illustrated in Section 11 (AC-Link^{TM} technology and EMC), the correct installation of the variable speed drives from the EMC standpoint, especially VFDs, is crucial to limiting the common mode (and differential mode) voltage to acceptable levels and this to minimize any disruption to other electrical and electronic equipment.

EMC filters are not often applied on drilling rigs due to the use of IT networks (i.e. isolated neutrals) and other techniques to reduce the EMI emissions, such as isolating transformers with electrostatic shielding may be required. As required for marine vessels, the correct type of cable must be used with the screening/armour terminated correctly for EMC minimisation. All grounding/bonding also must be equipotential (i.e. at same potential).

12.3. Offshore oil production platforms

Whilst the majority of oil platforms worldwide are structures, rigidly fixed to the seabed (Fig 28), there is an increasing requirement for 'dynamically positioned' platforms for seas which are too deep to permit fixed platforms and where the size of the field is relatively small and therefore it would be uneconomical to build a rigidly immovable platform.

Fig 28 – Typical offshore oil production platform

As discussed in section on drilling rigs, 'dynamic positioned oil production platforms' would also require six to eight large thruster motors of typically 3.2MW to 5MW each, either variable speed via VFDs or possibly fixed speed motors with controllable pitch propellers.

All oil platforms use a relatively large number of electrical submersible pumps (ESPs) to pump the oil-water mixture from the reservoir(s) beneath the sea bed to the platform. In the mid to late 1980s AC VFDs were introduced on a number of platforms, not necessarily for variable speed control, but for 'soft starting' the ESPs. Nowadays almost all ESPs (Fig 29) are variable speed controlled via AC VFDs.

Fig 29 – Electrical submersible pump been fed into the 'hole' (Centrilift)

Due to the depletion of older reservoirs and the operation of new ones, the ability to control the pump speed is crucial. Whilst in the North Sea a typical ESP is around 900HP (630kW), higher powered pumps are also available.

Over recent years, due to the intermittently very high price of crude oil there has been a significant investment in additional ESPs worldwide by all oil companies, the larger ESPs very often driven by 24 pulse VFDs in an attempt to reduce the harmonic current produced below the 21^{st} harmonic. Their installation in large numbers however, can lead to space restraints onboard many platforms as well as a significant and often unacceptable increase in total harmonic voltage distortion (THDv) including above the 21^{st} harmonic.

Some offshore oil production platforms may also have drilling packages. These are usually DC drives on older platforms and AC VFDs on newer installations. The total installed power is similar to that found on drilling rigs at around 4000kW-9000kW (6,000HP-12,000HP). In addition to ESPs, oil platforms have large compressors, pumps, separators/centrifuges, all increasingly variable speed via VFDs. The non linear drive load therefore can be up to of 20-25MW. To the knowledge of the authors, the vast majority of VFDs, installed onboard production platforms, are standalone drives.

Harmonic distortion is, as with any generator based power systems, a serious concern and should ideally be addressed on regular basis as equipment is added to the platform. However, in opinion of the authors, oil production platforms tend to operate with higher levels of THDv then recommended, some significantly so. In the authors experience platforms operating with up to 25-30% THDv is not uncommon. To date, the Health & Safety authorities have been somewhat lax in enforcement of THDv limits which are usually in the region of 5% to 8%.

The variable speed drive non linear loading may increase by up to 30-35MW on future production platforms which are dynamically positioned (i.e. with the position maintained via up to eight variable speed AC thrusters). Future production platform applications are ideal candidates for common DC bus or DC ring power systems.

12.4. FPSO (floating, production, storage and offloading) vessels

FPSOs (floating, production, storage and offloading) vessels are the primary means of treating, storing and transferring (i.e. to shuttle tankers) product in the majority of offshore oil and gas producing regions around the world.

A ‘FPSO’ is a floating production system that receives fluids including crude oil and water from a subsea reservoir (Fig 30). Most FPSOs are ship-shaped, often rebuild from older tankers and are 'anchored' (moored) by a ‘turret; (i.e. a turret mooring system is defined as a mooring system with lines connected to the turret via bearings to allow the vessel to rotate around the anchor legs).

On many vessels there are also electrically drive thrusters, often VFD driven, to assist in maintaining station. The type of turret used is determined by the environment of the FPSO. In calmer waters, spread mooring is often sufficient. In environments where cyclones or hurricanes occur, dis-connectable mooring systems are used in order that the vessel can be moved and then reconnected when the storm has passed.

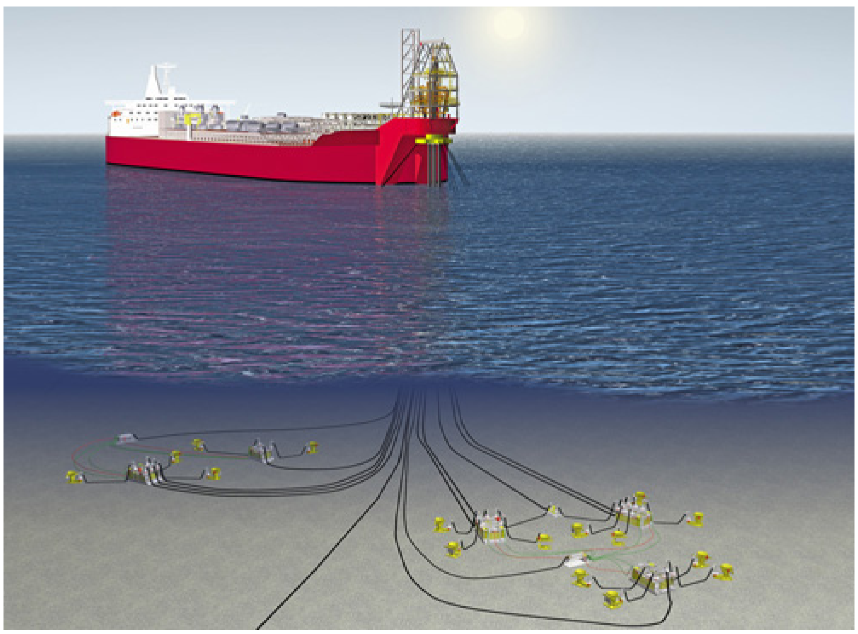


Fig 30 – Turret moored FPSO connected to five well centres

In recent years there has been a growing trend towards FPSOs in ultra-deep water (i.e. >2000 metres/6500 feet) worldwide, including Brazil, West Africa and the Gulf of Mexico. At these depths the standard FPSO turret based solutions have significant technical and economical constraints compared to the more attractive and cost efficient solution of ‘dynamic positioning’. In the North Sea, British Petroleum (BP) successfully operated the dynamically positioned FPSO ‘BP Seillian” for eight years before deployment in deep water (1853 metres/6085 feet) off Brazil in the Roncador field.

Fig 31 – Artists impression of dynamically positioned FPSO (Schottel, AG)

Typical dynamically positioned FPSOs have up to 6 off 5MW thrusters controlled by AC VFDs (Fig 31). Irrespective of whether the FPSO is turret-moored, assisted dynamically-positioned turret moored or fully dynamically positioned, the FPSO also requires significant power to operated pumps, fans, compressors and other applications, a increasingly, a significant number will be driven by AC motors controlled by VFDs. Larger FPSOs can have installed generation in excess of 100MW and individual AC drives up to 36MW. Due to the large number of VFDs this type of vessel should be ideal candidates for DC ring main systems.

13. AC-Link™ derived DC power for marine and offshore VFDs

Prior to presenting some sample marine and offshore applications it may be worthwhile to reiterate the important, tangible benefits which can be derived through the use of AC-Link™ active transformer derived DC power supplies for marine and offshore variable speed AC VFD applications. Following this, a number of applications will be detailed to in order illustrate these benefits.

a) The physical space requirements of the AC-Link™ 'active transformer' converters are small compared to similar ratings using conventional power conversion technology, especially where voltage transformation is also required. Due to the smaller physical size, AC-Link™ converters could be installed in machinery spaces, deemed impossible for conventional power converters, without even considering the additional space required when installing or retrofitting any harmonic mitigation equipment.

b) On marine vessels, drilling rigs, and oil production platforms space is always at a premium. Often in industrial projects, additional buildings or equipment containers have to be provided in order to house all the conventional power conversion and any associated equipment. For marine and offshore applications, the equipment often has to be designed based on the available deck space. This can be problematic with respect to 'bolt-on' harmonic mitigation equipment, transformers, protective equipment, for example. With AC-Link™ technology the usual conventional additional items of equipment including harmonic filters, circuit breakers and transformers are simply not required. The space saving therefore can be very significant.

c) As indicated above, with AC-Link™ converters no additional harmonic mitigation equipment such as active filters or passive filters are required. This is a considerable cost saving as, for example, when the cost per amp of an active filter can be well in excess of US$160/Amp, often considerably more expensive than the equipment the active filter is mitigating. Of course, any type of harmonic mitigation requires significant space; this can be a significant issue, especially when retrofitting is required.

d) Conventional AC and DC power conversion produces high emissions of EMI, both conducted and radiated. This is particularly the case with IGBT and other high switching frequency based converters. In order to reduce the common mode voltage and other EMI emissions, additional equipment such as special passive 'floating' EMC filters or isolation transformers with electrostatic shielding, for example, have to be installed, requiring more space and adding cost. In addition, special EMC installation practices also have to be adopted with respect to cabling, grounding and bonding to ensure the drive system(s) EMI is attenuated to such a level that no equipment is adversely affected. As described in Section 11.1 AC-Link™ is 'soft switching' (i.e. only commutates when the current when the current is at zero) therefore, the EMI footprint associated with AC-Link™ conversion is very low compared to conventional converters, therefore no additional equipment for EMC filtration should will be required.

In addition, on AC-Link™ common DC bus or DC ring mains systems powering IGBT VFD output bridges, galvanic isolation is provided for safety and in addition, grounded, electrostatic shielding between the primary and secondary windings provides a similar function to EMC filters with respect to both common mode and differential mode voltages/currents. This ensures than any IGBT VFDs and induction motors connected do not require any special EMC filters or other equipment in order to comply with EMC recommendations.

e) Conventional transformers are large, very bulky, and costly items and are not required for AC-Link™ based power systems, not even for galvanic isolation (which is performed internally). The MV or HV supplies can therefore be connected direct to the AC-Link™ converters with any voltage transformation, up or down, carried out internally via the high frequency transformer. The transformation of both AC and DC voltages is possible. This results in both large space and cost savings compared to conventional power conversion systems and should not be understated.

f) As a consequence of the very fast response of AC-Link™ technology, the short circuit protection provided (i.e. between 25uS-50uS depending on the switching frequency) far exceeds the quenching time available from any conventional circuit protection device such as circuit breakers and fuses. Therefore, no additional overcurrent nor short circuit protection is required with AC-Link™ converters for either the AC supply side or DC side protection; only mechanical isolators are required. This saves considerable expense, especially in the case of DC protection.

g) The higher efficiency of AC-Link™ technology yields lower operational costs and higher reliability. On large systems the reduction in energy costs on even a few percentage points can be financially significant.

13.1. AC-Link™ applications in the marine and offshore sectors

This section illustrates a few examples where an AC-Link™ common DC bus or DC ring main could be implemented.

13.1.1. Cutter dredger

Fig 32 shows a typical cutter dredger which was designed and operates a significant number of AC VFDs, powered via essentially three discrete common DC bus systems; one 12 pulse system driving two cutter motors (1100kW each), one 6 pulse system driving 5409kW of various winches and the other connected to 810kW of switched pump-sets. As can be seen from the schematic in Fig 33 there is also a 2200kW submersible pump driven by a 12 pulse VFD.

Fig 32 – Example of a cutter dredger with VFDs propulsion and other duties (Bakker Sliedrecht)

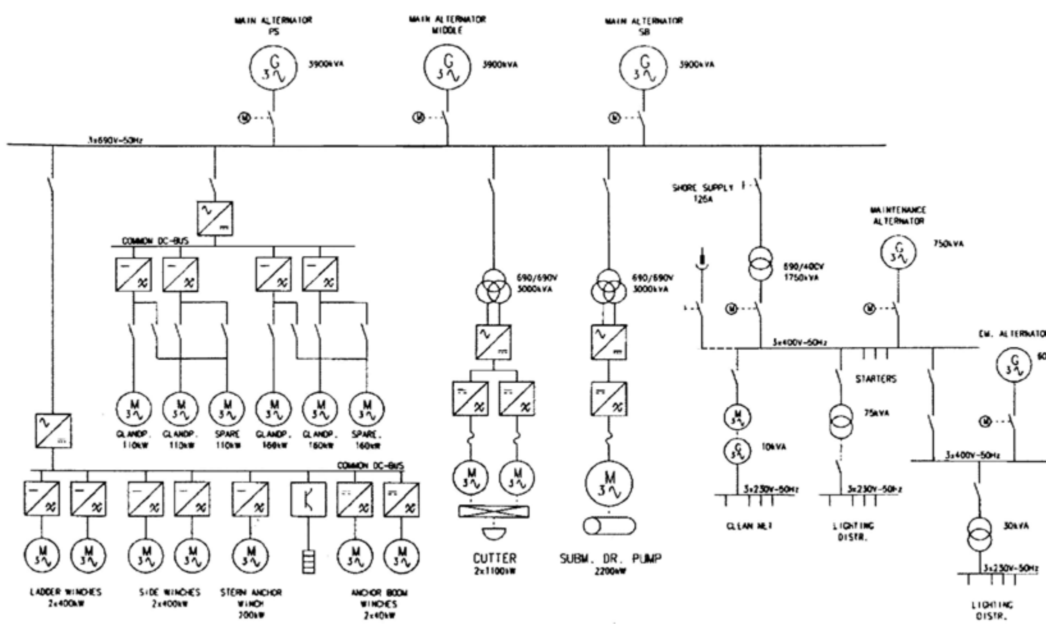


Fig 33 – Schematic of cutter dredger with details VFDs (Bakker Sliedrecht)

Fig 34 below illustrates the system depicted in Fig 33 but with all the VFD DC power supplied via an AC-Link™ DC ring main system. Note that no conventional transformers are required, with the exception of the domestic and hotel supplies. All the protection on AC side and DC ring man side is provided within the AC-Link™ active transformers.

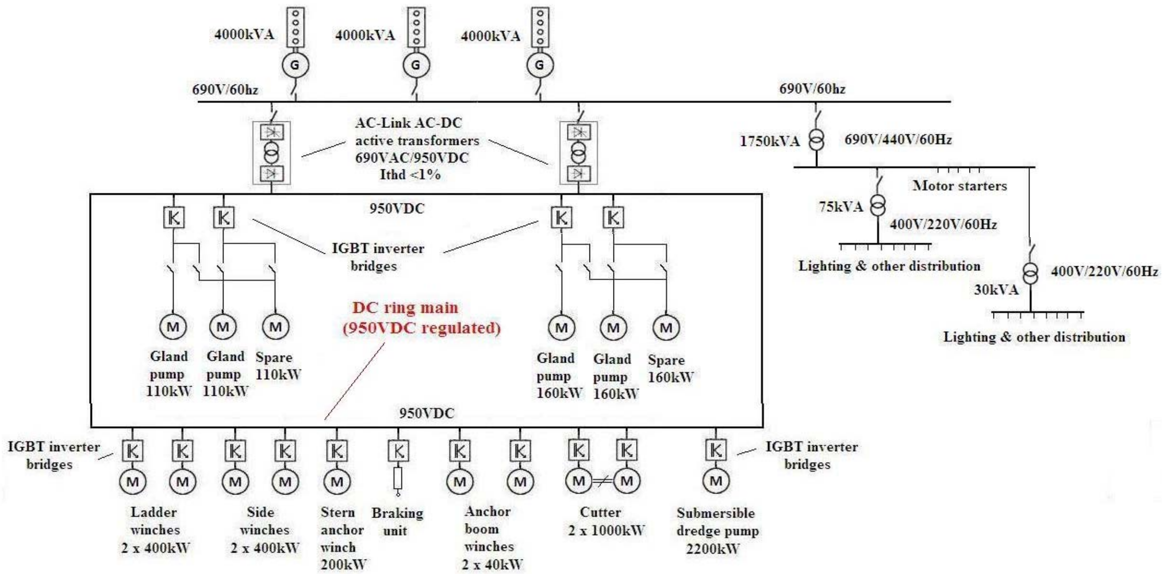


Fig 34 – Cutter dredger schematic redrawn to illustration VFD installations Based on an AC-Link™ DC ring main system implemented

It should be noted that the DC ring main does not require two AC-Link™ active transformers. The other is included to provide 100% redundancy. Redundancy can also be provided within a single modular active transformer designed with spare modules and automatic and hot changeover capability.

Calculations show that with the conventional system (Fig 29) the THDv, during typical operational duties and loading, with three generators running would be in the region of 9-10%. This is based on the total harmonic current distortion (THDi) of 14.1%, neglecting any linear load, which on this vessel is not significant. Most marine classification bodies, with the exception of Lloyds Register, have a limit of 5% for the maximum steady state voltage distortion. Additional harmonic mitigating equipment would therefore be required to bring the vessel depicted in Fig 33 into compliance with marine THDv limits for class.

With the AC-Link™ system as illustrated in Fig 34, the THDi based on the same duties and loading would be less than 1%. Consequently the THDv would be around 0.6-0.7%, a fraction of that permitted by the marine classification authorities.

Subject to spare sufficient capacity in AC-Link™ active transformer(s) and associated DC ring main, additional VFDs could be added to the vessel on the proviso that required DC voltage matches that of the DC ring main. With any AC-Link™ converter it is possible to build in extra power capacity into the original specification. Alternatively, had spare capacity not been inbuilt, additional power modules can be added in parallel to the original converter(s) to achieve any desired power uprating.

13.1.2. DP3 Semi-submersible drilling rig

Dynamically positioned drilling rigs and drillships generally rely on variable speed electrical motor driven thrusters, rated up to around 4MW and driven by VFDs. For semi-submersible rigs up to eight thrusters are used to maintain position over the 'hole'.

Fig 35 shows a typical schematic diagram for a DP3, dynamically positioned semi-submersible similar to that depicted in Fig 27. As can see been there are eight, 12 pulse 3200kW thrusters operating from the 11kV supply, each via 4000kVA, 30 degree phase shift transformers. There is also a 5000kVA common DC bus drilling VFD package fed via two 30 deg 11kV/0.66kV shift transformers to provide a quasi 24 pulse system when the bus tie is closed.

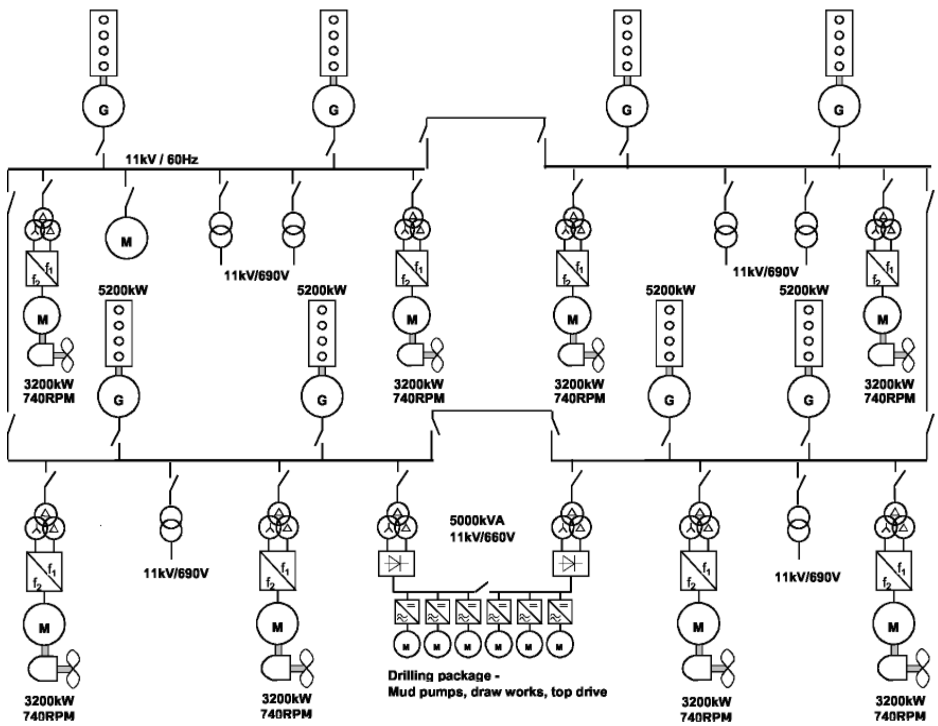


Fig 35 – Schematic of a DP3 (dynamically positioned) Class 3 semi-submersible drilling rig with AC variable frequency drives for propulsion/ thruster and drilling package duties

Calculations based on the four generators shown in Fig 35 being rated at 8500kVA each with a subtransient reactance of 20%, show approximate harmonic voltage distortions as being around 14%. Note that the thruster and drilling package duties have been scaled on realistic operational loading. Until February 2006 this level of THDv would have been acceptable to the American Bureau of Shipping (ABS). However, from that date, strict limits were imposed on all new build ABS classed ships, drilling rigs and installations.

For MODUs (i.e. modular offshore drilling units) the harmonic voltage distortion limit was initially 5% but was raised in 2008 to 8%. In any case, if a rig of this design were designed or built now it would not comply with ABS (or any other classification body rules) without significant modifications and/or additional harmonic mitigation equipment; both of which are expensive and require significant space.

Fig 36 below illustrates a modified schematic of a DP3 Class 3 drilling rig (as per Fig 35) is depicted. The conventional power system has been modified to show an AC-Link™ active transformer based system, comprising a DC ring main (for the eight 3200kW thrusters) and common DC bus (for the 5000kVA drilling package).

It is assumed that the thruster VFD input voltage is 4.16kV. This equates to a 5.6kVDC requirement from the VFD IGBT inverter bridges. The design voltage of the AC-Link™ DC ring main is therefore 6.0kV which can be adjusted and regulated as desired.

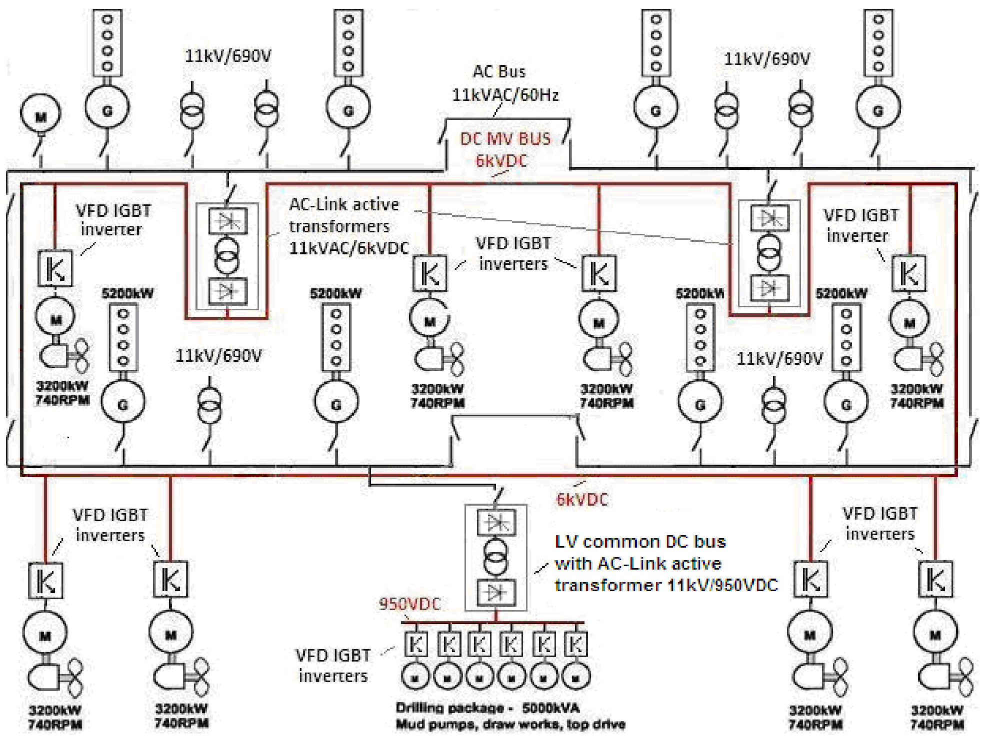


Fig 36 – DP3 Class 3 drilling rig schematic, modified to show AC-Link™ DC ring main and common DC bus systems

As the drilling package VFD drive system is low voltage (i.e. 660VAC which equates to 900VDC) it is more economical to supply it directly from the 6kVDC ring main. Therefore, a 950VDC common DC bus system has been implemented.

It will be obvious that there are no conventional transformers supporting the AC-Link™ power system. The reduction in financial cost and in space required for the eight 40MVA, three winding transformers for the thrusters and two off 5000kVA three winding transformers for the drilling package (i.e. each transformer is required to carry all the load in the event of the other transformer failing) is very, very significant indeed.

In addition, as previously mentioned, a benefit of AC-Link™ technology is that the harmonic current emission emissions (THDi) are very low, typically less than 1%. This normally equates to below 1% harmonic voltage distortion so no additional equipment is required to meet any current or future harmonic recommendations or rules, no matter how onerous.

As with marine vessels it should be noted that the DC ring main two AC-Link^{TM} active transformers. The second active transformer provides 100% redundancy. Redundancy can also be provided within a single modular active transformer, or as in the case of the common DC bus system, designed with spare modules and automatic and hot changeover capability.

Ideally, any AC-Link^{TM} based common DC bus or DC ring main should have a reasonable measure of additional capacity inbuilt such that it is large enough to handle future VFD requirements. In that is the case then additional VFD IGBT inverters could be added to the system based on the proviso that required DC voltage matches that of the DC ring main. Alternatively, had spare capacity not been inbuilt, additional power modules can be added in parallel to achieve any desired power uprating.

Full short circuit and overcurrent protection on both the AC and DC sides of the converter and all voltage transformation is fully provided within each AC-Link^{TM} active transformer thus ensuring minimum financial cost, minimum space requirements, almost zero harmonic voltage distortion and almost zero EMC emissions.

13.1.3. Future subsea pumping stations

Over recent years, as shallow offshore oil and gas production reservoirs continue to be depleted, more operators are becoming increasingly interested in deep water offshore oil and gas fields. These fields utilize subsea multi-phase pumping systems to extract and pump the oil and/or gas from the reservoirs to the surface platform or FSPO.

The subsea, multi-phase pumping systems transfers a multi-phase fluid, usually consisting of a mixture and oil, water and gas, from a subsea pumping station over long distances through pipelines to a remotely located processing plant (e.g. a FPSO) where the effluent is separated into the different fluid components prior to the further processing either on a platform, a FPSO or on shore.

There are several types of subsea multi-phase pumping systems which are either available or are in development; each type consists of similar components including a multi-phase pump, a drive to power the pump, a power supply system, a control system and ancillary systems for pressure compensation and maintenance, cooling and lubrication. The component parts are assembled on a base, lowered into the sea, installed on ‘subsea trees’ and connected to a subsea wellhead.

Currently, the main types of multi-phase pumps used are positive displacement or rotodynamic types. Both of these types can pump one phase or more of the effluent. In deep water, the former type of pump is preferred due it being less sensitive to density and therefore the pressure variations of the effluents. Irrespective of the type, the subsea multi-phase pump has to maintain or increase the production flow of the effluent regardless of variation is well pressure, hence the pumps must be variable speed.

Due to the requirements for variable speed, the multi-phase pumps must be driven by either a hydraulic motor or by an AC squirrel cage motor driven by a VFD (AC variable frequency drive). The latter is acknowledged to be more power efficient, more flexible in operation and less sensitive in a remote location with respect to the power source.

Fig 37 depicts a subsea pumping field with multiple pumps, each controlled by a variable speed drive.

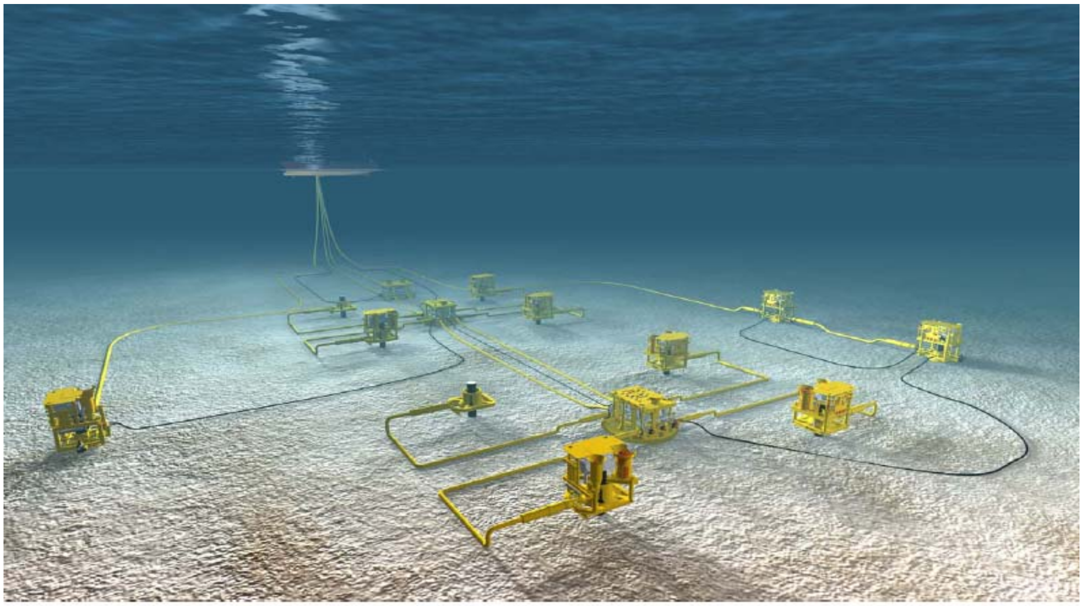


Fig 37 – Depiction of subsea multi-phase pump field

As stated earlier, the use of AC VFDs to drive subsea, multi-phase pumps is increasingly popular. Fig 38 give an artist's impression of a small subsea pumping station complete with transformers and VFDs.

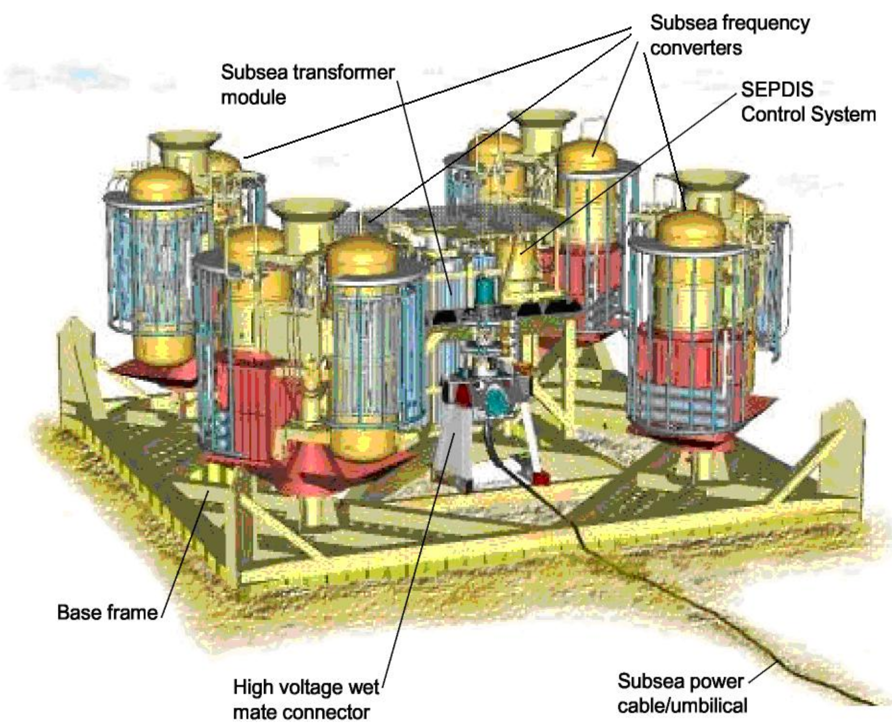


Fig 38 – Artists impression of small subsea pumping station

Subsea multi-phase pump fields obviously comprise a number of discrete pumps, each often complete with its own transformer and VFD. As these fields increase in size, the power requirements will be considerable. Fig 39 shows the schematic of a proposed future subsea pumping field.

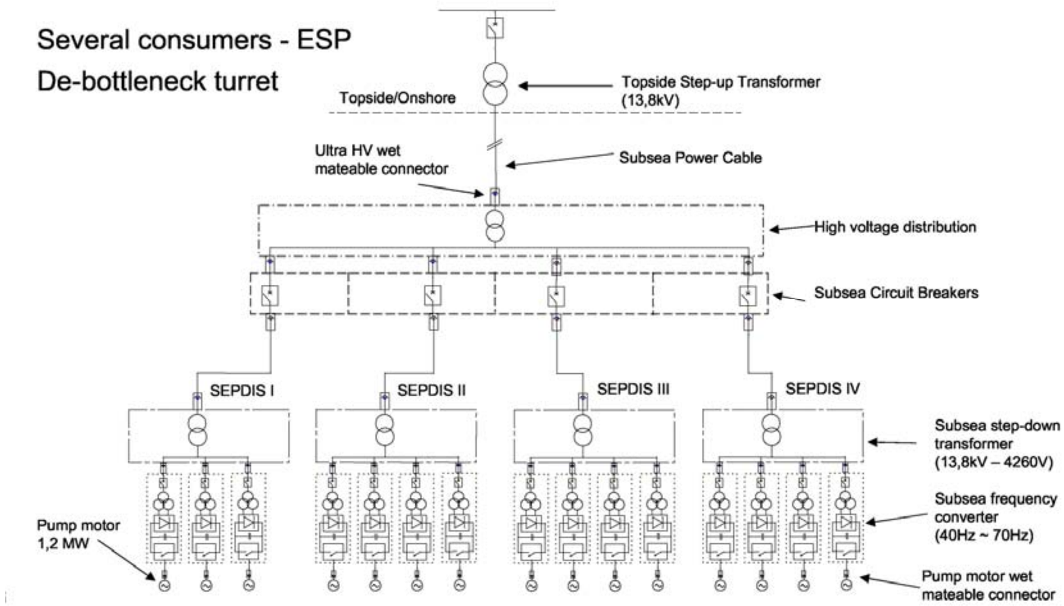


Fig 39 : Schematic diagram of large future subsea VFD based pumping system (Vetco)

As can be seen in Fig 39, the overall system comprises of an AC 13.8kV supply 'topside' (i.e. on the platform) to subsea transmission line which is then fed via a subsea transformer and circuit breakers to each of the four subsea pump modules, each of which contains four (4) 1200kW/1600HP VFDs, each with a dedicated 30 degree phase shift transformer (to attenuate the 5^{th}, 7^{th}, 17^{th} and 19^{th} …..harmonic currents) and other equipment whilst a fourth subsea module has three (3) transformer/VFD sets.

The total number of transformers is twenty one (21); fifteen (15) phase shift types for the VFDs. Each would be in the order of 1400-1500kVA. In addition there are four transformers, one for each subsea pumping module (around 5-6MVA each). The transformers at each end of the transmission line would be in the order of 20MVA.

Even though each subsea VFD has a 12 phase configuration, the harmonic voltage distortion (THDv) topside and at the terminals of each VFD would be significant and would exceed all marine and offshore harmonic recommendations. Therefore, at least, harmonic mitigation would be required on the platform. Arguably, the harmonic voltage distortion (THDv) subsea would also require mitigation to ensure it does not exceed the individual VFD limits and affect reliability. In addition, as the transmission line utilized is AC then maximum distance the pump field can operate front the platform or shore is limited due to the cable capacitance.

Fig 40 depicts the same subsea system regards the number of pump modules and pumps but based on an AC-Link™ MVDC transmission and common DC bus system. The common DC bus system depicted in Fig 40 was to match (as far as possible) the original design of the conventional system shown in Fig 39. However, in the opinion of the authors, a DC ring main would be more suitable in type of application; the main advantage being security of supply since the DC power is provided from two sides.

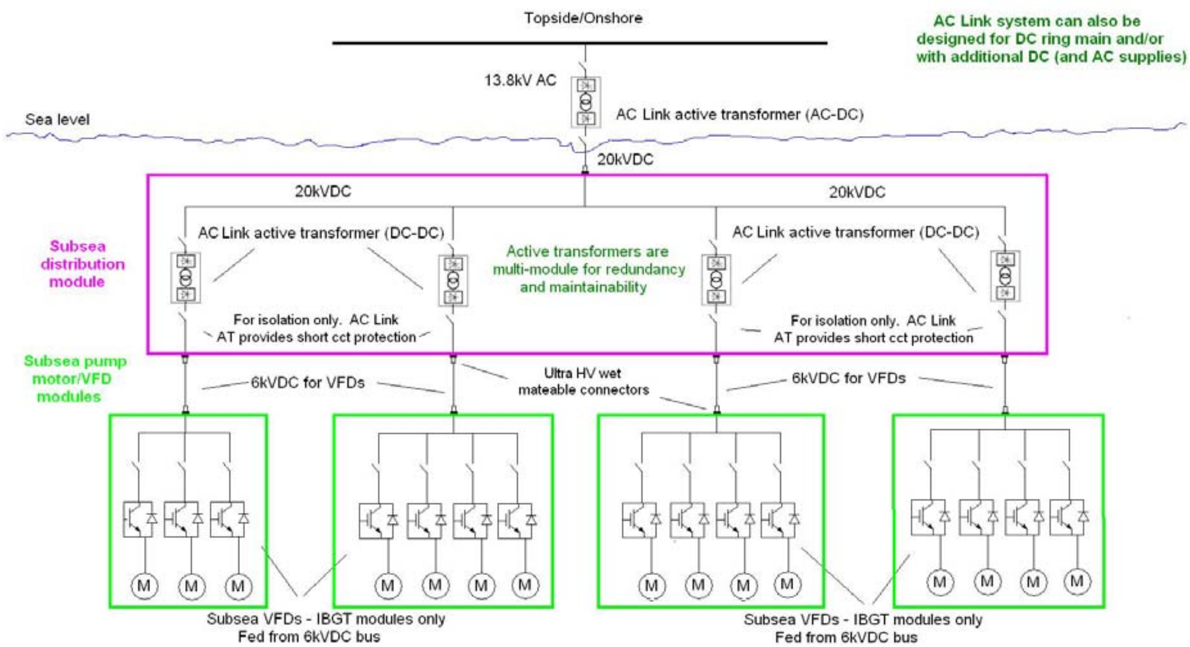


Figure 40 - Future subsea pumping system based on AC-Link™ active transformers

The supply voltage proposed from topside (i.e. the platform or shore) to subsea is 20kVDC via an AC-Link™ 13.8kVAC/20kVDC active transformer. The DC voltage selected is best determined by the available DC cable availability and cable cost optimization. This optimization has to take into consideration the power requirement and cable length. The AC-Link™ transmission system is designed for that cable operating voltage. The use of DC permits power to be transmitted far longer distances from the platform or form the shore than possible with AC transmission systems. Once subsea, the DC voltage is 'transformed' to a regulated 6kVDC, this being the required DC bus voltage for the VFD IBGT bridges which controls each subsea pump.

Each AC-Link™ active transformer has an inbuilt high frequency transformer and input and output overcurrent and short circuit protection. The space requirements for a subsea pumping system based on AC-Link™ technology is a fraction of that required for the conventional system depicted in Fig 37 as none of the fifteen, 1400kVA phase shift transformers are required, nor the four 5-6MVA transformers for each pump module. The weight and cost savings also would be considerable as would be the reduction in maintenance costs.

In addition, as AC-Link^{TM} technology produces virtually zero harmonic current emissions, no additional harmonic mitigation equipment would be required. Overall, the reduction in first costs and life cycle cost of the subsea pump systems would be very significant indeed.

13.2. Offshore HVDC transmission and All Electric Subsea systems

Before concluding this White Paper it may be beneficial and of interest to the reader, to briefly mention two additional offshore application areas where AC-Link^{TM} technology could provide significant advantages over conventional power conversion technology,

These application areas are :

- HVDC transmission
- All Electric Subsea Systems

13.2.1. HVDC transmission

In early 2005 the world's first offshore HVDC transmission system was commissioned. The 40MW, 132kV system connects the Norwegian Troll A gas platform (Fig 42) with mainland Norway.

Fig 42 – The Norwegian Troll A gas platform. The 40MW HVDV enclosure is in the centre

Essentially, as can be seen from Fig 42, the Troll A HVDC transmission system supplies a 40MW variable speed, synchronous motor directly from the shore thus relieving the platform generators from the burden of supplying such a large machine. This system in reality functions therefore as a high power AC variable frequency drive (VFD) albeit with a novel DC bus.

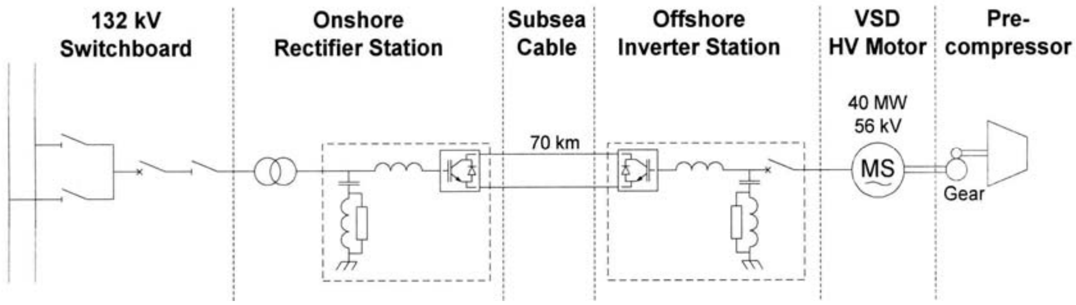


Fig 42 – Basic single line diagram for Troll A HVDC system

HVDC transmission utilized in a more conventional role (i.e. to supply power platform to platform or from shore the platform) is now becoming increasingly popular. BP Norway's Valhall Redevelopment Project (Fig 43) is an example. The installation comprises five bridge link platforms and three wellhead platforms installed around 6km from the main complex.

Fig 43 – BP Norway Valhall platform complex

The complex, which is between Scotland and Norway, is supplied from shore via a 292km/183 mile cable. With reference to Fig 44; the supply onshore is 300kV, which is reduced by transformers and rectified to produce 150kVDC, the transmission voltage. On the platform the 150VDC is inverted to AC, before being transformed down to the platform AC voltage of 11kV. The power requirement for the field is 78MW.

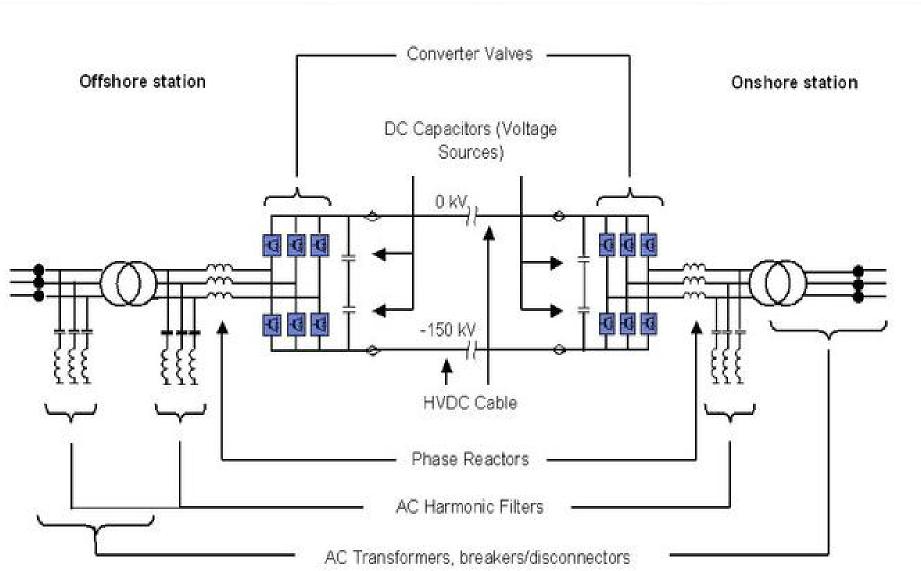


Fig 44 – BP Norway Valhall simplified single line diagram (ABB)

The rationale for offshore HVDC system is based on many factors including :

- Increases in cost efficiency
- Reduce space and weight on the platforms since no additional generators required
- Less offshore maintenance and therefore less maintenance costs
- Reduction in greenhouse gases produced
- Due to DC transmission, power can be supplied over long cable distances

However, in common with other conventional power conversion technologies the issues of harmonic distortion (onshore and offshore) has to be addressed. In addition, large, heavy and expensive conventional transformers are still required.

The recognized benefits of AC-Link™ technology such as very low harmonic current production, lack of conventional transformers, small physical size and low EMI emissions are even more valid in the field of high power HVDC transmission systems.

The AC-Link™ AC to HVDC and HVDC to AC power conversion is illustrated in Fig.45. Unlike the HVDC Classical, ABB HVDC Light or Siemens HVDC Plus systems, low frequency (5Hz or 60Hz) transformers are eliminated with the HVDC AC-Link™ system where the AC is converted directly to HVDC and stepped down to AC in one integrated operation. This is totally revolutionary, as is the integration between the high frequency transformer and the AC-Link™ inverter. In addition, the harmonic current distortion produced (THDi) is <1%, therefore no harmonic mitigation required.

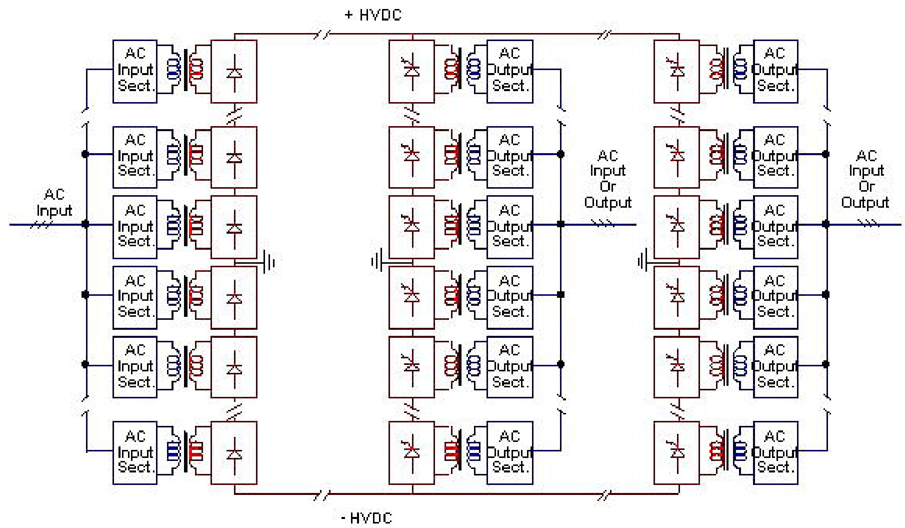


Figure 45 - Multi MW, multi-module AC-Link™ DC transmission and conversion configuration

Most of the power is generated by rotating machinery on platforms as AC is in the voltage range of 6.6kV to 13.8kV. In this voltage range, the AC-Link™ technology is ideal for HVDC DC transmission. However, at the transmission end it is not necessary to invert (i.e. convert DC to AC) the power to AC since AC-Link™ can convert (and distribute) with similar ease the HVDC to a medium voltage DC (MVDC) via HVDC to MVDC operation. The simplified illustration is shown in Fig. 46.

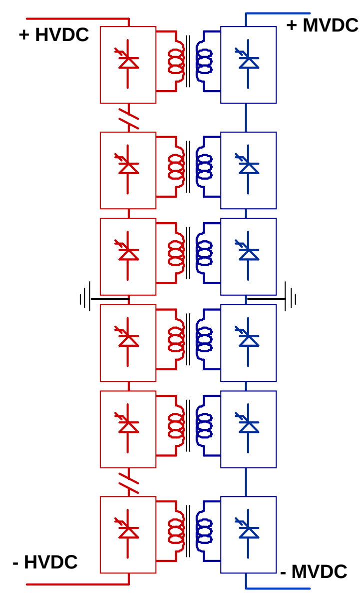


Fig 46 - Direct HVDC to MVDC transformation

As can be seen on the left side, the active HVDC side is identical to the HVDC-AC converter shown previously in Fig. 45, whilst on the right side (i.e. the AC reconstruction side) has been replaced by a second active DC section, which can be either 'active' if bi-directional operation is required or simply 'passive' for uni-directional power flow. The system is again reconstructed to with 'N' number of HVDC section to yield the desired power and HVDC input voltage. Each output section may be constructed for a voltage step-down, such as 200 kV DC to 60 kV DC for additional power distribution.

In the above case the secondary module voltage is 60 kV/N (where N is the number of modules), with all of these modules connected again in series. It is also possible to have two MW modules designed for a 60 kV x 2/N voltage with two modules operating in parallel. Or, if a step-down is to low voltage DC, then all of the right hand modules can be paralleled.

The system can be configured to provide additional DC step-down transformation and reduce the DC power to the user in low voltage DC. The DC power may be used directly as a DC bus for variable speed motor drives (VSD) such as described in the Norwegian Troll A project or other multiple inverter systems which require DC ring main or common DC bus type supplies, to a voltage that can be directly used by the user with DC appliances or convert to standard 50Hz or 60 Hz AC.

In addition, the power flow of the DC transmission and offshore distribution lines would be controllable in order to maintain individual power delivery requirements (e.g. to individual platforms), short circuit current is electronically controlled and instantaneously interrupted. Essentially, much simpler, more stable, and cheaper offshore power grids could be configured.

The AC-Link™ converters for a DC transmission and distribution system can be designed for redundancy as described earlier. The AC-Link™ modules can be load-idled (i.e. sit quiescent until energized instantaneously if the load requires more power). The individual configuration can idle some of its series section, while a complete module in a HV configuration can be switched out, while the system is such that other modules take over the power flow. This redundancy will significantly increase the system availability and provide a reliable DC power transmission and distribution system.

An offshore HVDC transmission system based on AC-Link™ would be much less expensive to purchase and to operate, would be significantly smaller physically and weigh much less, both serious concerns on platforms.

13.2.2. All Electric Subsea Systems

HVDC AC-Link™ systems can also be implemented for lower power applications where the power is supplied from topside (i.e. a platform) or from the shore to a subsea location or locations. It should be noted that another application requiring subsea power, albeit multi MW, has already been mentioned in this White Paper with respect the Future Subsea Pumping Station (Section 13.1.3 - Figs 39 and 40).

Over recent years there has been an increasing trend toward subsea based systems to provide precise valve, choke and manifold control in order to achieve the optimum flow and production of oil or gas whilst increasing flexibility, reducing costs and increasing reliability.

Fig 46 – Example of subsea wellhead control system installation (FMC)

At present the majority of any subsea installations are supplied via long and large diameter umbilical cables which carry hydraulic power to control valves, actuators and other equipment together with electric power and control cables. Due to the requirement for the hydraulic power, the umbilicals are very expensive indeed, up to US$ 800,000 per kilometer/US$ 1,300,000 per mile. Therefore, one of the of the main impetus for the All Electric Subsea System is a reduction is cost by replacing the large umbilicals with much lower diameter electric cables. It is muted that this reduction in cost could be as much as US$ 500,000 per kilometer. In addition, the reduction of topside equipment including conventional transformers is also a significant factor.

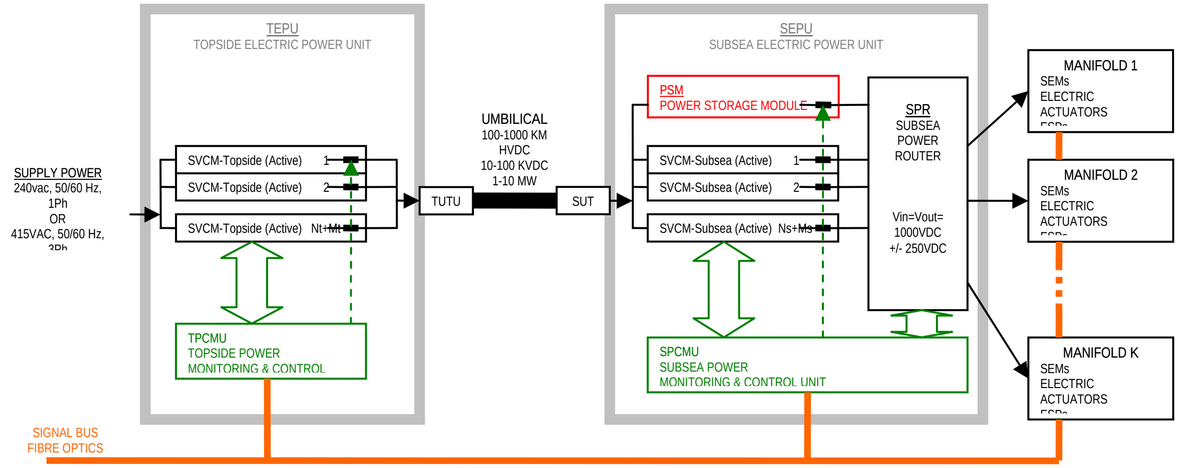
The power requirement for such All Electric Subsea Systems is currently relatively low as the majority of the valve, actuator and other control are still achieved hydraulically. However, this expected to increase significantly over the next few years as electric valves, actuators and other equipment become fully available.

A range LV or MV DC voltages would be available to match equipment voltage requirements. In addition, pure sinusoidal AC supplies or both DC and AC supplies can be provided if required. It is presently envisaged that topside power would be converted from AC (at whatever voltage level) to 10kVDC, the currently preferred subsea DC transmission voltage level. However, higher subsea DC voltages can be accommodated, subject to the suitable DC cables being available.

With AC-Link^{TM} technology, DC power can be transmitted over very long distances (including from distant shore) to subsea locations as there no cable capacitance limitation issues. In addition, as no conventional transformers, harmonic mitigation nor ancillary overcurrent/short circuit current protection equipment is required topside, the reduction in footprint and weight, both important factors offshore, are very significant when an AC-Link^{TM} All Electric Subsea System is utilized.

The AC-Link^{TM} HVDC power can be delivered "point to point" (i.e. from topside {or shore} to a single point subsea) OR it can be transmitted from topside then distributed at the appropriate DC and/or AC voltage levels to match the equipment requirements (this can be multiple requirements for different pieces of equipment). Control signals for the individual items of equipment can also be superimposed on the local voltages as required.

Fig 47 illustrates an AC-Link™ All Electric Subsea 1-10MW DC concept system with a topside electric power unit (TEPU) and a subsea electric power unit (SEPU). The system has inbuilt short circuit protection, built in redundancy topside and subsea via parallel, duty cycled power modules via the subsea router (SPR). Short term power storage (PSM) is also included in the concept system.



SVCM = STANDARD VOLTAGE CONVERETER MODULE.
CHARACTERISTICS:

- STANDARD MODULES, FOR ANY POWER DELIVERY AT LOAD.
- CONSTANT POWER DELIVERY PER SVCM.
- EMBEDDED CIRCUIT BREAKER, UNDER "TPCMU" CONTROL.
- "HOT SWAP" PARALLEL TECHNOLOGY.
- OUTPUT POWER IS CONTROLLED BY "TPCMU".
- N = MINIMUM NUMBER OF SVCM UNITS FOR ADEQUATE POWER DELIVERY.

SPR = SUBSEA POWER ROUTER
CHARACTERISTICS:

- POWER ROUTING FROM ANY SVCM CONFIGURATION TO FIXED MANIFOLD/TREE LOADS.
- UNDER "SPMCU" CONTROL.
- TYPICAL LOADS: SEMs, ELECTRIC ACTUATORS, ELECTRIC SUBMERSIBLE PUMPS.

Fig 47 – Concept 1-10MW AC-Link™ All Electric DC Subsea System

All Electric Subsea Systems is a very exciting area of application for AC-Link™ technology. The lack of conventional transformers, flexibility, compact size, low comparative weight, high specification, comprehensive control/protection and lack of harmonic and EMI emissions all are major factors which make it the ideal subsea solution for the future.

14.0. Conclusions

Until very recently AC-Link™ technology was almost solely for used for development of certain products for all arms of the US military. However, it is now also available for commercial applications.

This White Paper has outlined a number of very significant benefits which can be derived through the use of AC-Link™ technology including negligible supply side harmonic current production, very low levels of EMI and high conversion efficiency which all collectively impact positively in terms of both purchase and operational costs.

The physical space requirements for AC-Link™ based converters are considerable less than for comparable power conversion systems. The use of integral high frequency transformers for both AC and DC voltage transformation is especially important. With AC-Link™ technology conventional transformers, harmonic mitigation and EMC filters are no longer required, thus reducing costs and space requirements dramatically.

The provision of ‘clean’ DC power for both the present and future marine, drilling and offshore oil applications is a very significant potential market sector worldwide. This entails the utilization of AC-Link™, AC-DC converters to supply ‘clean’ LV and MV DC power, depending upon application criteria. Conventional PWM IGBT VFD output bridges, currently available from multiple manufacturers, can be configured within either a common DC bus systems, or for large systems, a DC ring main system of an appropriate DC voltage. The AC-Link™ DC power system also provides both AC and DC side overcurrent and short circuit protection. The use of the high frequency transformers provides galvanic isolation for the IBGT bridges to attenuate the common mode voltage normally associated with VFDs. The advantages of using AC-Link™ based common DC bus and DC ring main systems should now be very apparent to the reader.

The application of AC-Link™ technology for future subsea pumping station applications can revolutionize the future design and subsequent procurement, installation and operational cost of such systems. Similarly, AC-Link™ technology can be at the very forefront of the emerging All Electric Subsea Wellhead Systems.

AC-Link™ is the first of new generation of exciting technologies which are set to revolutionize power conversion in the 21st Century.

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