High Power Clean DC BUS Generation Using AC-Link AC to DC Power Voltage Conversion, DC Regulation, and Galvanic Isolation

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Abstract

The proliferation of large non linear loads such as main propulsion and thruster variable frequency drives (VFDs) on both warships and commercial vessels, high voltage power supplies for lasers and other advanced weapons on warships require both AC voltage transformation and power conversion from AC to DC. For VFDs, rectification from AC to DC and inversion from DC back to AC is necessary; a process also applicable for some types of naval electric weapons and defensive systems.

AC power transformation and rectification requires large conventional, low frequency transformers (i.e. 50Hz or 60Hz operation) in order to achieve voltage transformation and then rectification to provide the required level of DC voltage. The rectification process results in the production of harmonic currents and subsequent voltage distortion which, as is widely acknowledged, can adversely affect the operational integrity of the vessel or installation.

The purpose of this paper is to propose a marine power system distribution system based on 'clean DC power' for some classes of naval vessels, commercial shipping and drilling/offshore applications. The paper introduces AC Link™ technology, a 'soft switching' (i.e. it has no switching losses), high frequency technology which can transform voltages from any AC source within the converter (i.e. no conventional transformers are required) to either low voltage or medium-high voltage as part of the AC to DC conversion process.

The AC Link™ converter draws virtually harmonic free AC current (THD<1%) at unity displacement power factor and can provide single or multiple, regulated and galvanically isolated DC outputs (or AC outputs if required). The DC power can be supplied without any harmonic ripple, based on various 'active transformer' derived configurations: a) as discrete front end rectifiers for dedicated systems; b) as the DC supply for common DC bus systems and c) as the input converter stage to low voltage or medium to high voltage DC ring main systems. Voltage transformation (AC or DC) is via internal, high frequency transformers (20kHz) which are a fraction of the size and weight of conventional transformers.

This paper also outlines important weaknesses in present harmonic mitigations technologies with respect to cost, real world performance and physical size. The proposes an exciting, advanced technology which is poised to take marine, offshore, and industrial electrical power system engineering into the 21st Century.

Introduction

The proliferation of large non linear loads such as main propulsion, thrusters, and other variable frequency drives (VFDs) on both warships and commercial vessels, high voltage power supplies for lasers and other advanced weapon and defensive systems on future warships require both AC voltage transformation and power conversion from AC to DC. For VFDs, rectification from AC to DC and inversion from DC back to AC is necessary; a process also applicable for some types of naval electric weapons and defensive systems.

The UK's Royal Navy's Type 45 destroyers (Fig 1) have 2 of 20MW/4.16kV multi-level VFDs for main propulsion. On commercial vessels, AC VFDs up to 40MW per shaft for main propulsion duties and for thrusters up to 8-10MW are increasingly common.

Fig 1 –Type 45 Daring class destroyer the 2 x 20MW, 4.16kV, 15 phase, multi-level, PWM AC drives can accelerate the 7500 ton vessel from zero to 29 knots in 70 secs (Navy News)

Numerous ancillary drives are also utilized, ranging in power from a few kW to over 6-8MW (Fig 2).

Drilling rigs (Fig 3), FPSOs (i.e. floating production storage and offloading vessels) and offshore oil platforms rely heavily on AC VFDs for applications such as propulsion, station keeping, drilling, and pumping product to the surface.

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

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Fig 3 –Modern, dynamically positioned semi-submersible drilling rig

On drilling rigs, drill-ships and offshore production platforms non-linear variable speed drive load constitute up to 85% of the installed kW (Fig 4). The oil industry is very conservative and historically rigs used DC SCR drives for drilling duties but over recent years AC drives have made significant inroads into this application area, either as discrete drives or more commonly as part of a common DC bus system. Typically, the installed drive power for a drilling package is 5000-12,000HP (3.7-9.0MW). As can be seen in Fig 4 the thruster drive power alone is almost 26MW.

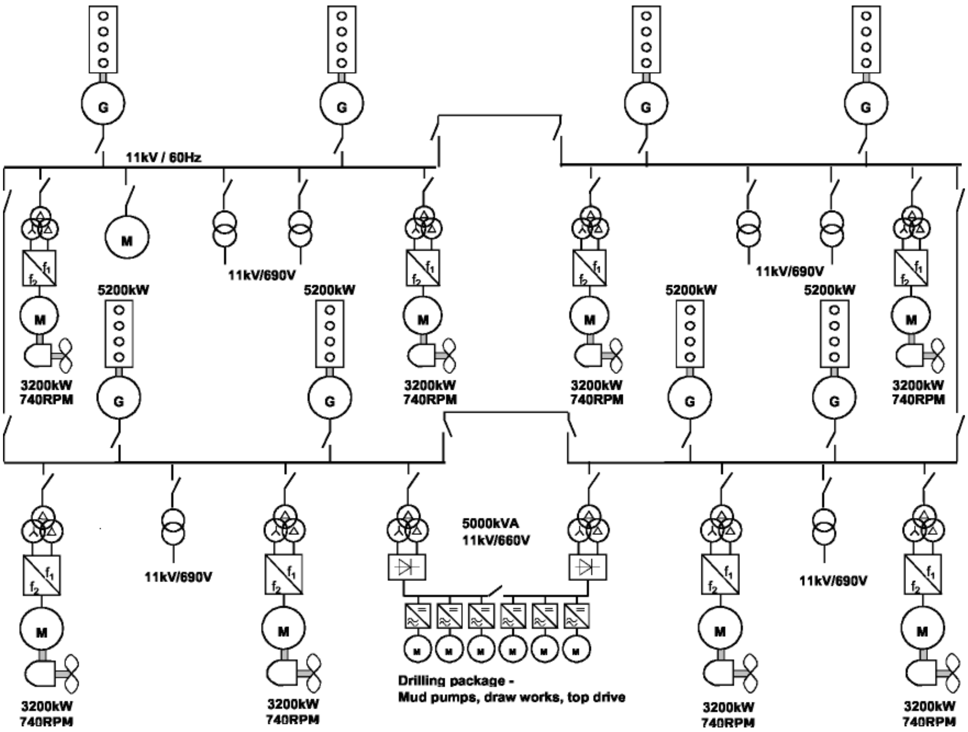

Fig 4 – Schematic of a DP3 (dynamically positioned) Class 3 semi-submersible drilling rig with AC variable frequency drives for propulsion/ thruster and drilling package duties

On oil production platforms it has been the norm to pump the sea-water mixture from the seabed via the use of VFD controlled electrical submersible pumps (ESP) which are inserted into the 'hole'. The very long cable lengths involved and the associated voltage drops and resonant wave front cable problems associated with PWM VFDs have resulted in the use of sinus output filters and at times output transformers, in order to try to ensure that the VFD output voltage and the ESP motor voltage are the same. In the author's experience the ESP VFD installed base on platforms can be up to 10-15MW.

However, over recent years there has been considerable interest in the concept of subsea VFD based pumping stations. Fig 5 depicts an artist's impression of a small subsea pumping station.

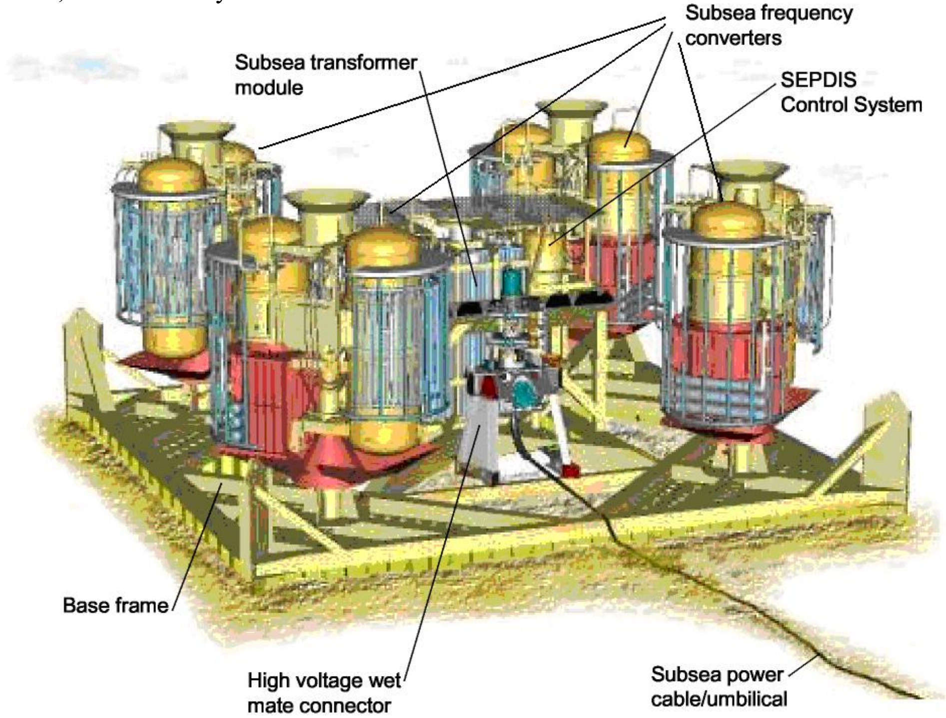

Fig 5 – Artists impression of small subsea pumping station with VFDs

Fig 6 illustrates a single line diagram of a large future subsea pumping station with 15 of 1.2MW 12 pulse, 4.26kV VFDs and comprising no less than twenty-one power transformers for voltage transformation VFD phase shifting.

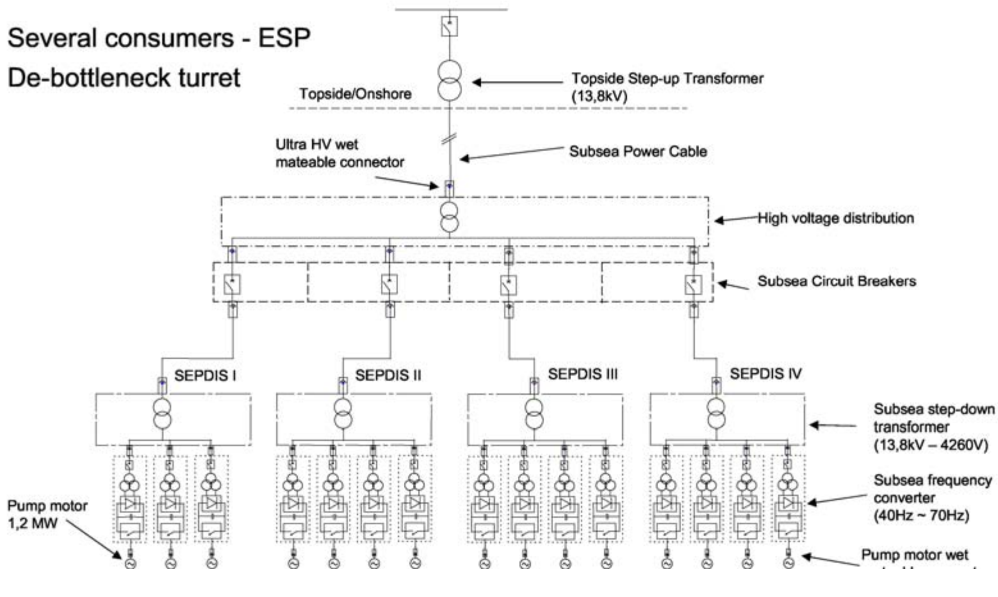

Fig 6 – Single line diagram of large future subsea VFD based pumping system (Vetco)

As can be appreciated the electrical non linear load on warships, commercial vessels, drilling rigs/ships, and oil platforms is increasing, placing considerable harmonic strain on generators and degrading the quality of the voltage supplies. It should be stated that power quality is degraded due to harmonic currents produced during the conversion from AC to DC for VFDs unless, of course DC SCR drives are installed.

Harmonic distortion in the marine and offshore sectors

NATO navies and most marine classification bodies such as the American Bureau of Shipping (ABS), Det Norse Veritas (DNV), Bureau Veritas (BV) have 'rules' to limit the harmonic voltage distortion. The harmonic limits for general systems are based on IEEE 519 (1992) voltage limits (not current limits) and are 5% THDv with no single harmonic being >3%. The exception is Lloyd's Register which stipulates 8% THDv with any harmonic voltage above the 25th <1.5%.

Most classification bodies cite limits up to the 50th harmonic with the exception of ABS and Polish Register of Shipping (PRS) who both state that *"for vessels with active front end (AFE) drives the harmonics shall be measured up to the 100th harmonic"*. The problem is most power quality analysers only measure to the 50th.

However, in the author's opinion the THDv rules are not being policed as effectively as they should be. This is especially true in the oil industry where THDv levels regularly reach up to six to seven times the prescribed limit. The rational for the 'rules' is safety and operational integrity of the plant and equipment. Harmonic distortion and the effects on plant and equipment has to be addressed to ensure that the safety of the platform (or ship), the protection of both the crew, and where appropriate, the passengers and the marine environment are to be assured.

It is not beyond the realms of possibility that harmonics were a contributory factor in the world's worse oilfield disaster (i.e. the explosion and fire Piper Alpha, Scottish North Sea) in 1988 when 167 crew members died). The harmonic problem on oil platforms is significantly greater today and has reached potentially dangerous levels (Fig 7).

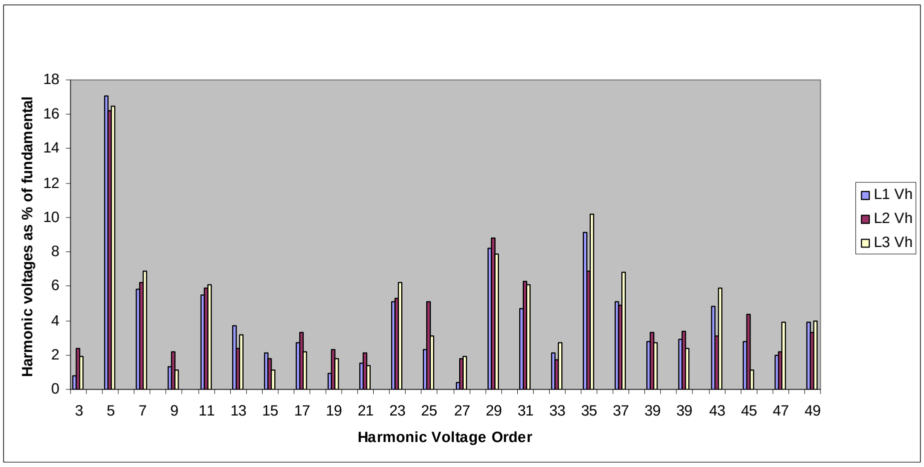

Fig 7 – Oil production platform harmonic voltage spectrum at 690V. Note : 27.3% THDv with 20.2% THDv above the 21st harmonic due to multiple, high power MV ESP VFDs

Fig 7 illustrates a typical harmonic voltage spectrum of an oil production platform. 24 pulse MV VFDs for ESPs is now very popular. As can be seen, the result is that voltage distortion is pushed up the spectrum to 'induction heating' territory. The effect of these uncharacteristically high, high order harmonics on explosion proof motor rotors and other equipment is unknown. A year later, the IEC has still to start to investigate and the authorities have still be address, not just the dangerously high order harmonics, but the THDv levels which are up to 6-7 times the limit. To date the oil companies are permitted to 'police' themselves. I think we all know what happened to financial, self-regulation!

It is now widely known that standard fixed speed IEC explosion proof motors for Zone 1 use are only permitted 2% background HVF (harmonic voltage factor) before they are legally uncertified. For Type N for Zone 2 only the permitted HVF is 3%. Piper Alpha used Type N motors and double cage rotors (compressor application); the explosion occurred in the compressor room after an escape of gas or vapour!

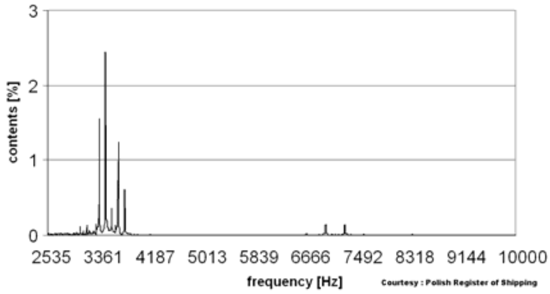

Fig 8 – Vessel with 4 AFE VFDs. THDi >50th harmonic was 3.4%

Current harmonic mitigation methods

There are various methods of harmonic mitigation available including passive L-C filters, Lineator passive wide spectrum filters, multi-pulse drives and quasi multi-pulse techniques, active filters and active front end rectifiers (AFEs). However, this additional equipment requires significant additional space, often in vessels and installations where space is at a premium. The mitigation can be expensive and has additional losses which have to be taken into account.

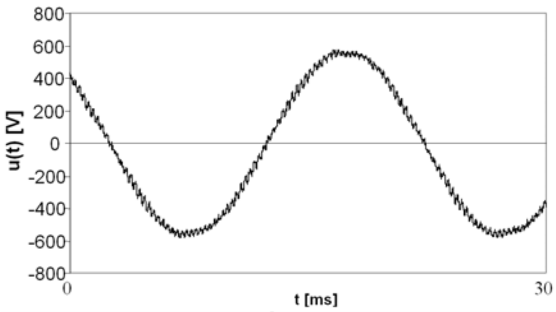

Fig 9 - Supply voltage waveform on research vessel with 4 AFE VFDs

The suitability and performance of the various mitigation options are also highly dependent on the given application. AFE rectifiers can offer a low harmonic footprint, for example, but can have significant disadvantages including harmonic current production above the 50th harmonic (Fig 8), the production of large amounts of EMI in the range above 8-10kHz and the AFE switching frequency ripple being impressed on the voltage supply network (Fig 9). There is also the possibility of interaction with 6 pulse VFDs on the same supply, raising the DC bus voltage by up to 15%. For main propulsion drives, the excessive regenerative energy imposed on the generators during crash-stop or violent astern manoeuvres could trip or even damage the generators or prime movers.

Active filters can offer excellent performance but their success is determined by many factors including the type of filter, especially for dynamic loads (e.g. 'selective FFT' or broadband) and the point of connection in the power system. It should be noted that due to its very low source impedance, the magnitude of harmonic currents drawn by the load(s) with the active filter operating will be higher than without it, and consequently the THDv downstream will be higher). Therefore, where the active filter is connected is crucial to its success. Connecting the filter to the main switchboard will protect the generators but will do nothing for the loads and drives downstream which will see a higher THDv which may cause additional operational problems.

The more advanced types of passive wide spectrum filters can also offer low harmonic performance in series devices (which also act as blocking filters) and currently are used only on low voltage supplies (<900V) to around 5000HP.

Multi-pulse drives (>18 pulse) can also be used to achieve <5% Ithd under ideal conditions but the additional weight and space required for the multiple rectifiers and phase shift transformer can be problematic. There are also issues with performance due to background THDv and also imbalance to consider.

Introduction to AC Link technology

This innovative power conversion technology was invented by Dr. Rudy Limpaecher in the 1990s as the basis for high energy laser power supplies. Currently, it is both in service with the US Navy for general duties and is being further developed as a multi-port converter for main propulsion, advanced electric weapon systems, and other duties within the US military.

In essence, AC Link™ draws 'energy packets' at a high frequency from the source to construct a desired output AC waveform or DC voltage. The basic converter (Fig. 10) has no DC-link (only a central capacitor for instantaneous transfer) and is considered pseudo-galvanically isolated since the input is never directly connected to the output. In a multi-port configuration AC-link™ 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, several types of motor drive loads, DC for charging Direct Energy Weapons (DEW) or similar defensive systems.

The salient benefits of AC Link™ technology are :

- Very high power density (~5.5MW/cu.m) – <75% smaller than PWM systems
- High efficiency (~98%)
- Direct AC-AC conversion with <1% total current harmonic distortion (THDi). (AC-DC, DC-AC, or DC-DC are all simpler versions of AC-AC operation)
- Transformers are eliminated for galvanic isolation requirements (large weight reduction). Direct connection to MV supplies
- If used as VFD motors and generators sees a dv/dt of less than <15 V/usec thus eliminating insulation failure, bearing erosion and motor cable problems
- No additional harmonic or EMI filtering required so reduces component weight, losses and overall cost compared to convention technologies
- Soft switching enables inverter operation over 20 kHz and high efficiency operation at medium voltage (IGBT operation)
- Voltages, AC and DC, can be transformed without conventional transformers
- Multi-port operation yields instantaneous redirection of power flow
- Scalable to any power level with time-interleaved module operation
- Fault-immune operation, natural fault current limiting (zero-current turn-off, no PWM shoot-through

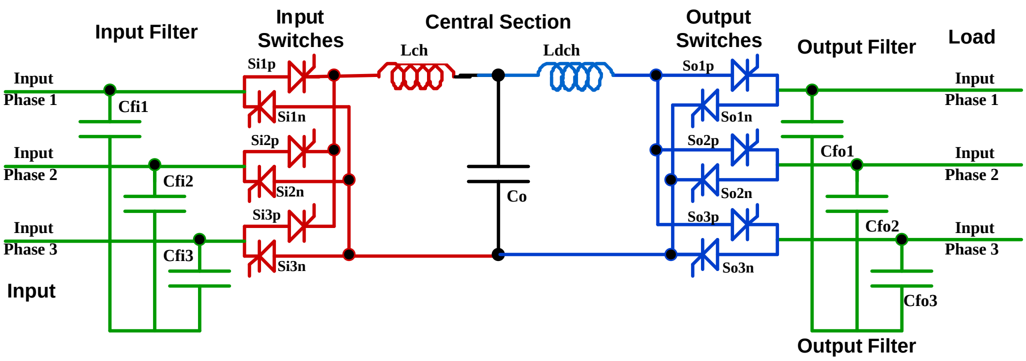

Fig 10 – AC Link is soft-switching, resonant, bi-directional, self-commutating converter

For marine and offshore applications, compactness, very low harmonic current production (<1% THDi) and the absence of conventional transformers are the salient significant benefits of AC Link™ in applications where the available space and harmonic distortion are of paramount importance.

Active transformer based common DC bus and DC ring main systems

Common DC bus systems based on PWM VFDs are relatively common, especially on drilling rigs and other specialized vessels (Fig 11).

This design utilises common input rectifier and DC capacitor bank to which are connected a number of PWM inverter IGBT output bridges, each controlling an induction motor. This reduces the footprint of the drives and can lead to decrease costs. The input rectifiers are however of the conventional type and usually require some form of harmonic mitigation in order to satisfy the rules on Vthd plus voltage transformation, if applicable.

DC ring main systems are also not new, in fact the majority of warships utilized ring main systems derived from DC generators from before WW1 until the 1960s. What is different now however is the type of loads being powered by the DC voltage and the method of obtaining the DC power without generating harmonics and without conventional transformers via AC Link™ 'active transformers'.

Fig 12 illustrates a dual module AC-Link™ system in an AC-XtrDC (AC-DC) configuration.

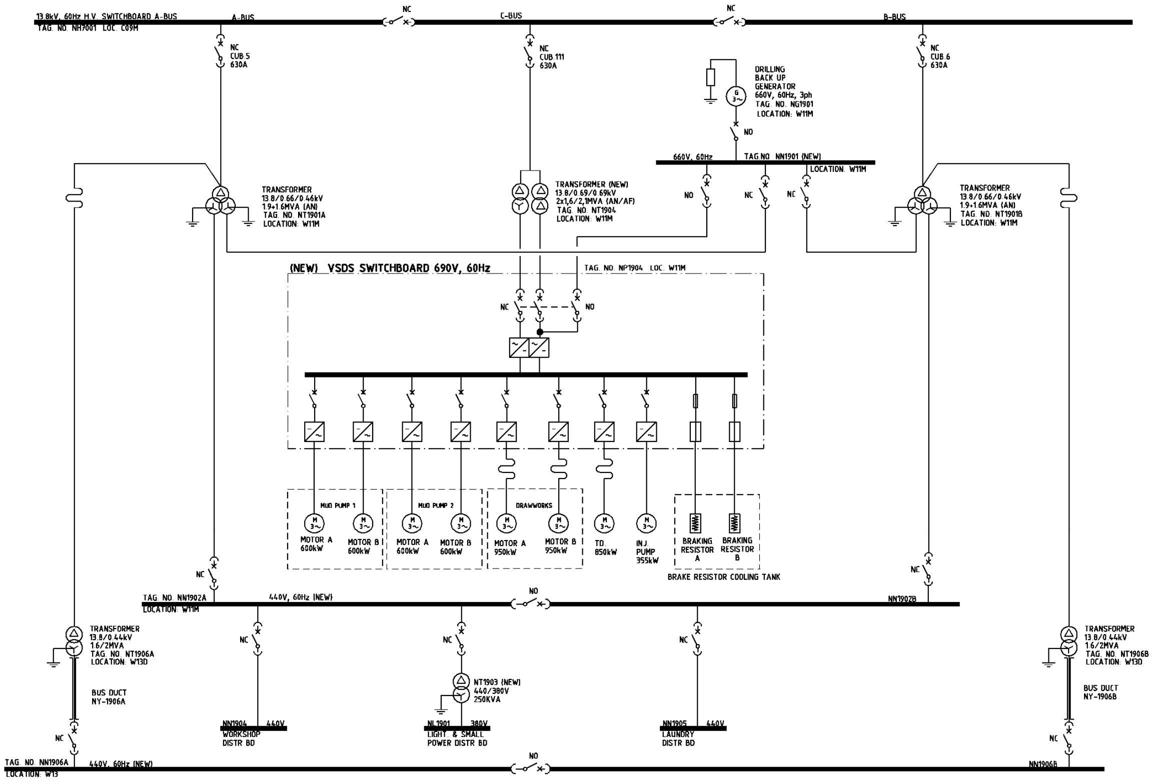

Fig 11 – Schematic of conventional common DC bus system for drilling rig 'drilling package'

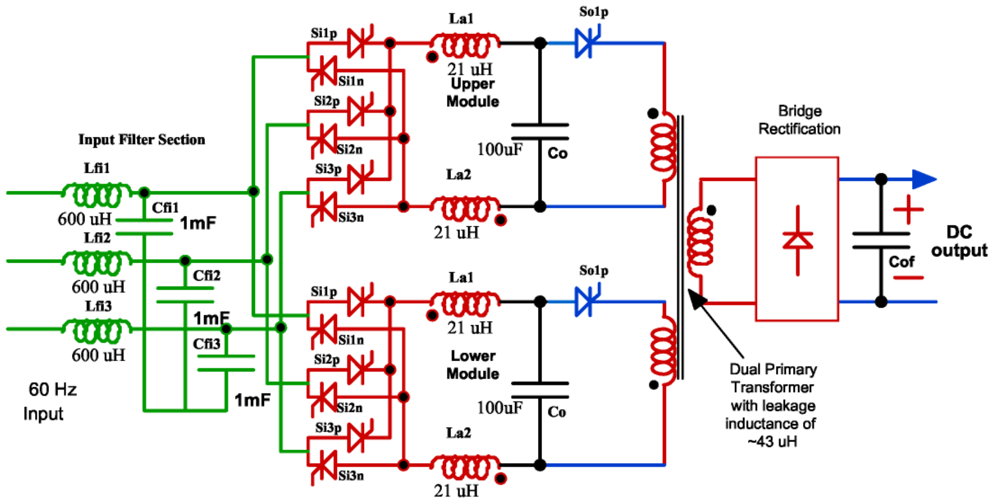

Fig 12 – AC Link active transformer system for DC ring main or common DC bus systems

The high frequency transformer design can incorporate either step-up or step-down voltage ratio. This circuit uses two AC-Link™ modules which draw power from the AC source and discharge it into the high frequency transformer primary. The operation is identical to that of two parallel modules operating in an AC-to-DC configuration except that in this instance the output inductor is replaced by the leakage inductance of a high frequency transformer. As the central capacitor of the first module is charged from the AC source, the energy stored in the second module central capacitor is discharged. The central capacitor and the leakage inductance form a resonant circuit and produce a half sinewave on the transformer secondary. The transformer secondary current waveforms are rectified and passed into the output filter capacitor. With that cycle completed, the role of the two modules reverses and the second module recharges while the first module injects an identical energy and current pulse into a second primary winding. For the second pulse, the magnetic flux is reversed to produce a second half-sine wave with opposite polarity into the secondary winding to complete a full sine wave. Since the AC Link™ inverter has a soft-switching topology, high voltage switches such as 6.5 kV IGBTs and IGCTs can be operated at high frequencies since there are practically no switching losses. This permits the transformer also to operate at the same high inverter frequency, minimizing both the size of the core and transformer windings. The transformer weight is of the order of 40 to 60 kg/MW. The transformer core uses a small cross section nanocrystalline core and the winding requires Litz wires at that operating frequency. Since both the core and windings are small, their combined cost, physical size and weight are a small fraction of that required for a conventional AC transformer of the same rating. Also, by operating the inverter at a frequency of 20kHz, the 40kHz ripple can be effectively filtered using small capacitors. There is no 360Hz DC ripple (60Hz AC power input) and therefore only the 40kHz output ripple (due to two interleaving modules) requires a filter utilizing only small capacitors.

It is therefore possible to install DC ring main (or common DC bus) on vessels and installations in order to take advantage of AC Link™ technology's almost zero harmonic current emissions and electronic voltage transformation, thereby completely replacing transformers, rectifiers and harmonic mitigation with ONE unit. VFDs based on PWM drive technology can thereby still be used (Fig 13).

The use of AC Link™ common DC bus or DC ring main DC systems significantly reduces both the drive cost/kW and reduces the required space per kW/MW as only the VFD IGBT output inverter, which is connected directly to the DC power, required. The AC Link™ configuration eliminates any harmonic issues on the vessel or installation's power system. Fig 14 illustrates the AC Link™ equivalent of the future subsea pumping station as depicted in Fig 6.

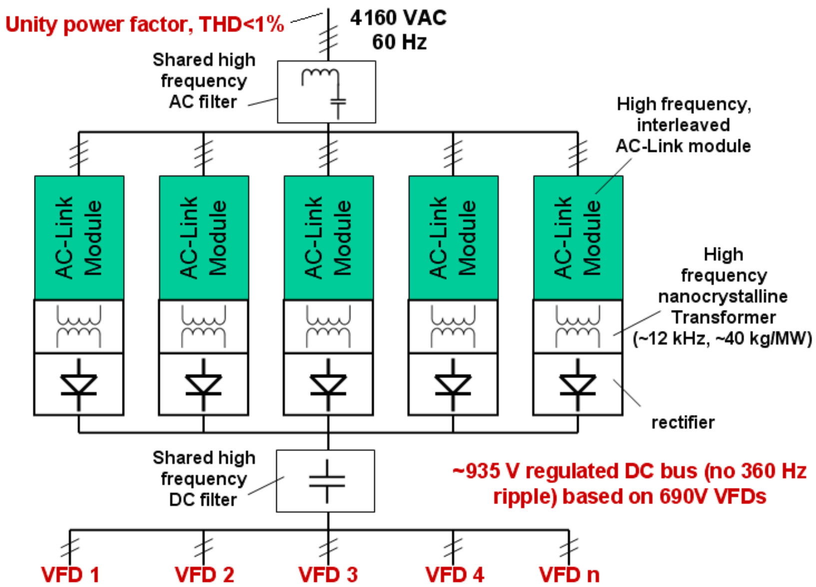

Fig 13 –Low power, AC Link™ multi-module, active transformer system with >3MW/cu.m density for marine and offshore drive systems.

For vessels with both medium voltage (MV) or low voltage (LV) drives either two separate DC ring mains (one MV and one LV) can be installed or alternatively, for example, the MV DC ring main could, via smaller AC Link™ DC-DC active converters, supply the LV DC ring main with DC voltage at the appropriate level. If required, pure sinusoidal single or three-phase supplies (50, 60, 400Hz for example) could also be derived from the DC bus using AC Link™ DC-AC converters.

It is envisaged that two separate active transformers would be installed in order to provide redundancy as is current practice within the marine and offshore industries. For added redundancy each active transformer would have multiple standalone modules.

Application areas for AC Link™ derived DC power

DC main ring systems are ideally suited for vessels or installations which require large and/or multiple VFDs and/or other DC loads including:

- Vessels with large installed MW of VFDs (e.g. FPSOs, dredgers)
- Drilling rigs/ships and oil platforms

● Naval propulsion and ancillary drives, weapon/defensive systems
● Subsea systems (including subsea pumping stations)
● HVDC from platform/shore to subsea (e.g. All Electric Subsea Systems)

Of course, the common DC bus and DC ring main systems can be used onshore for large drive systems (e.g. paper lines, steel works), aluminium smelters or anywhere where direct or indirect medium-high DC power is required.

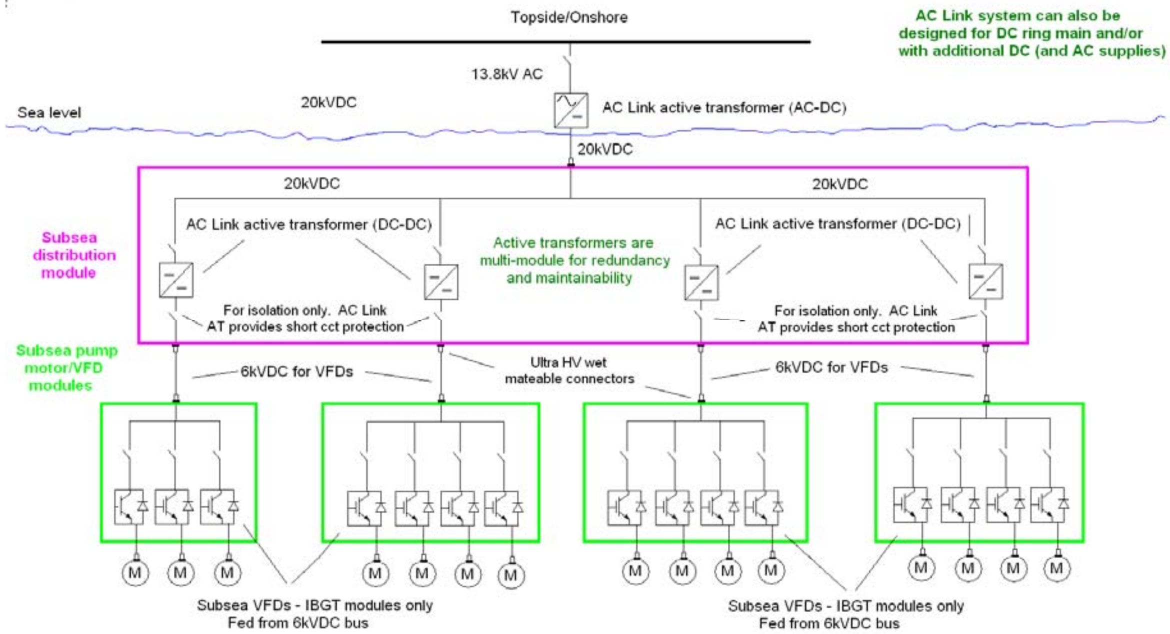

Figure 14 - Future subsea pumping system (Fig 6) but based on AC Link™ active transformers

Protection (short circuit) offer by AC Link™ active transformers

Operating at a frequency of 10kHz, typical for large MW converters, the AC Link inverter delivers 20,000 small energy packages to the output. The energy stored in the output filter is of the order of 6 to 10 energy packages, storing about 500 Joules per MW of inverter power. Should a load fault occur, the 50 Joules discharge will completely and subsequently would isolate the input from the output, shutting down the system in less than 100uSec. This is significantly faster than any other protection system per MW of power. Subsequently, after a preselected time, a restart can be attempted, if required, by gradually reapplying a voltage under stringent current limit conditions, even if the fault still exists.

Multi-Port DC outputs

The AC-Link ™ converters in figures 10 and 12 are shown with single AC or DC outputs. Since the transformer may have multiple isolated windings, multiple isolated and regulated DC sources can be generated. For this operation output the rectifier diodes would be replaced with output switches (e.g. IGBTs or IGCTs) such that the output for each DC output bus can be separately regulated. A dual output is the most practical multiple DC output configuration with one secondary coil of the "C" core transformer dedicated to one output each. With a multiple module system, a number of isolated DC output windings can be generated with the output voltage controlled on demand of the VSC. If the input of AC Link™ converter is implemented to switch from one DC bus to the next, not only redundancy is obtained, but also the optimum DC input voltage can be switched depending on the power level and output frequency.

Provision of DC-DC and DC-AC supplies

The AC-Link™ architecture permits either AC or DC inputs to transform and regulate an output with voltage step-up or step-down. The output of such system may be either DC or three-phase AC reconstruction. For an AC output, any frequency can be reconstructed that either drives a variable speed motor or a standard equipment voltage and frequency such as 50Hz, 60Hz or 400Hz for example.

On the input side, the AC Link ™ converter can interface with any power AC power source with any generator frequency. This permits the utilization of unsynchronized generators and more important high speed generators that are directly coupled to high power turbines. For such interfaces the inverter has to operate with a minimum frequency of 18 inverter cycles per AC cycle to draw low harmonic power. Therefore, this requires a minimum inverter frequency of 7.2kHz for a 400Hz output reconstruction, while with a 20kHz inverter can draw low harmonic power from a turbine power source of 1100Hz. The power drawn from the AC power source has not only a low THD but also in most cases a unity power factor. However, if VAR support is required, leading or lagging currents can be drawn and controlled with a bandwidth of over 100Hz.

Figure 14 (future subsea pumping system based on AC Link^{TM}) shows two types of converters; 13.8kV, 50 or 60Hz AC is drawn topside (or from shore) and transformed to 20kVDC for transmission. The DC voltage can be selected to optimize the DC transmission efficiency or match the DC cable and connector voltage and current rating. The internal high frequency transformer not only provides the necessary voltage transformation but also galvanic isolation.

The subsea distribution module received the 20kVDC power and uses for this configuration, four DC to DC step-down converters. Again, high frequency transformers are used for transformation and galvanic isolation. The regulated 6 kV DC output is that required for the input voltage of a VFD. A separate isolated transformer winding may be incorporated to add also an AC output such as for a 480 V AC three-phase 60Hz power source. Such a system would be a multi-port inverter with a separated DC and AC output. Such a system has to share the throughput power. If the AC demand is high, the functions can be separated in to a 20kVDC to a 4.16kV or 480V AC converter.

Summary

AC Link™ active transformer common DC bus and DC ring main systems offer very significant benefits in terms of cost, efficiencies and space requirements to the naval, marine and offshore sectors wherever medium to high DC power required. The active transformer based solution permits high power electronics to be installed where it may be deemed impossible with conventional technologies. In addition, the virtually harmonic-less operation of AC Link™ maintains the electrical system operational integrity without the need for additional harmonic and EMC mitigation equipment. It is truly 21st Century technology.

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