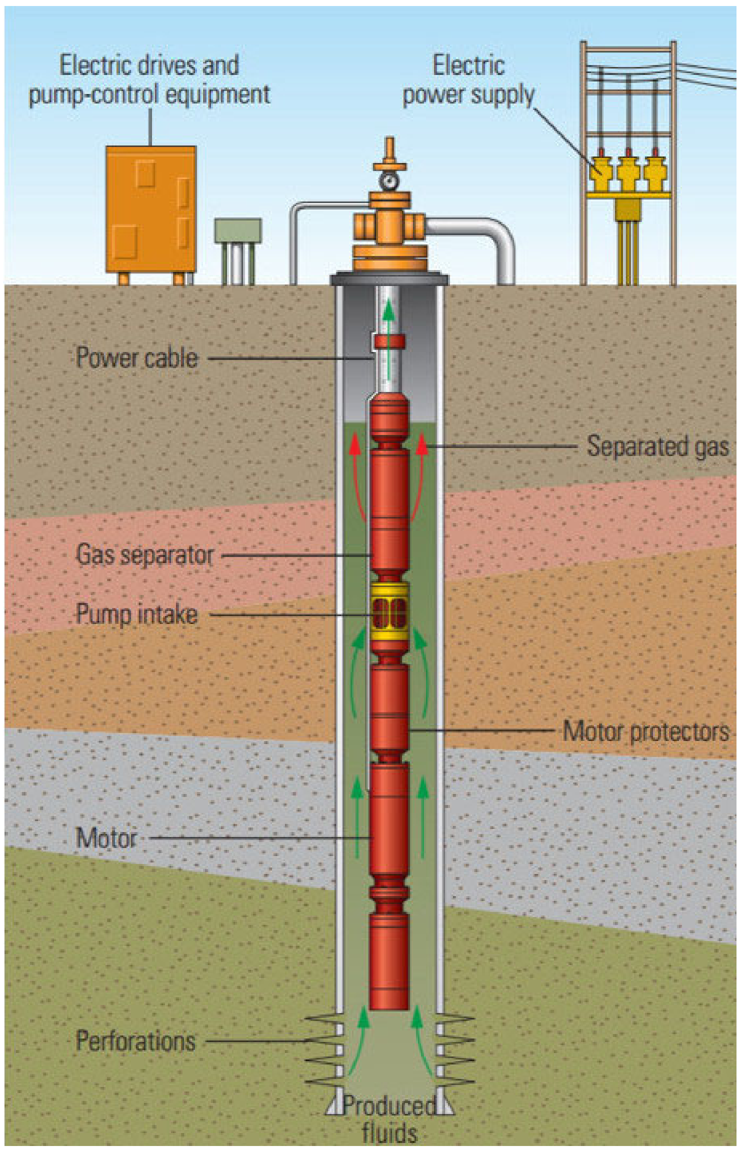
RESONANT LINK TECHNOLOGY

Comparison of PWM VFDs versus Resonant Link Converters for Oilfield ESP Duty. Part 1



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AC variable frequency drives (VFDs) have been in existence in a number of forms since the early 1970s. In the early 1980s the "pulse width modulated" (PMW) VFD versions began to appear. This form of motor control produced less motor rotor and stator harmonic heating and delivered smoother torque control at slow motor speeds. Thirty years on PWM VFDs are still most popular form of motor speed control on the market for low voltage (LV) and medium voltage (MV) applications. However, there are still significant problems to be addressed after 30 years regarding PWM VFDs, including 'active front end' variants, currently sold as "low harmonic drives".

6 pulse PWM VFDs

Figure 1 illustrates the simplified circuit of a 6 pulse PWM VFD. The incoming supply is rectified by the input converter to AC voltage x 1.35 (e.g. ~540VDC for 400VAC) and is stored in the DC bus where the DC voltage varies according to the instantaneous energy demanded by the motor. The IGBT output inverter produces an output voltage/frequency ratio based on the speed setpoint demand and to maintain the fluxing and

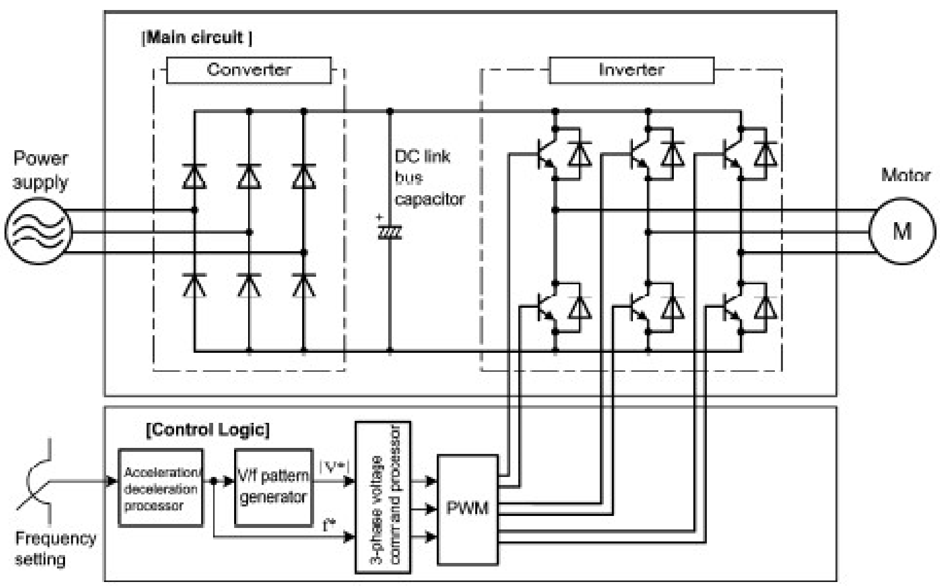

Figure 1 : Typical 6 pulse PWM VFD

The characteristic input current of a 6 pulse VFD is two current pulses per half cycle (See Appendix One). Typically, a VFD with no AC line or DC bus reactor exhibits a THDi (total harmonic current distortion) of between 85-135%. Using say, a 3% AC line reactor based on 5% source impedance, decreases to 36-40% THDi. AC line or DC bus reactors are highly recommended for 6 pulse VFDs but cannot offer compliance with harmonic recommendations such as IEEE-519-1992, IEEE-519-2014, IEC 61000 series et al. Therefore, additional equipment including series passive or parallel active filters are applied to bring the THDi to within <5-8% at rated load. This increases the cost of the VFD(s) installation significantly, as offer the harmonic mitigation cost can exceeds that of the VFD(s). Additional space is also required to house the harmonic mitigation.

For more information on 6 pulse PWM VFD input harmonics refer to the Part 2, Appendix.

AFE 'low harmonic" PWM VFDs

In an attempt and reduce the THDi due to 6 pulse VFDs, a VFD variant entitled the "active front end" (AFE) drive was introduced (Figure 2) in the mid-1990s. It is also known as a "low harmonic drive", which unfortunately can be more of a marketing tool than reality.

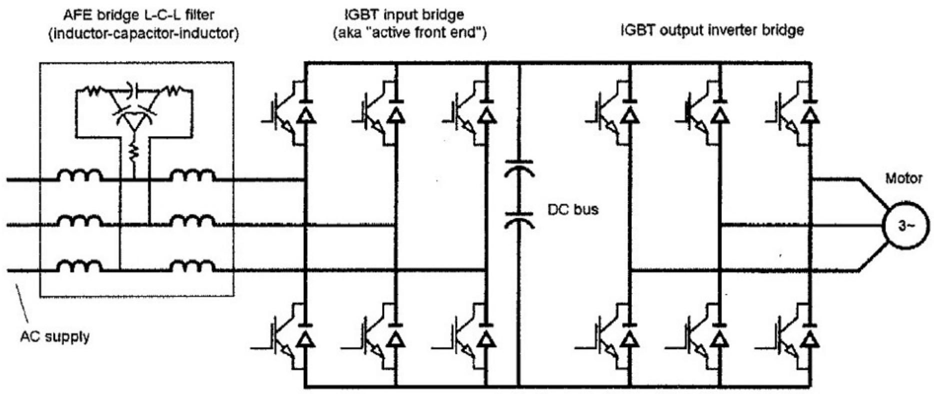

Figure 2 : Typical simplified schematic of AFE VFD

In an AFE VFD, the normal 6 pulse diode or SCR pre-charge is replaced with IGBT rectifier which attempts to synthesize sinusoidal current waveform. This requires a passive L-C-L filter upstream to 'clean up' the phase currents and attenuate the AFE switching frequency which, otherwise would promulgate throughout the system. There are issues to be considered with AFE VFDs (see Appendix One).

At no-load, light load or intermittent load, the capacitors in each L-C-L filter injects uncontrolled reactive power (kVAr) into the power system which if excessive, causes unstable displacement power factor and overexcitation of generators, especially if multiple AFE VFDs are operating.

For more information on the input of AFE "low harmonic" PWM refer to Part 2, Appendix.

Comparison of VFD and various harmonic mitigation option overall efficiencies and THDi

AFE VFDs or "low harmonic drives" are commonly specified by consultants or energy saving applications for pumps and fans. However, compared to other common harmonic mitigation options, AFE VFDs are the least efficient. These results in higher running cost for users or AFE VFDs. See Table 1 below :

AC VFD and type of mitigation	Efficiency (nominal load)	Ithd/THDi (nominal load)
6 pulse VFD/without reactor	97.5%	85-100%
6 pulse VFD/with 3% reactor	97.2%	36-40%
6 pulse VFD/with series passive filter	97.0%	5-8%
6 pulse VFD/active filter	96.0%	4-8%
18 pulse VFD	95.0%	5-8%
Active front end drive (AFE)	95.0%	5-8%

Table 1 : Comparison of efficiencies and THDi (to 50th order only) of various harmonic mitigation options

Output of 6 pulse PWM and AFE VFDs

Whilst the input power stages of 6 pulse and AFE VFDs differ, the output inverter stages are identical. Figure 3 provides an overview of the salient voltages and currents characteristic of PWM VFDs.

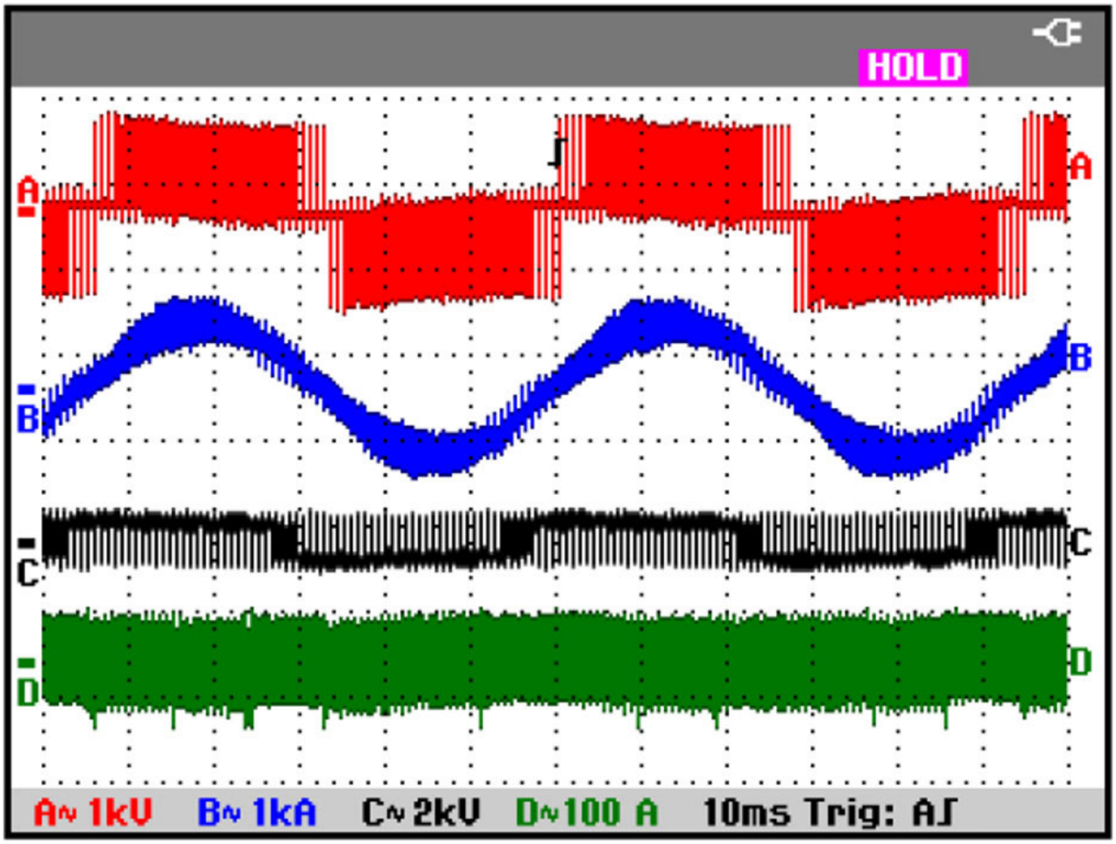

Figure 3 :** A = line voltage. B = phase current.* ***C = common mode voltage. *D = common mode current.*

As can be seen above the line voltage is modulated (i.e. chopped) rectangular waveform whilst the current is a roughly synthesized sinewave. The switching frequency of the output voltage and the accompanying du/dt (i.e. rate of rise of voltage) are responsible for the vast majority of EMC and other related problems due to VFDs including :

- Motor insulation failure. Then insulation is stressed by excessive rate of rise of voltage.
- 'Standing waves' (i.e. reflected overvoltages) due to long cable lengths. These can trip the VFD on overcurrent and damage the motor winding.

Common mode voltage is measured between each phase and ground and if excessive, is very disruptive and damaging to susceptible and sensitive equipment on the same ground. The accompanying common mode current is renowned for destroying bearings in VFD-fed and also fixed speed motors which share the same ground.

For further information on the output of 6 pulse PWM and AFE VFDs refer to Part 2, Appendix

PWM VFDs for oilfield electrical submersible pump (ESP) applications

In order for low voltage 6 pulse PWM VFDs to operate effectively with ESPs, additional equipment is required to overcome the input harmonics and problems caused by the output line voltage quality. This is termed the 'drive string'. See Figure 4 below. This usually includes an input transformer, series passive (or parallel active) harmonic filter as well as a passive output sinus filters. Output transformers are also required to compensate for the voltage drop, typically around 30V per 1000 feet (~300m) of the ESP cable. The voltage supply can be via a generator or the local power network. If the ESP is fed via the utility, an input transformer may also be required.

Low voltage 6 pulse ESP PWM VFDs can vary in power up to around 1500-2000kVA. The additional equipment cost required for the functionality often well exceeds the cost of the PWM VFD. However, the additional physical footprint required to house the additional equipment can be challenging whether it be in a container, offshore platform or FSPO. Indeed, the number of ESPs, and hence the production capacity installed, can be limited by the available physical space.

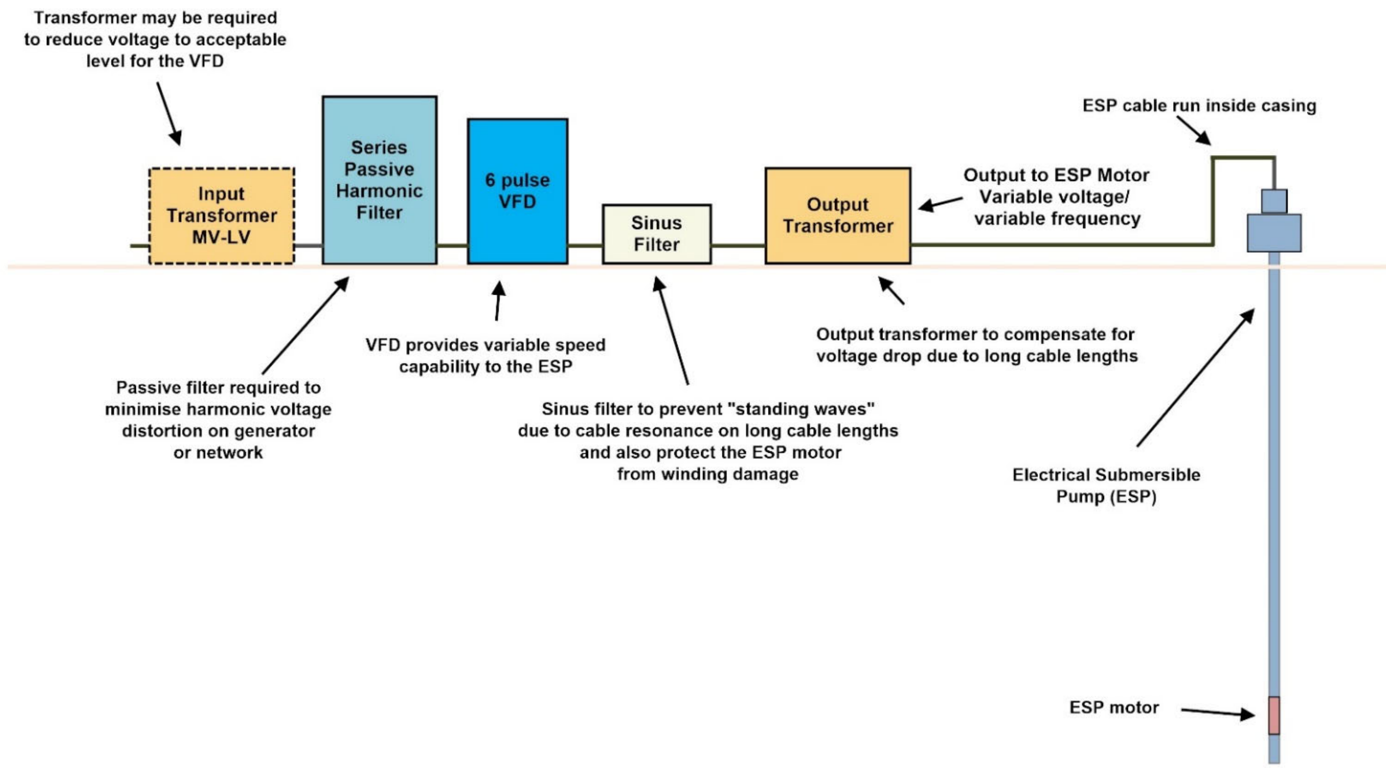

Figure 4 : Typical drive train for low voltage 6 pulse ESP PWM VFD

Low voltage AFE VFDs are now also being applied in oilfields. Whilst an input harmonic filter is not required, an L-C-L filter is to 'clean up' the input waveforms and to attenuate the AFE rectifier switching frequency this causes other problems as mentioned previously. The output of an AFE PWM VFD is the same as a 6 pulse PWM so all the additional output equipment is required also.

Medium voltage (MV) PWM VFDs are available which may negate the need for an input transformer. 18 pulse VFDs do not require additional input harmonic mitigation. Multi-level PWM VFDs can reduce the harmonic heating on the motor and may attenuate, but not eliminate, excessive du/dt and common mode voltage and their effects.

Resonant Link converter for ESP motor control

However, there is now a serious challenger to PWM VFDs for oilfield application entitle Resonant Link technology. Resonant Link technology is not a product per se but a very advanced power conversion technology with multiple applications. It originally emanated from the US Star Wars program as a military technology.

The salient benefits of Resonant Link technology are :

- Converts AC-DC, AC-AC, DC-AC and DC-DC with <1% THDi.
- Does not require conventional transformers for voltage transformation. High frequency, nanocrystalline transformers which are a fraction of the size and weight of conventional. types (e.g., 250kVA weighs 11kg, 1000kVA weighs ~45kg).
- DC voltages can also be transformed up and down.
- For VFD applications the Resonant Link converter requires no additional equipment and is around 15-20% of the physical size of a PWM VFD of similar kW rating.
- Overall efficiency throughout the power range is >98%.
- The Resonant Link converter has a du/dt <1/1000th of that of standard PWM VFD (LV/MV).

An example of the scale of a Resonant Link converter application is illustrated below (Figure 5) for a classified military project. The internal 250kVA transformer weighed only 11kg and ran at 20kHz.

Figure 5 : Example of 250kW Resonant Link converter (3 x 480V in/50kVDC out).
11kg, 250kVA nanocrystalline transformer mounted below. Military application.

To appreciate why Resonant Link presents a serious challenge to the dominance of oilfield PWM VFDs, one only has to look at Figure 6 below ! As can be seen, no additional equipment whatsoever is required for oilfield ESP (or any other) applications so less costs, is more efficient, no power quality or EMC issues and at a fraction of the size the PWM drive string show in Figure 4.

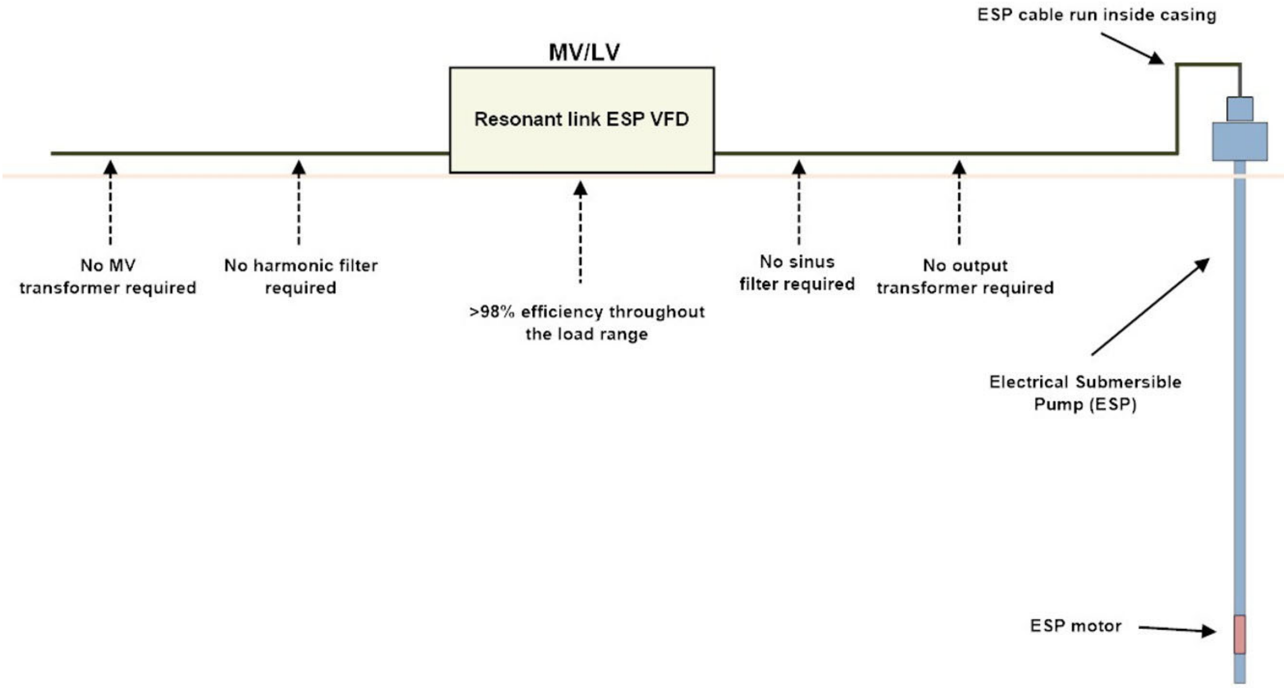

Figure 6 : No additional equipment required for Resonant Link converter for ESP VFD applications

The Resonant Link converter has many advantages for motor speed and torque control including ESP motor control. One of the major features is that the resonant converter is "soft switching" and therefore the low voltage and/or higher voltage IGBTs have no switching losses. With no switching losses, the Resonant Converter can switch at higher frequencies (6kHz to 20kHz), reducing the passive component size and the size of the converter very significantly, often to 20-25% of a similarly rated (kVA) PWM VFD.

With no IGBT switching losses, high voltage IGBTs (e.g. 6.5kV) can be used for both the Resonant Converter input (supply side) and output (ESP motor side) sections. This negates the requirement for LV or MV input transformers. The Resonant Link converter 'actively rectifies' the incoming three phase AC supplies directly, whether LV or MV. The resultant input currents are sinusoidal with less than <1 THDi. No harmonic mitigation or other filters are required.

Conventional output transformers are also not required as the output voltage and frequency of the Resonant Link converter is reconstructed and adjusted to the exact requirements of the individual well and the ESP cable length by electronically controlling internal nanocrystalline transformer.

PWM VFD versus Resonant ESP Converter System Comparison

A comparison between the additional equipment required for 6 pulse PWM VFDs and that required for Resonant Link converters for the same ESP VFD duty is striking. As seen in Figure 6, the only component between the incoming AC supplies and the ESP motor cable run is the Resonant Link Converter itself. Compared to PWM VFD based system, there are no input transformer, no harmonic filter, no sinus filter and no output transformer required for the Resonant Link ESP converter.

The Resonant Link converter does not require harmonic mitigation as it is intrinsically "harmonic-less" with <1% THDi, which results in both sinusoidal input and output voltage and current. The resultant output du/dt (rate of rise of voltage) to the ESP motor is typically <3.0V/micro-second at 480VAC and <12V/microsecond at medium voltage (<6.6kV). PWM VFDs are typically 500-600V/per microsecond at LV and ~30kV/microsecond at MV.

The internal design of the Resonant Converter provides the necessary voltage and frequency for the ESP cable and the depth of the well. Since the switching losses for the Resonant Link converter are eliminated, the efficiency is increased to >98.0% over the full power range. This compares with 97.5% (without reactors) efficiency for a 6 pulse PWM VFD only at rated load, not the complete drive string, which is significantly less. The reduction of losses also impacts significantly on the thermal heat rejection management.

However, the PWM VFD realistic overall efficiency requires all the components in the drive train to be considered including the input transformer (if applicable), the harmonic filter, the sinus output filter and output transformer. Even at rated load (100%) for each component, the maximum overall efficiency would be in order of 82-84%. ESP VFDs and their respective motors rarely run at full speed. At lower speed and loads the overall efficiency of the PWM VFD based system would be much lower, perhaps to around 65-72%. These overall efficiencies have to be compared to the constant >98% overall efficiency throughout the speed/load range for the Resonant Link converter. It should be obvious to the reader that the running cost of the Resonant Link converter is significantly less for an equivalent PWM VFD based system, in the region of 15-20% less.

Resonant Converter Construction and Operation

Figure 7 shows the complete electrical schematic of a Resonant Converter ESP motor drive circuit. The single modules can be paralleled up for higher powered drives. The left input side connected to a three-phase AC supply. The right-hand side output is directly connected to the ESP motor cable and downhole ESP motor.

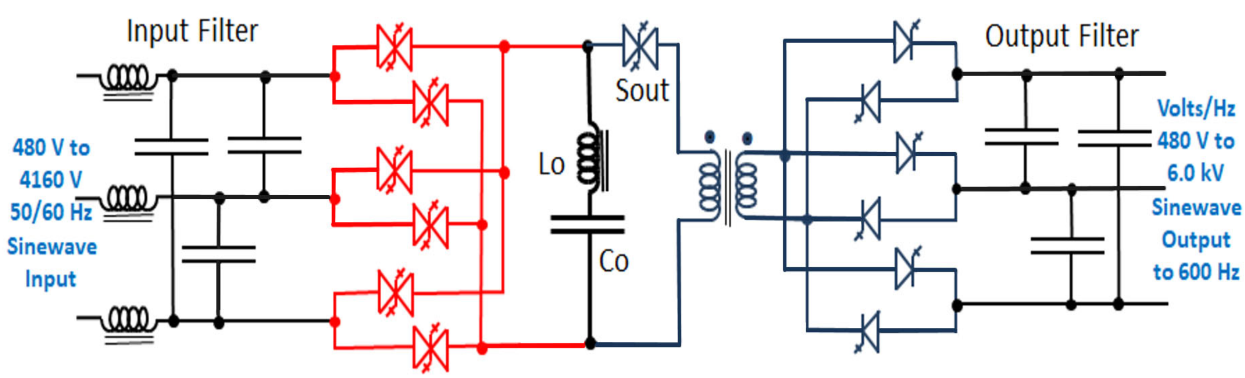

Figure 7 : Single module LV/MV Resonant Link ESP converter with step-up/step down

The Resonant Link converter behaves completely differently to a PWM VFD; there is no DC bus and no modulation of the output voltage. Instead, the technology is based on innovative energy pulse transfers to and from a 'central capacitor (Co)'. For 60Hz input AC power, the design entails an inverter output frequency of 7.2kHz with a corresponding 120 energy charges and discharges per AC input waveform. A charge would therefore occur every three (3) electrical input degree or per every 139 micro-secs.

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

The amount of energy drawn is determined by the output energy requirement, the control of which is implemented by the length of the inversion cycle. This is followed by the primary to secondary voltage charge and finally completed by the primary to tertiary voltage charge. The timing for all 120 input pulses triggering per one AC input cycle duration of the three-step operation is stored in an FPGA lookup table. A FPGA and DSP are integrated, with the DSP modifying the active FPGA table depending on the voltage, current, power and other dynamic requirements.

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

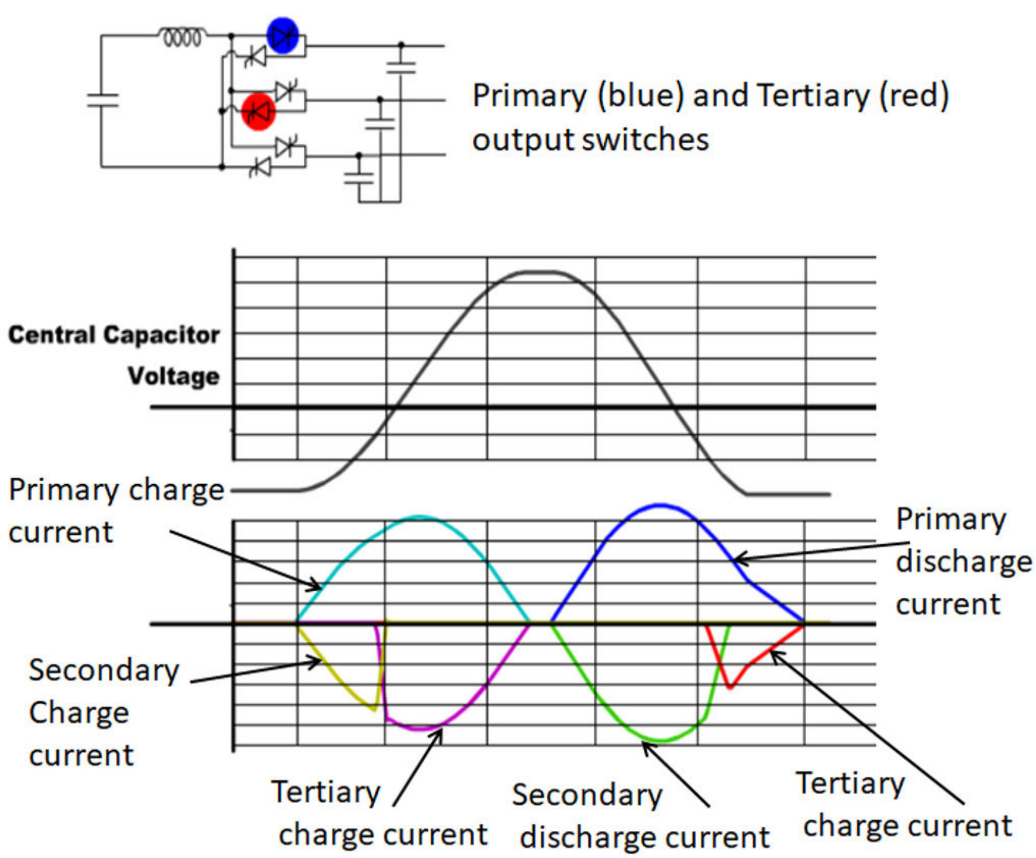

Figure 7 : Resonant Link converter charge and discharge operation

With reference to Figure 7 above. Following the charge process, the output IGBT switch 'Sout' is triggered to connect the 'Co' voltage into the primary winding of the high frequency nanocrystalline transformer, whilst at the same time two output IGBTs are connected to start the discharge cycle. Depending on the output voltage/frequency requirement of the ESP motor setpoint, the voltage is either automatically stepped up or stepped down. The resultant input waveforms of the resonant converter can be seen in Figure 8 below.

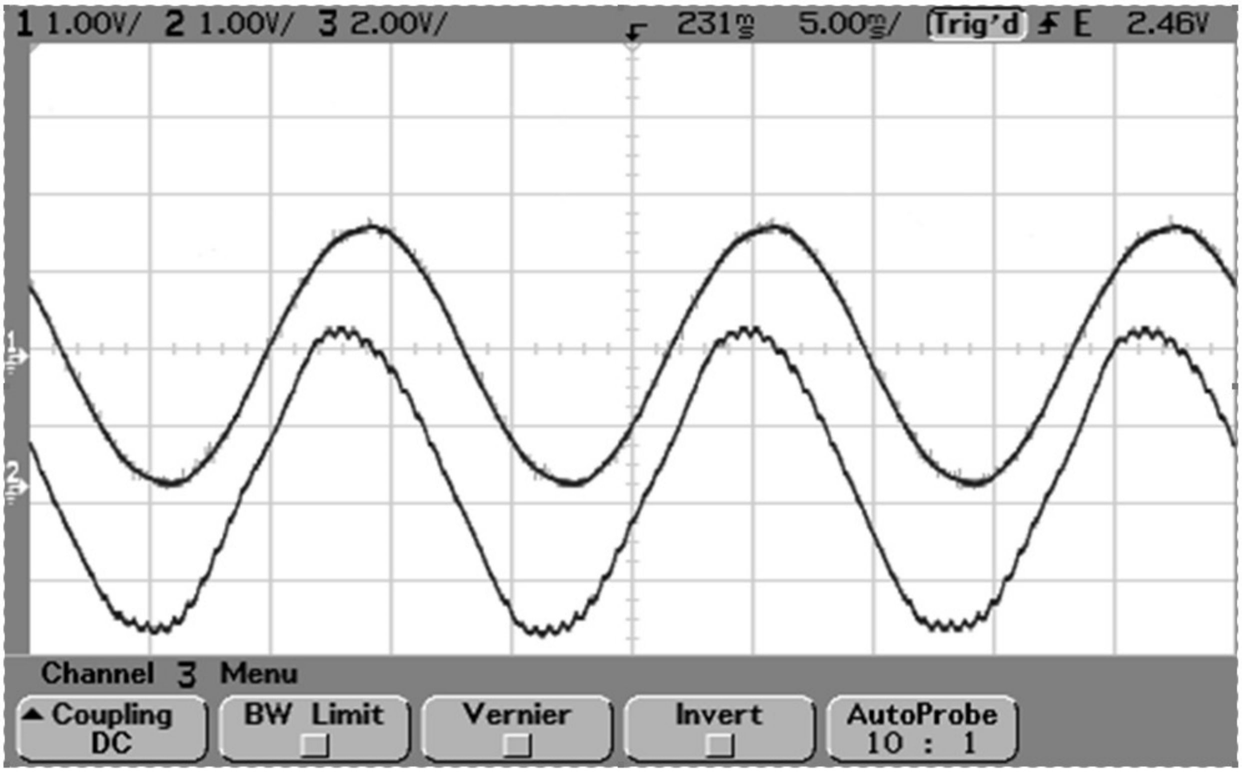

Figure 8 : Typical input voltage (top) and current (bottom) of 250kW Resonant Link converter. THDi < 1%. Unity displacement power factor.

The output consists of two sub-cycles. The output primary and tertiary output phases are connected and charges flow into these two phases. Once the predetermined tertiary charge has been injected, the lower secondary output switch is triggered, which in turn back-biases the tertiary output IGBT. The output charge transfer is completed by the primary and secondary output charge injection. The output charge injected per phase is proportional to the instantaneous current required for the ESP input base on the desired output voltage/frequency ratio. The exact voltage required at the terminals of the ESP motor is adjusted within the Resonant Link converter during commissioning so conventional output transformer (with tappings) are required to compensate for ESP cable length.

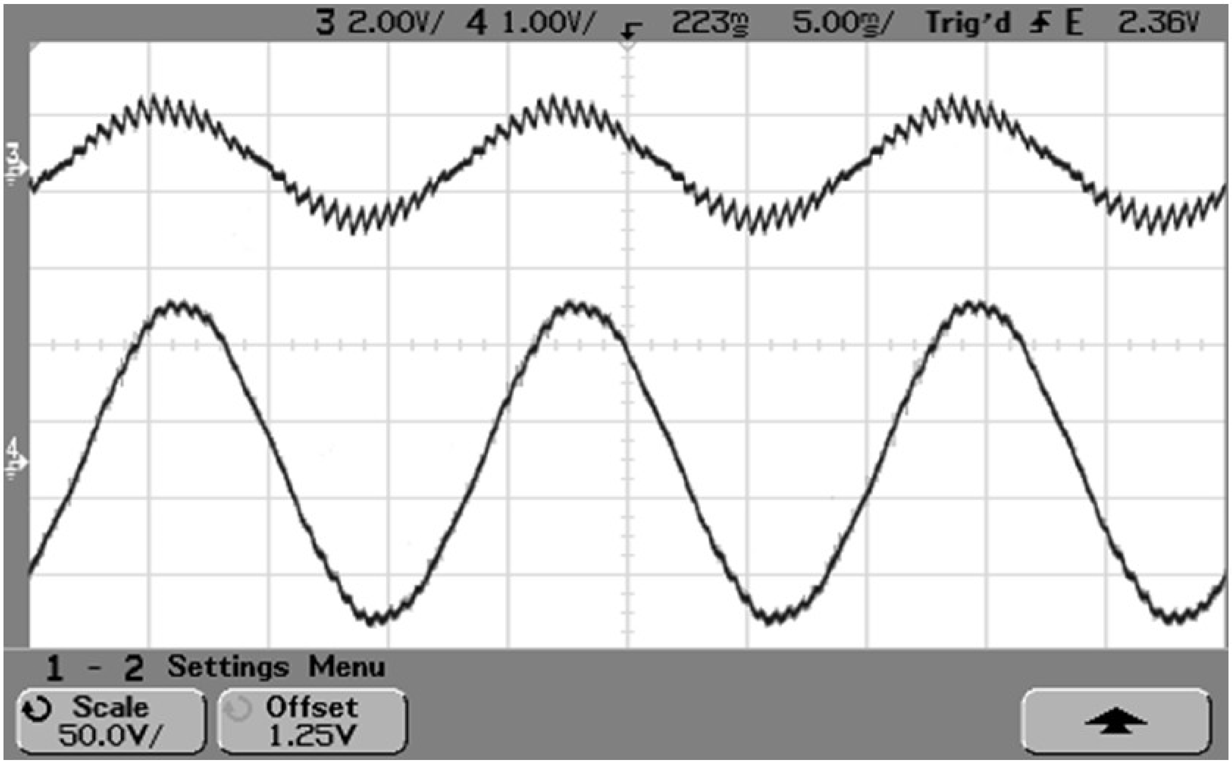

Figure 9 : Typical output voltage (top) and current (bottom) from 250kW Resonant Link ESP converter. du/dt recorded was 1.2V/microsecs. Both converter outputs were unfiltered.

With the previous output pulse, the magnetic core flux of the transformer is driven unidirectional. In order not to saturate the core, the input high frequency transformer current is reversed for every alternative output pulse. For the next charging pulses, the resonant capacitor 'Co' is charged with the opposite polarity and the output switch 'SOUT' reverses the discharge current in the transformer. This reverses the magnetic flux in the core. The input IGBT switches and the 'Sout' output IGBT switches are bidirectional and utilize commercially available back-to-back IGBT modules. The six output section IGBT switches are unidirectional with the diode function arranged in the blocking mode.

The resonant inductor 'Lo' uses also a nanocrystalline core therefore minimizing core and winding losses. The core resets occur on every pulse since the charging current and discharge current is in opposite direction. Both the inductor and transformer windings use Litz conductor to minimize conductor skin-depth losses at the high converter switching frequency of 7.2kHz. This is only possible with the elimination of the IGBT turn-on and turn-off losses, using the innovative resonant converter topology.

The Resonant Link ESP converters provide an 'EMC filter' function internally via the 7.2kHz-20kHz, galvanically isolated, high frequency transformer and a special grounded shield which is inserted between the high voltage primary and secondary winding (or winding primary and secondary windings if a 1:1 ratio transformer).

The nanocrystalline transformer core is extremely small compared with conventional electromagnetic transformers (i.e. which operate at 50Hz or 60Hz) due to the core cross-sectional area reducing in inverse proportion to the converter frequency. A beneficial consequence of this is that the parasitic capacitance between the primary and secondary windings is significantly reduced. By inserting a small grounding 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) voltages and currents from circulating irrespective as to whether a single secondary rectification section or a multiple rectification section, high frequency transformer is utilized.

With an output inverter frequency of 7.2kHz, the key challenges are to sustain an accurate real time, control system. The signal monitoring and active, dynamic control is performed by the control board (Figure 10). It has two controller systems on onboard, i) a high-speed Digital Signal Process (DSP) and an ii) a FPGA Field Programmable Gate Array (FPGA). The complete timing and triggering control functions are performed via the FPGA, where pre-programed lookup tables and other data are downloaded and stored. A large number of lookup tables are stored by the FPGA, which in conjunction with the DSP, control dynamic operational parameters such as power, current, inverter frequency, input and output voltages.

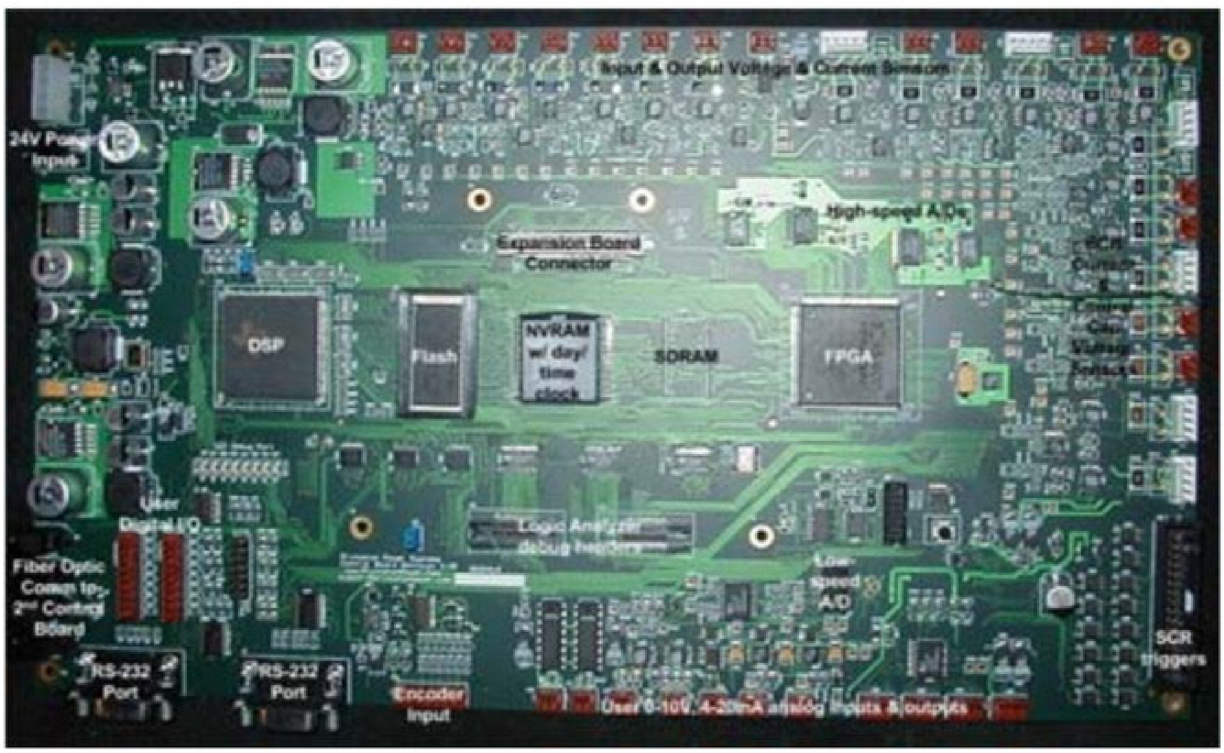

Figure 10 : Resonant Converter control board)

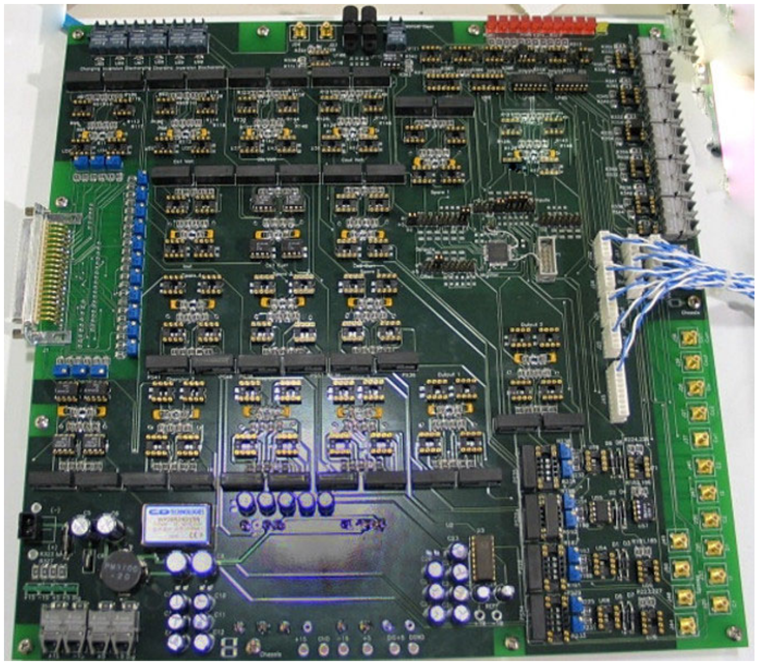

Figure 11 : Resonant Link converter instrumentation board

To start the converter, the DSP provides an ‘initiation confirmation request’, the FPGA accesses pre-selected stored memory and places the data into the ‘active’ table, powers up and starts running the Resonant Link converter.

The DSP performs all the measurements and, on the basis of continuous feedback, dynamically updates the active lookup table. The majority of DSP operational time ensures the correct operational performance of the Resonant Link converter. If a fault is detected, the DSP can make correction adjustments or shut down the operation. The shutdown may occur during the charge or discharge cycle by simply inhibiting any further triggering within less than one half inverter cycle (<100 microsecs). This ensures no short currents can occur within the converter or its components.

Installed alongside the control board is the instrumentation board (Figure 11) which provides short wire interfaces. The FPGA trigger signals are carried to the IGBT drivers via fiber optic cables. The currents and voltages are continually checked before being routed to the analog to digital converters. Both the instrumentation and control boards are enclosed within an EMI shielded box as a precaution.

All control and powers sources are continuously monitored by the fault detection system.   Prior to switching on, the control system undergoes a comprehensive self-check sequence. Any errors or anomalies are communicated so the control and operational programs can be modified if required.

Note that no AC or DC circuit breakers are required. All overcurrent and short circuit protection are inbuilt within all Resonant Link converters.   Only isolators are required for physical disconnection.

ESP motor voltage, frequency, current and other required data is available from the Resonant Link converter as inputs to the ESP monitoring system.

Conclusions

Physical size The Resonant Link converter is a standalone AC variable speed drive, which for ESP and any other applications, does not require any additional equipment whatever. Thus, the physical space requirements, especially for installations where space is at a premium (e.g. E-Houses, offshore platforms and FSPOs) can be onerous for PWM based systems, do not apply to Resonant Link converters. Typically, a 500kVA Resonant Link converter has a total volume of <1.0 cu.m., many orders of magnitude less than that required for the PWM ESP string ! Therefore, Resonant Link converters can be installed in very small spaces and/or can be installed in significantly larger numbers than PWM ESP VFDs in the same available space to increase production considerably.

Overall efficiency Running costs are a significant factor in ESP and other operations. The Resonant link ESP converter is up to 20% more efficient over the speed/load range than the PWM ESP VFD string shown in Figure 4. This ensures that over the life of the well, the electrical running costs will the minimized compared to PWM based system thus significantly improving its profitability. With the significantly decreased losses, the EPS motor will run cooler thus will maximize the ESP motor life. The reduction in output harmonic currents (<1% THDi) also minimizes the ESP cable and motor losses.

First cost and installation of equipment Figure 4 illustrated the amount of additional equipment required for PWM VFDs ESP operations. The total purchase price of the additional equipment is in the region of 3-5 times that of the PWM VFD alone. In addition, the cabling and installation of the additional equipment has also to be costed which may result in the PWM ESP VFD system purchase and installation price to be in the order of 5-6 times that of an equivalent Resonant Link ESP converter.

Input harmonic current distortion (THDi)

A 6 pulse PWM VFD with no AC line or DC bus reactance is ~85-135% THDi at nominal load. With a 3% AC line reactor the THDi reduces to 36-40% THDi. To comply the harmonic recommendations the THDi has to be reduced to <5-8%. This entails the use of additional passive or active harmonic filters at considerable additional cost and space. So called “low harmonic drives” or AFE VFDs do reduce the THDi to around 5-8% (only 50th harmonic) and are around 2% less efficient than 6 pulse PWM VFDs with either active or passive filters. The Resonant Link ESP converter as a THDi of <1% and using interleaving techniques can achieve <0.1% THDi.

Quality of output voltage and current

The output voltage of PWM VFD is a modulated rectangular waveform (Figure 3). This voltage is responsible for du/dt (rated of rise of voltage) which, if excessive, can damage motor insulation. In addition, the modulated voltage is the root cause of ‘standing waves’ (resonance due to long cable lengths) and also common mode voltage (conducted EMI), which as a voltage can be so disruptive to other equipment connected the same ground. The accompanying common mode current if excessive, destroys motor bearings with micro-arcs of current at the switching frequency of the VFD; this may not be apparent on LV PWM based systems where the output transformer is a double wound type with electrostatic shielding, but on MV ESP VFDs, which do not utilize output transformers common mode voltage and current may well be serious problems.

The Resonant Link ESP convertor produces a du/dt <1000x that of a comparable PWM VFD (e.g. typically 1.2V/micro-second at LV) and 13.3V/micro-second at 4.16kVAC). The output voltage and current are sinusoidal any common mode voltages and other EMI emissions, conducted and radiated are negligible whether based of LV or MV input power and either LV or MV output power.

Final conclusions

As can be now appreciated, the complete PWM ESP string as featured in Figure 4, comprising input transformer, harmonic filter, 6 pulse PWM VFD, sinus filter and output transformer, can all be replaced with **one** Resonant Link ESP converter which will reduce the CAPEX for ESP installations to very low comparative levels. The ESP running costs are reduced by up to 20% leading to more profitable wells. On installations where space is at a premium (e.g. offshore platforms and FPSOs), more Resonant Link ESP converters can be installed for a given space, which increases production without presenting any harmonic problems on the generators.

The Resonant Link ESP converter, based on the above, is the ESP VFD of the 21st Century.

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Resonant Link ESP VFD.

Part 2

Observations on PWM VFDs

White Paper : Resonant Link ESP VFD Part 2 – Observations on PWM VFDs

Input to 6 pulse PWM VFDs

The characteristic input voltage and current of a 6 pulse PWM VFD are illustrated in Figure 12. Note the characteristic two current pulses per half cycle. Typically, a VFD with no AC line or DC bus reactor exhibits a THDi (total harmonic current distortion) of between 85-135%. Using say, a 3% AC line reactor based on 5% source impedance, decreases to 36-40% THDi. AC line or DC bus reactors are highly recommended for 6 pulse VFDs but cannot offer compliance with harmonic recommendations such as IEEE-519-1992, IEEE-519-2014, IEC 61000 series et al. Therefore, additional equipment including series passive or parallel active filters are applied to bring the THDi to within <5-8% at rated load. This increases the cost of the VFD(s) installation significantly, as offer the harmonic mitigation cost can exceed that of the VFD(s). Additional space is also required to house the harmonic mitigation.

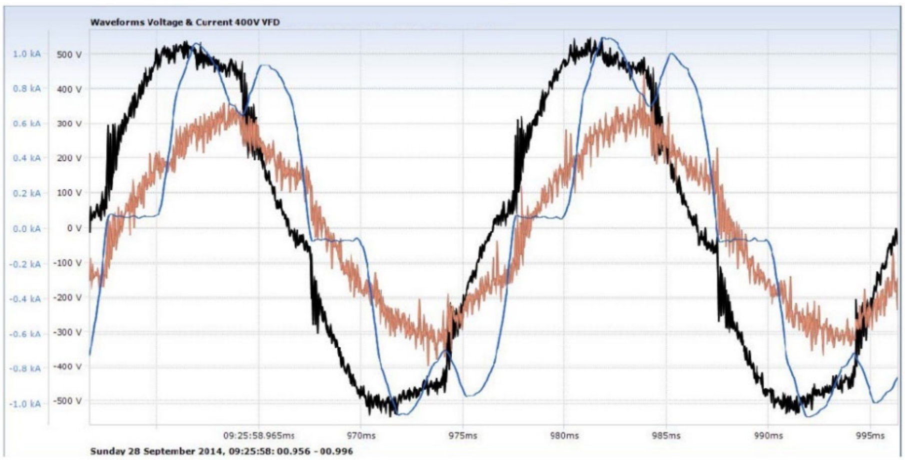

Figure 12 : Example of a 560kW, 6 pulse PWM VFD input voltage, common mode voltage and phase current using advanced cycle by cycle PQ recorder

Most conventional harmonic analysers only measure to the 50th order, some slightly above. Note in Figure 12, the slight current imbalance due to supply voltage imbalance, but more importantly, the high frequency components in both the line voltage and common mode waveforms which are not usually detectable using conventional PQ analysers (see Figure 13 below) which measure to the 50th harmonic.

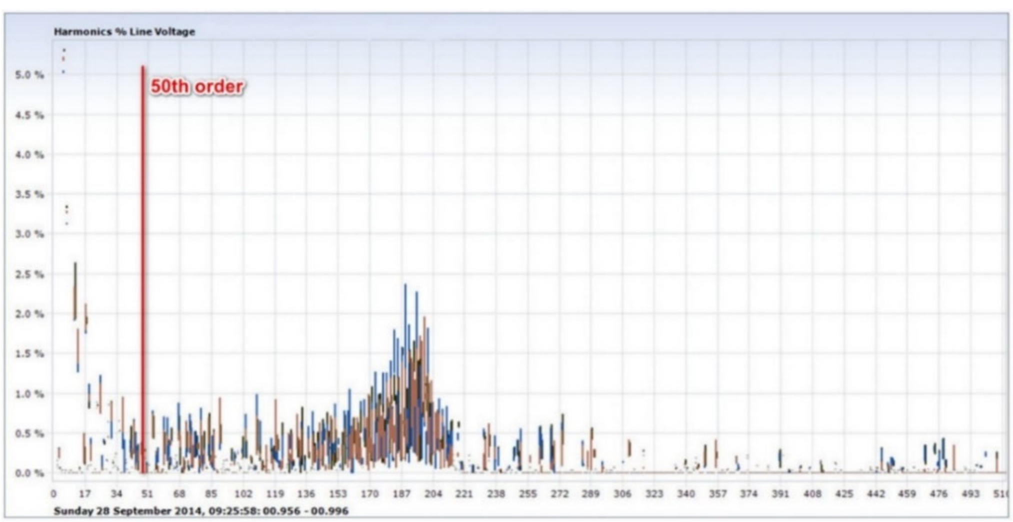

Figure 13 : The line voltage spectrum of a 560kW PWM VFD during heavy loading (from Figure 12).

As can be seen above, the harmonic line voltage spectra extended well above the 50th order (2.5kHz for 50Hz), where most harmonic standards end, unfortunately the problems thereof do not. Indeed, the THDu extended to over 25.2kHz in this case. Common mode voltage spectra exceeded 3.72kHz. This was part of a large project has serious problems with power quality and equipment damage and disruption over a period of 5 years until "fit for purpose" PQ equipment was utilized.

Many problems with PWM VFDs still go undiagnosed due measuring equipment shortcomings. Unfortunately, IEEE standard (50th order max) and IEC 61000 (40th order max) compliance does not guarantee anything other than the utility PCC. One can comply fully with these and have serious problems downstream in the facility or the field. In summary, it can be stated that 6 pulse VFDs, from a mains supply perspective, require additional equipment to operate in real world applications. That significantly increases their overall cost of applying PWM VFDs and puts pressure on the physical space requirements.

AFE or so called 'low harmonic" PWM VFDs

In an attempt to reduce the THDi due to 6 pulse VFDs, a VFD variant entitled the "active front end" (AFE) drive was introduced (Figure 14) in the mid-1990s. It is also known as a "low harmonic drive", which unfortunately more of a marketing tool than reality.

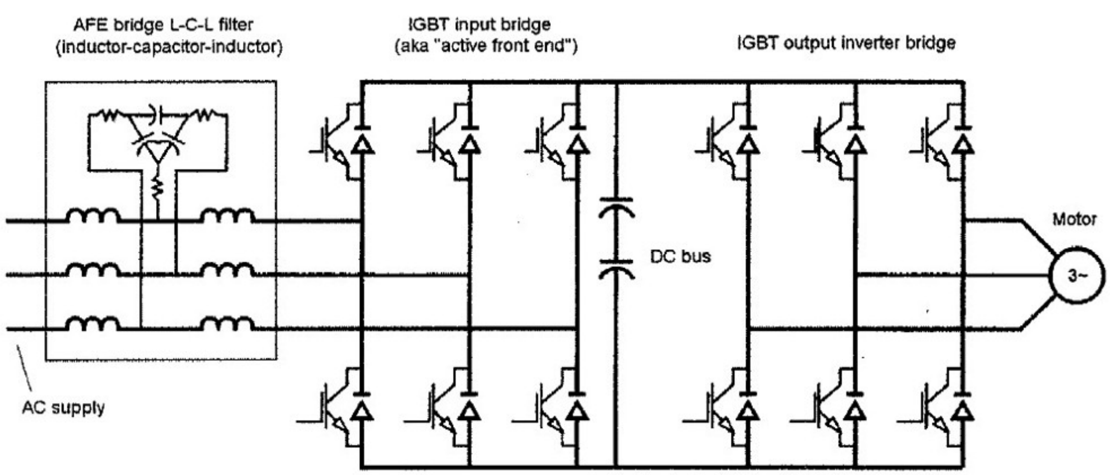

Figure 14 : Typical simplified schematic of AFE VFD

In an AFE VFD, the normal 6 pulse diode or SCR pre-charge is replaced with IGBT rectifier which attempts to synthesize sinusoidal current waveform. This requires a passive L-C-L filter upstream to 'clean up' the phase currents and attenuate the AFE switching frequency which, otherwise would promulgate throughout the system.

At no-load, light load or intermittent load, the capacitors in each L-C-L filter injects uncontrolled reactive power (kVAr) into the power system which if excessive, causes unstable displacement power factor and overexcitation of generators, especially if multiple AFE VFDs are operating.

Figure 15 depicts actual input voltage and current measurements on a 500kW AFE VFD on a pump application (loading 332kW).

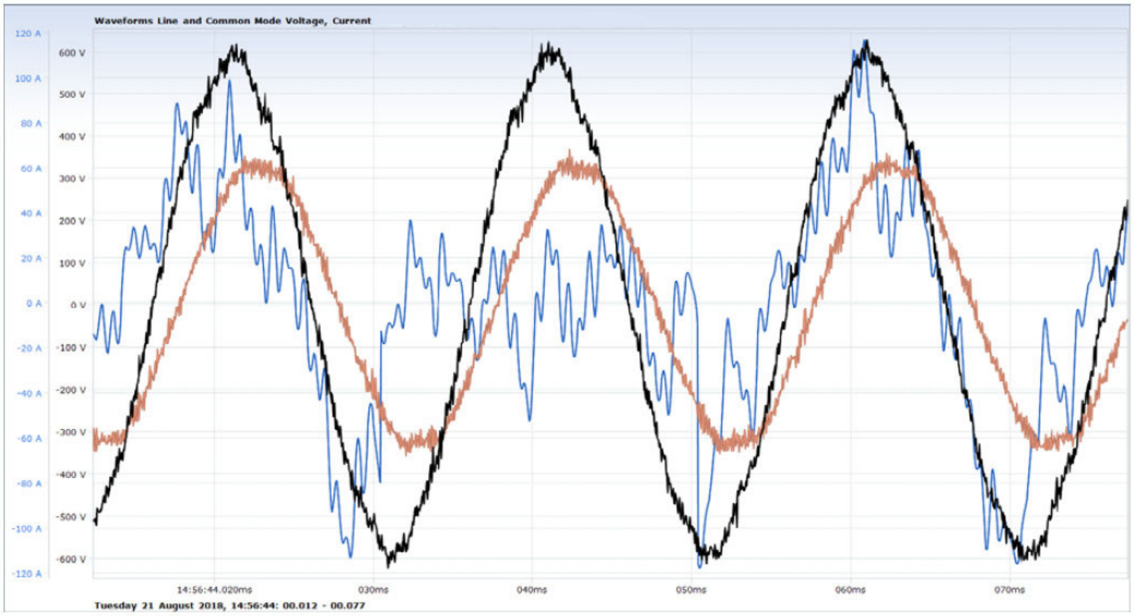

Figure 15 : Input voltage and current from 500kW AFE VFD at reduced load (332kW). Note the high frequency content of the voltage waveforms and non-sinusoidal and unbalanced nature of the phase currents.

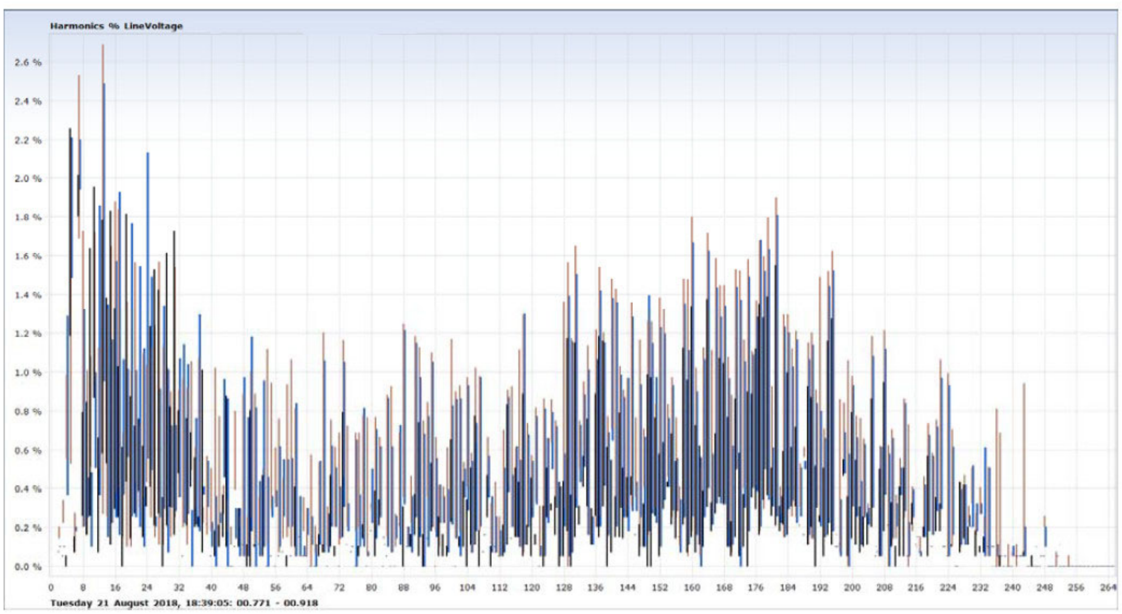

Fig 16 : Harmonic line voltage spectra of a 500kW AFE VFD (restricted to 256th order) at reduced loading (332kW)

Fig 16 represented the line harmonic min/max spectrum of a 500kW AFE VFD during a period of 6.57% THDu (limit was 5%). The harmonic voltage spectrum extended beyond the 256th order (12.75kHz). What can be stated is that the majority of harmonic voltages are NOT caused by the harmonic currents but due directly to the switching of the AFE rectifiers. The high frequency switching of this type is often masked when conventional power quality analysers, which limit the harmonic measurements to the 50th are used.

The higher frequency harmonics (>50th) largely go unseen due to obsolete harmonic standards and accompanying PQ analyzers but have a severe impact on adjacent equipment and other equipment connected to the same supply.

AFE VFDs often offer in their advertising a THDi performance of <5%. Table 2 below is actual measurements taken from a 315kW AFE VFD. The average and min/max measurements below (Figure S16 and Table 2) are based on cycle-by-cycle PQ recorders with 1024 samples per cycle and harmonic components to 512th order (25.6kHz). Refer to Figure 17 below.

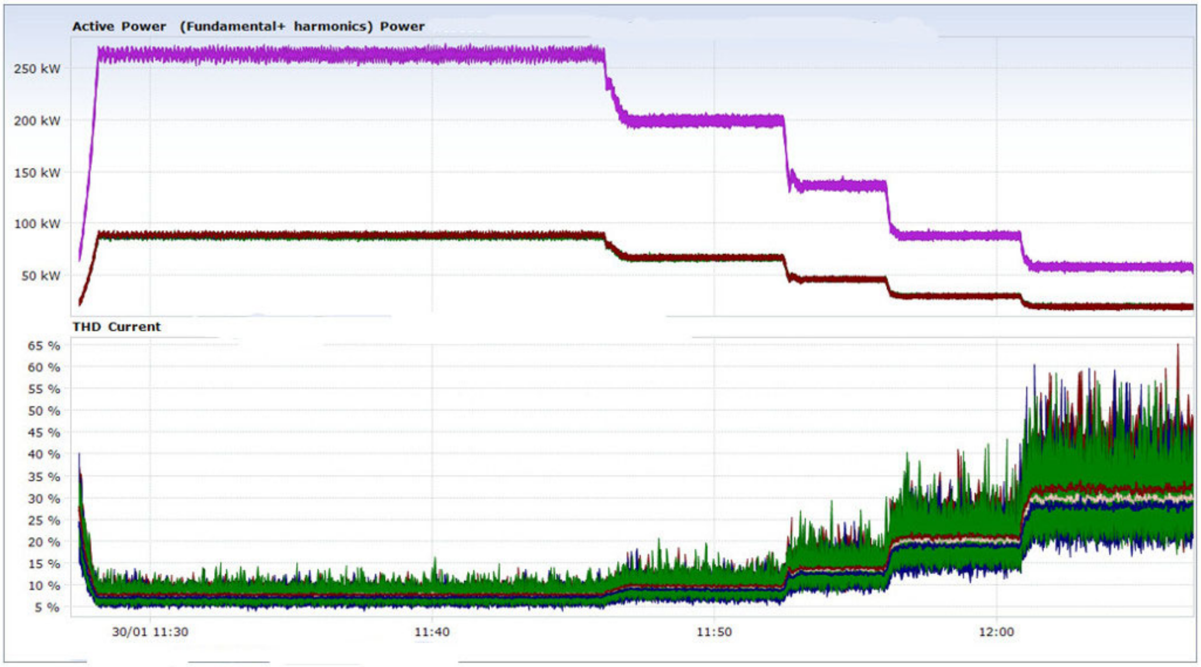

Fig 17 : Active power (kW) and THDi (average and min/max) of 315kW AFE VFD on centrifugal pump application

kW load	Average THDi (%)	Min/max THDi (%)	Motor kW (%)
267.37	7.77	16.39	84.88
204.74	9.54	18.11	65.03
146.21	13.55	19.38	46.42
90.93	20.19	36.52	28.87
60.82	31.56	40.48	19.33
19.12	110.18	483.01	6.07

Table 2 : 315kW AFE VFD. THDi* (average and min/max) *at various pump loads

Based on the information contained in Table 1 (Page 2), the accompanying Table 2 and the author's own experience over many years, it can be stated that the AFE VFD THDi performance is no better that 6 pulse VFDs with series passive filters or 6 pulse with parallel active filters at nominal load up the 50th harmonic order. Above 50th order, AFE VFDs are much less effective as they introduce additional voltage and current harmonics/frequencies.

At reduced loading the AFE VFDs, the THDi performance is relatively poor in comparison with all the harmonic components current are taken into account. The difference between perceived and actual AFE VFD THDi 'across the range' performance highlighted above, coupled with the decrease in efficiency and associated running costs, compared to other forms of harmonic mitigation may suggest that the performance and efficiency of AFE VFDs is overstated.

There are additional concerns with AFE VFDs including harmonic current generation at switching frequency of the AFE rectifier, which is above the 50th order and therefore not subject compliance testing, interaction with 6 pulse PWM VFDs on the same bus (those DC bus voltage can be increased by up to 13%) and at no-load, light load and intermittent load, uncontrolled reactive power (kVAr) injection into the power system by the AFE front end L-C-L filters which the AFE rectifiers cannot treat, multiple AFE VFD application can result in very unstable displacement power factor (DPF) ; this can particularly effect generators, leading to over-excitation and tripping.

Output of 6 pulse and AFE VFDs

As can be seen in Figures 18 and 19, the output current of PWM VFD is a synthesized sinewave whereas the output voltage is a modulated rectangular voltage wave; the mark to space ratio determines the average voltage level. The voltage/frequency ratio dictates the motor speed.

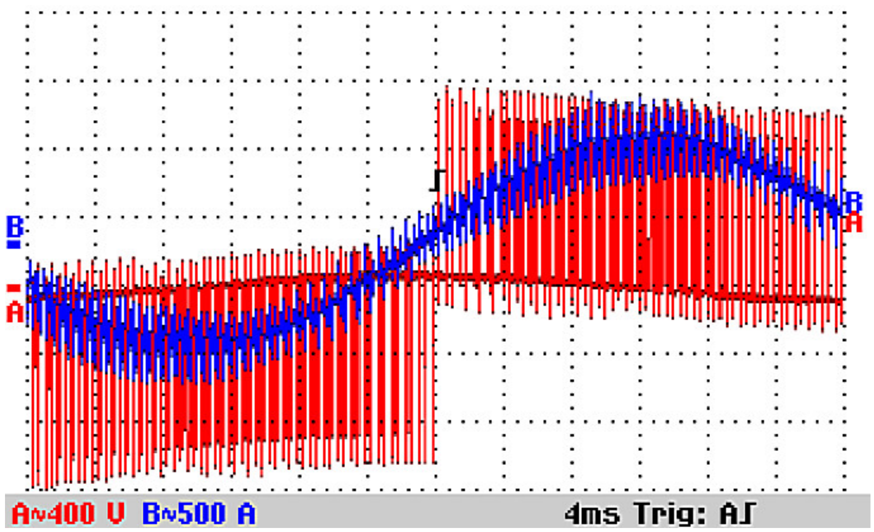

Figure 18 : Characteristic output voltage and current from PWM VFD

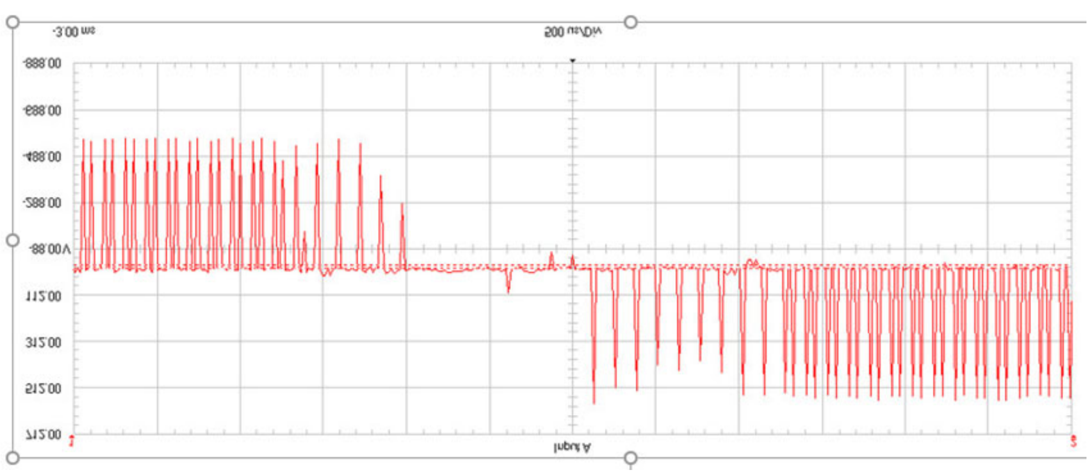

Figure 19 : Expanded PWM VFD output voltage waveform

On close in inspection (Figure 19) of the PWM voltage waveform there are very fast switching/fast rising edges visible. These are a main source of problems with PWM VFDs including du/dt (rate of rise of voltage) which is so damaging to motor windings), 'standing waves' (i.e. cable resonance) due to long cable lengths and EMI (electromagnetic interference) both conducted and radiated via the air.

Common mode voltage due to PWM VFDs

The section discusses the simplified paths for conducted EMI for 6 pulse PWM VFDs but the reader should be aware that AFE VFDs have an additional IGBT rectifier in place of the diode/SCR pre-charge rectifier, is an additional emitter of EMI energy. Refer to Figure 20 below.

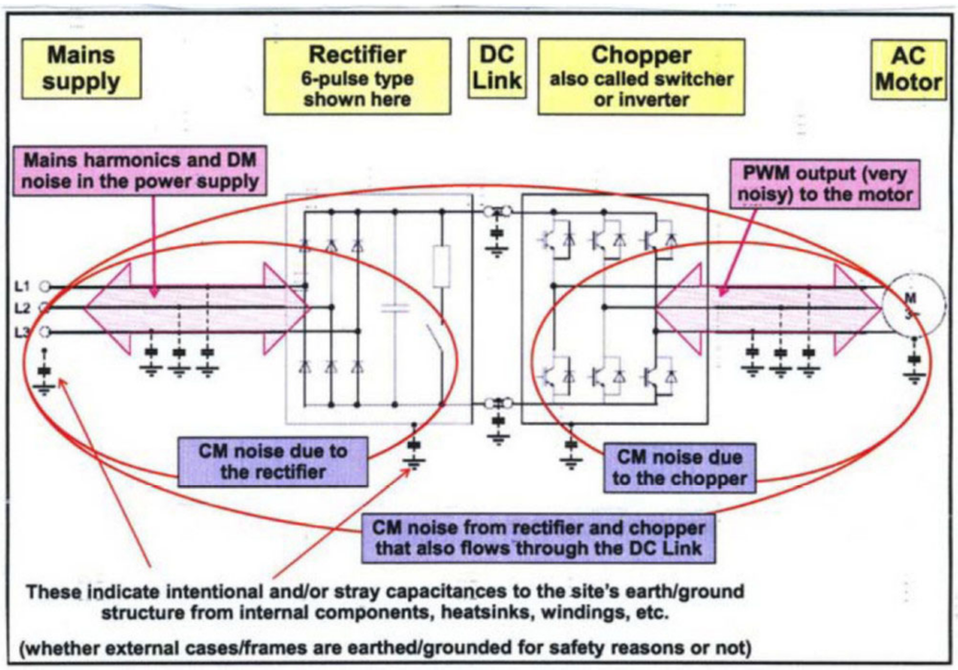

Figure 20 : Salient paths of EMI in 6 pulse VFD (AFE VFDs have IGBT rectifier)

Common mode voltage is measured between each phase and ground. Common mode voltage and its associated common mode current are rarely mentioned by VFD vendors to their customers despite the fact it is inbuilt into every PWM VFD, when 6 pulse PWM or AFE VFDs.

When a PWM VFD and its drive motor are NOT installed in strict compliance with EMC recommendations with regard to, for example, special 'VFD rated' shielded cables, dedicated EMC 360-degree glands, equipotential bonding, et al, the switching frequency of the IGBT inverter is superimposed on the phase to ground voltages as illustrated in Figure 21 below, and if excessive, can be very disruptive to susceptible and sensitive equipment connected to the same ground.

Figure 22 illustrates the destruction to a 3MW VFD thruster IGBT power pack on a marine vessel due to common mode voltage interference by an adjacent 3MW thruster VFD.

Figure 21 : Example of common mode voltage (1.26kHz switching frequency)

Fig 22 : Result of common mode voltage interference on 3MW PWM VFD

Additional examples of the result of common mode voltage (CMV) problems from the author's experience. Figure 23 was new jack-up drilling rig off Egypt. Figure 23, a water pumping station in England.

Figure 23 : Three large cranes on new drilling rig out of action (and off contract) for 5 months due to common mode voltages from draw-works (2 x 1500kW) and top drive (900kW) VFDs

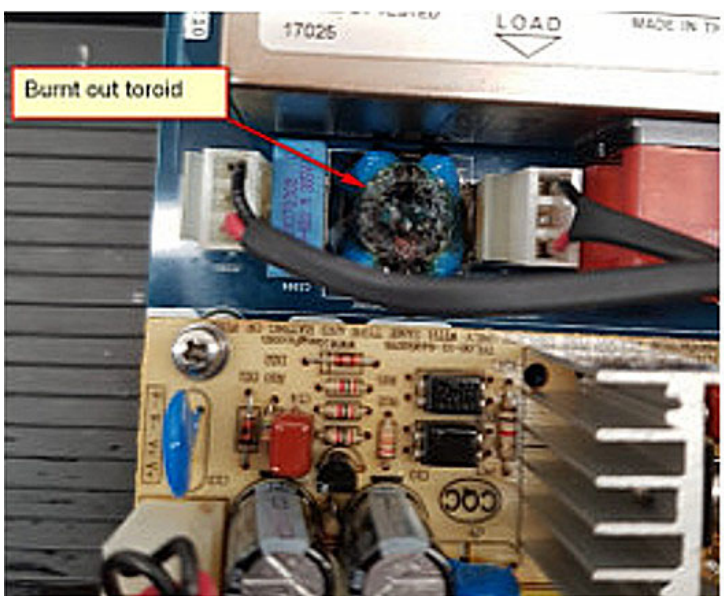

Figure 24 : Transformer burned out by common mode voltage in US$ 20,000 MIL spec PQ recorder by the AFE VFDs shown Figure 6. The CMV entered via the single-phase recorder mains supply.

Common mode voltage produces an accompanying common mode current which travels from the IGBT inverter along (and through the cable) to the motor, looking for a ground. Those paths, as illustrated in Figure 25 below, is via the motor bearing(s) which are subject to micro-arcs of current at the switching frequency of the IGBT inverter (Figure 26). The type of damage possible on PWM VFD fed motors is illustrated (Figure 27) and on fixed speed motors where the common mode voltage is being introduced to the fixed speed motor by the common ground connection (Figure 28).

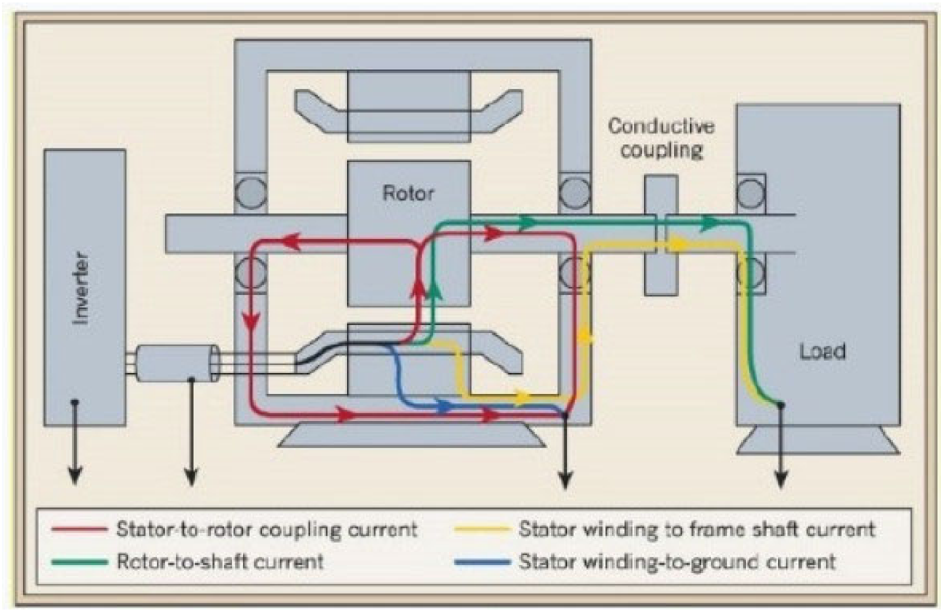

Figure 25 : Paths of common mode current in PWM VFD fed induction motors

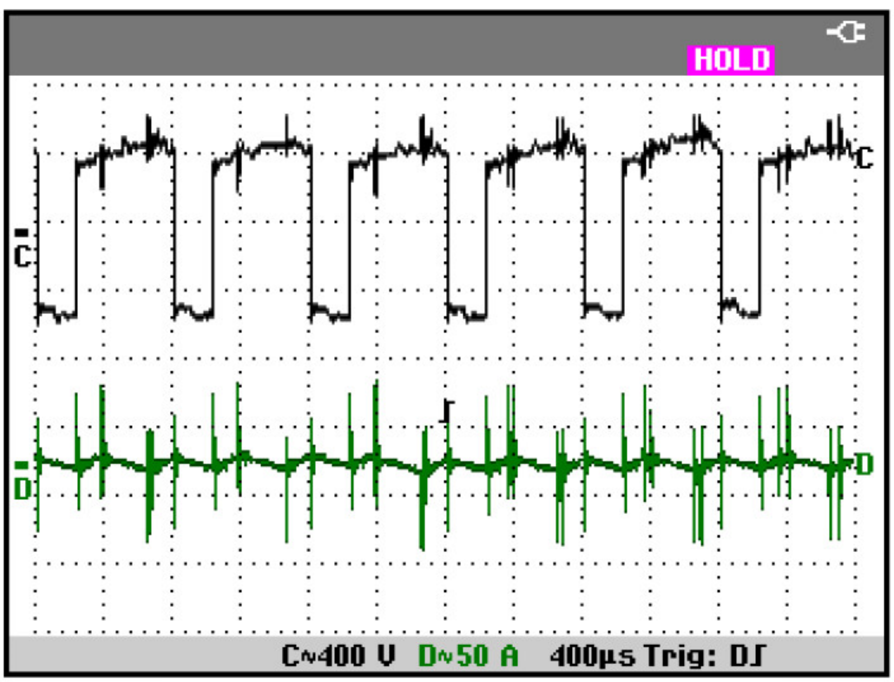

Figure 26 : Example of common mode current (green trend).
Note repetitive peaks of up to 80A, three times every 400 micro-seconds !

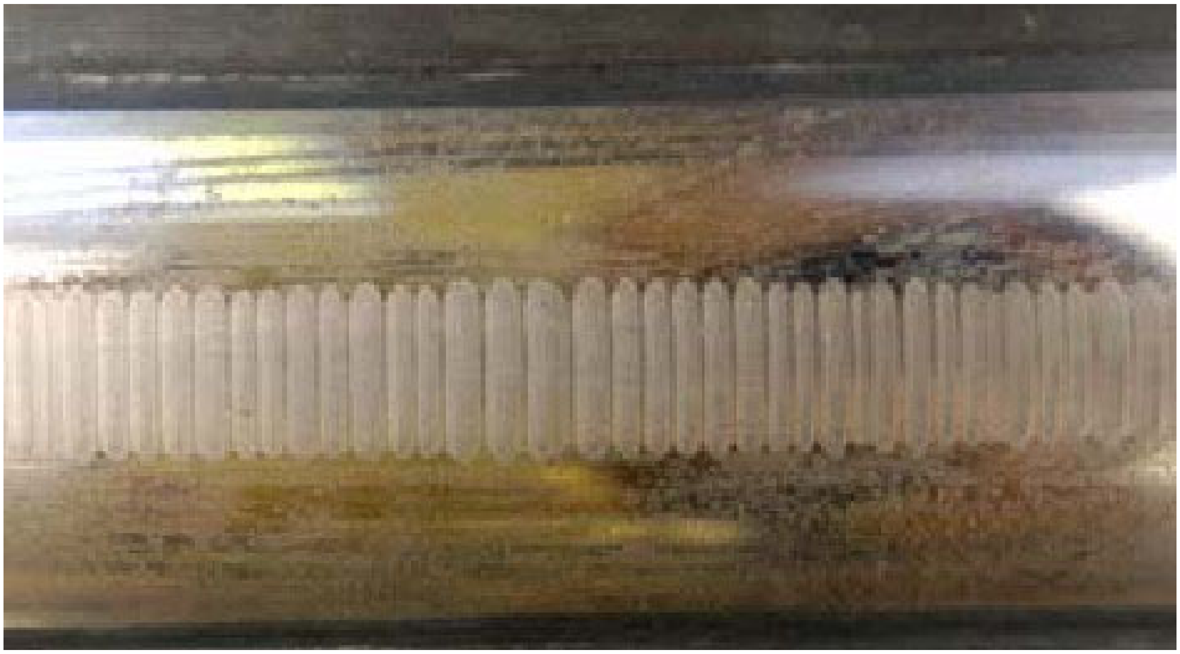

Figure 27 : Example of "fluting" due PWM VFD common mode current at the switching frequency of the VFD

Figure 28 : Example of "pitting" on 6.6kV EExd fixed speed motors due to common mode voltage emanating from 45MW of PWM VFD main propulsion on an LNG carrier marine vessel. Bearing life was <1400-1600hrs. This problem was common across all 15 vessels in the same class. It also presented a serious safety hazard.

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