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Comparison of PWM VFDs versus Resonant Link Converters - Part 2

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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.

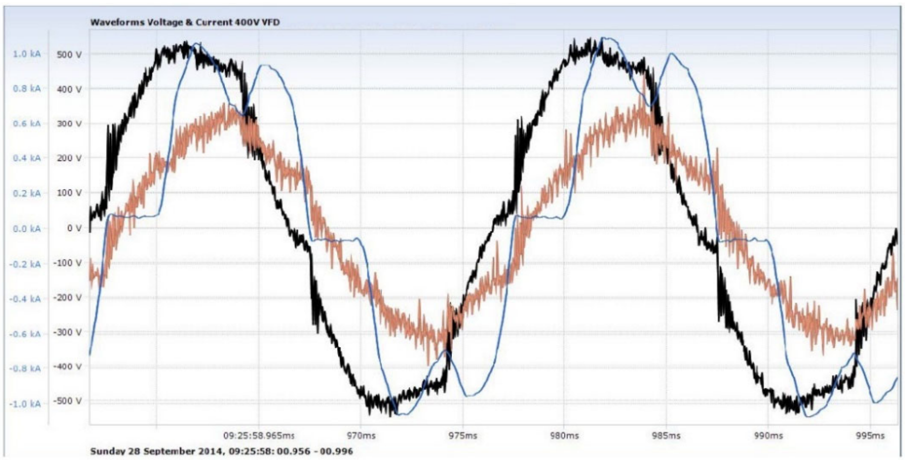

Figure 12 : Example of a 560kW, 6 pulse PWM VFD input voltage, common mode voltage and phase current using advanced cycle by cycle PQ recorder

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.

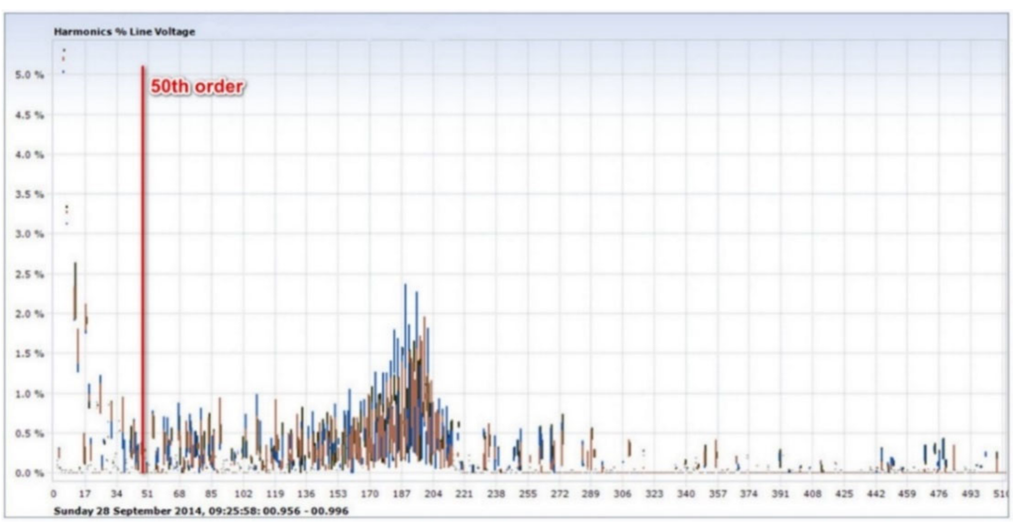

Figure 13 : The line voltage spectrum of a 560kW PWM VFD during heavy loading (from Figure 12).

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.

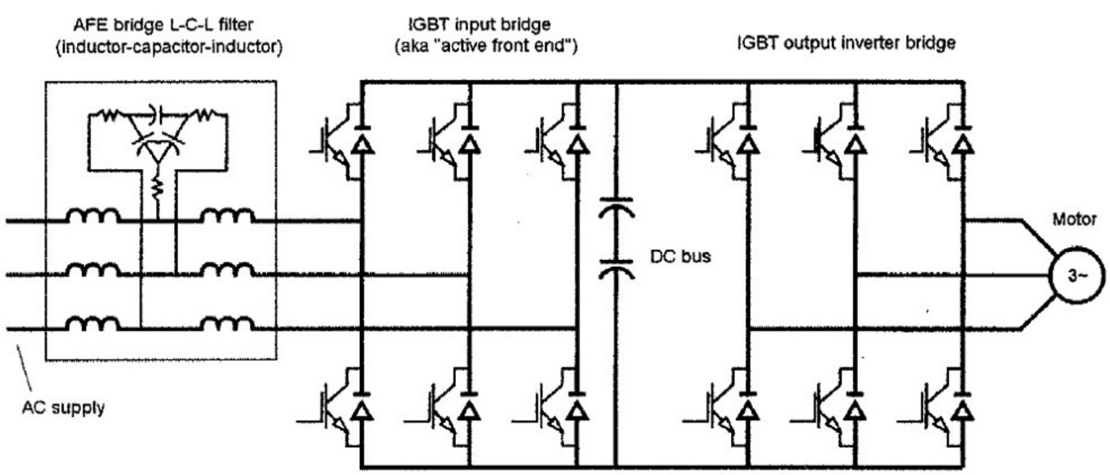

Figure 14 : Typical simplified schematic of AFE VFD

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).

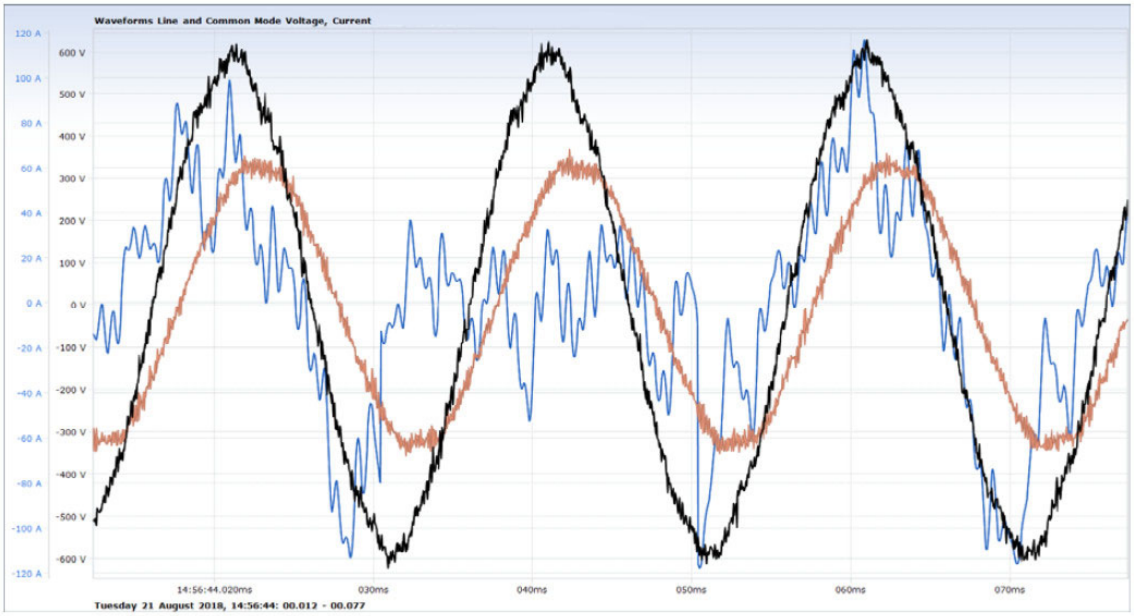

Figure 15 : Input voltage and current from 500kW AFE VFD at reduced load (332kW). Note the high frequency content of the voltage waveforms and non-sinusoidal and unbalanced nature of the phase currents.

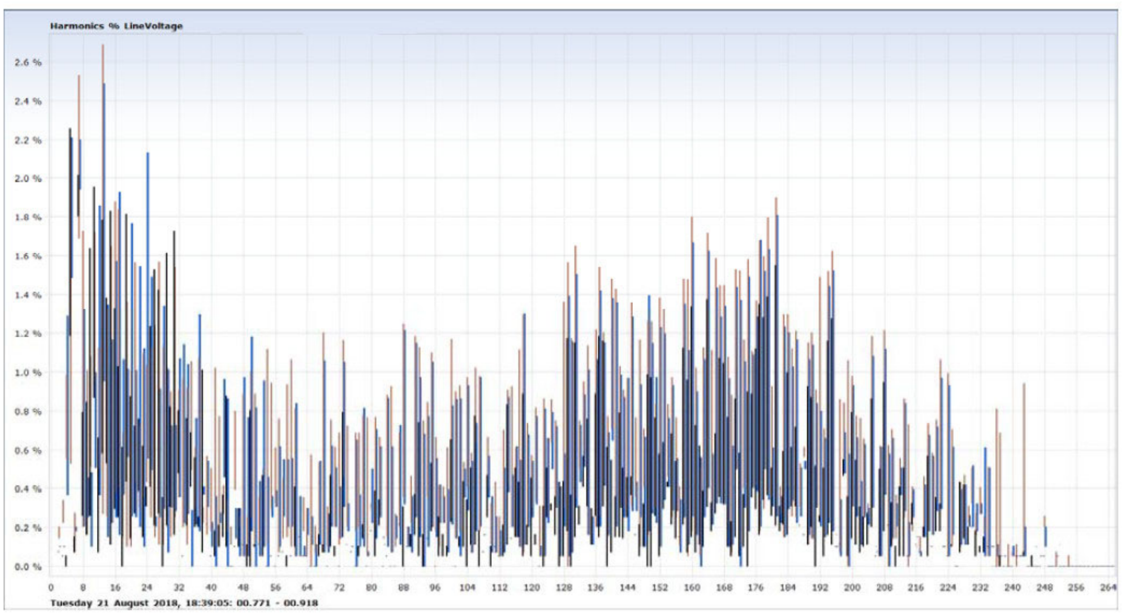

Fig 16 : Harmonic line voltage spectra of a 500kW AFE VFD (restricted to 256th order) at reduced loading (332kW)

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.

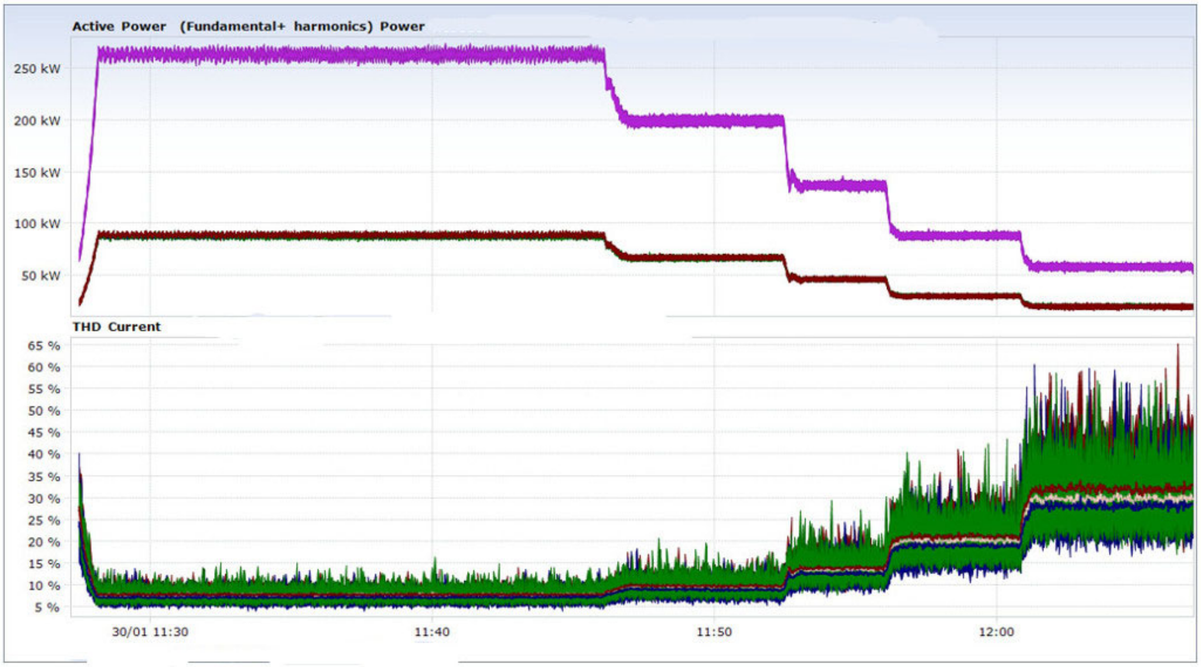

Fig 17 : Active power (kW) and THDi (average and min/max) of 315kW AFE VFD on centrifugal pump application

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.

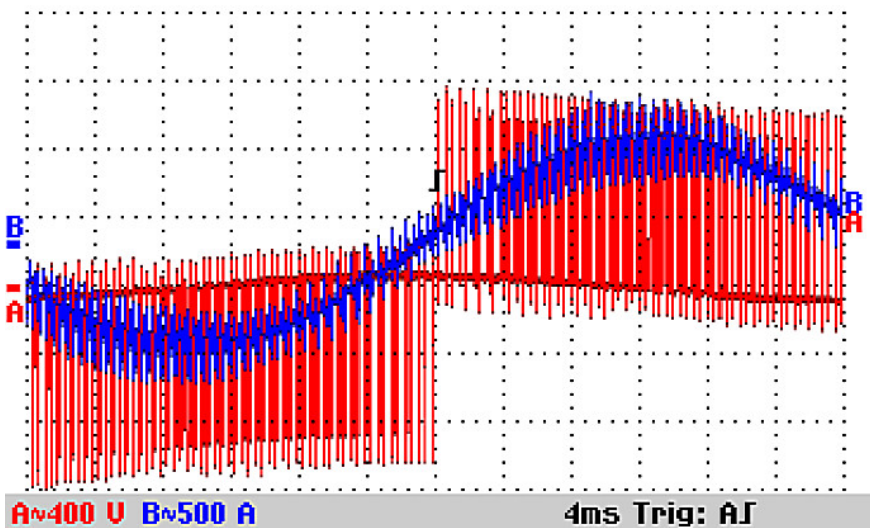

Figure 18 : Characteristic output voltage and current from PWM VFD

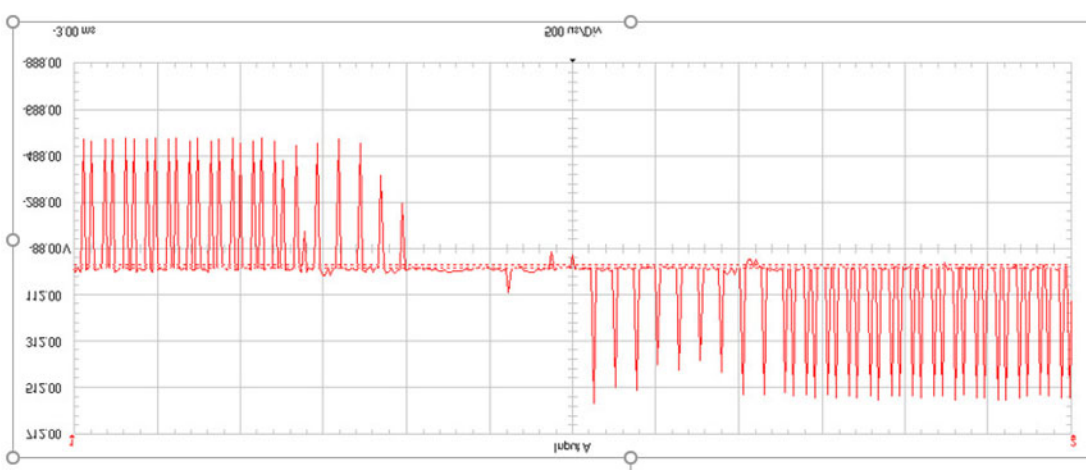

Figure 19 : Expanded PWM VFD output voltage waveform

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.

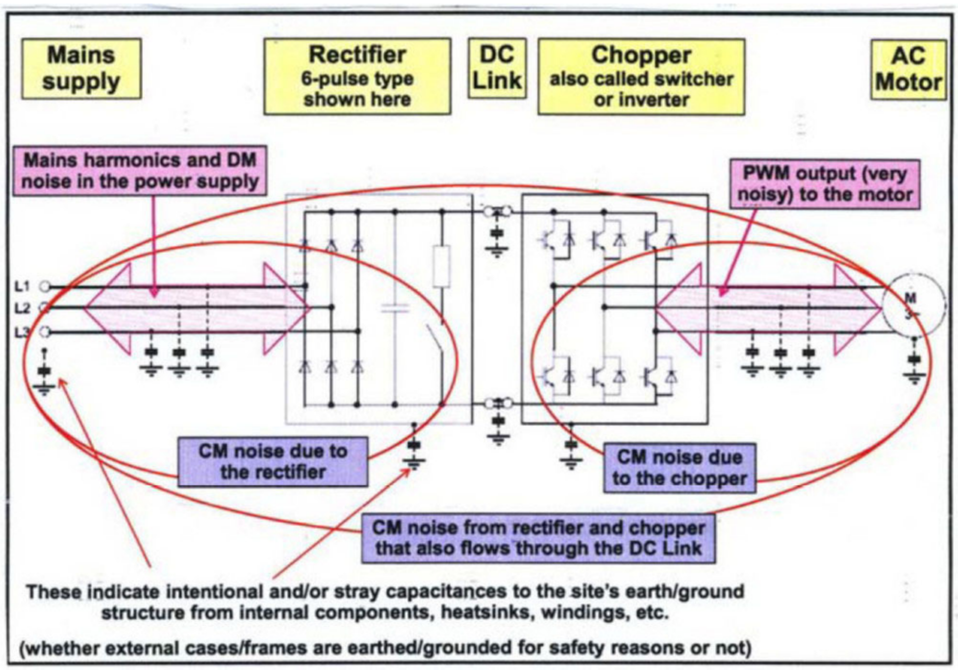

Figure 20 : Salient paths of EMI in 6 pulse VFD (AFE VFDs have IGBT rectifier)

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

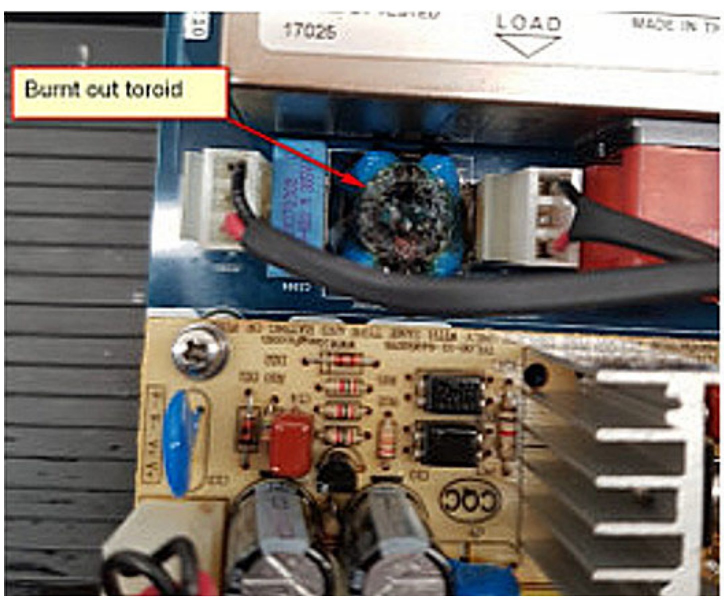

Figure 24 : Transformer burned out by common mode voltage in US$ 20,000 MIL spec PQ recorder by the AFE VFDs shown Figure 6. The CMV entered via the single-phase recorder mains supply.

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).

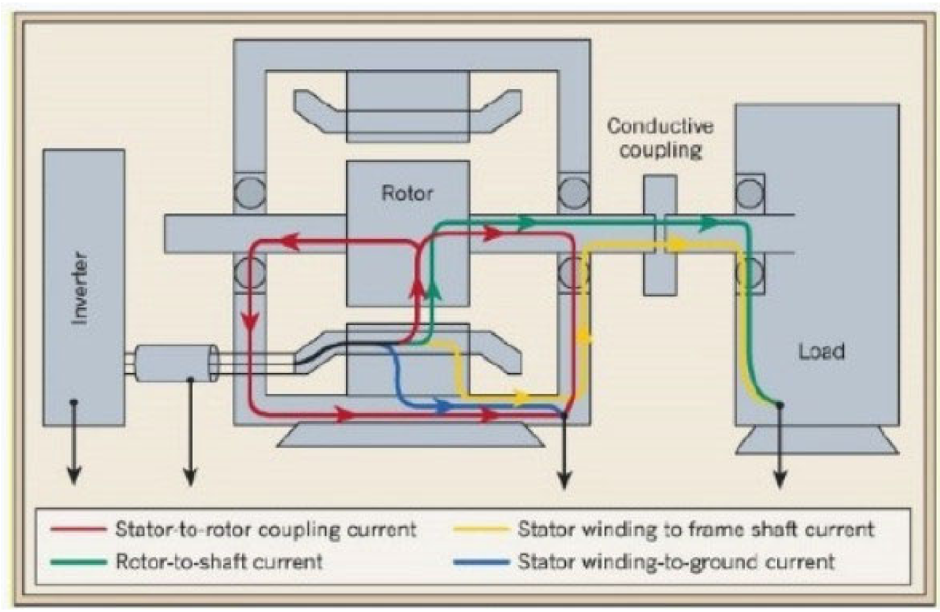

Figure 25 : Paths of common mode current in PWM VFD fed induction motors

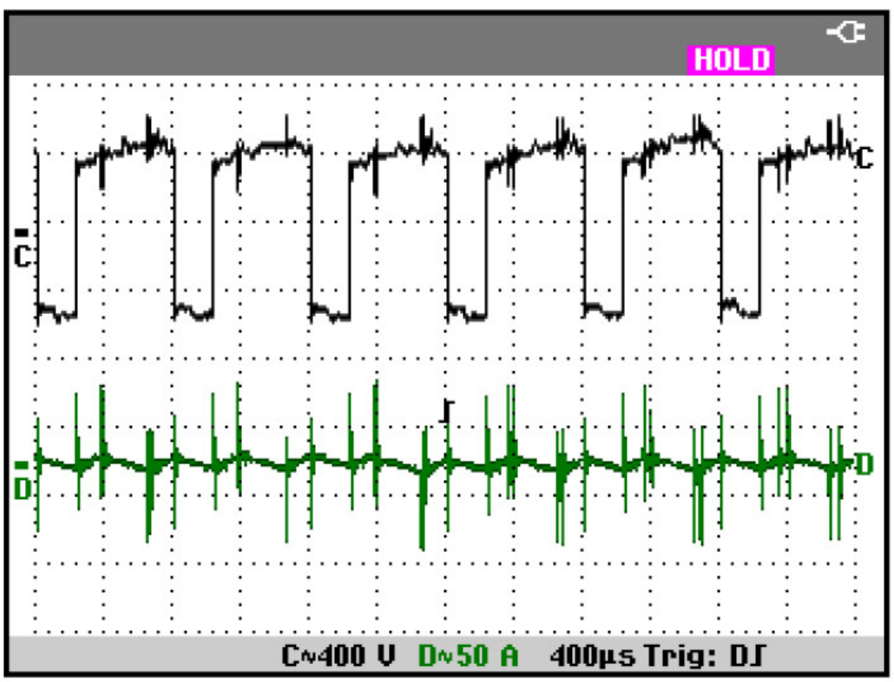

Figure 26 : Example of common mode current (green trend).
Note repetitive peaks of up to 80A, three times every 400 micro-seconds !

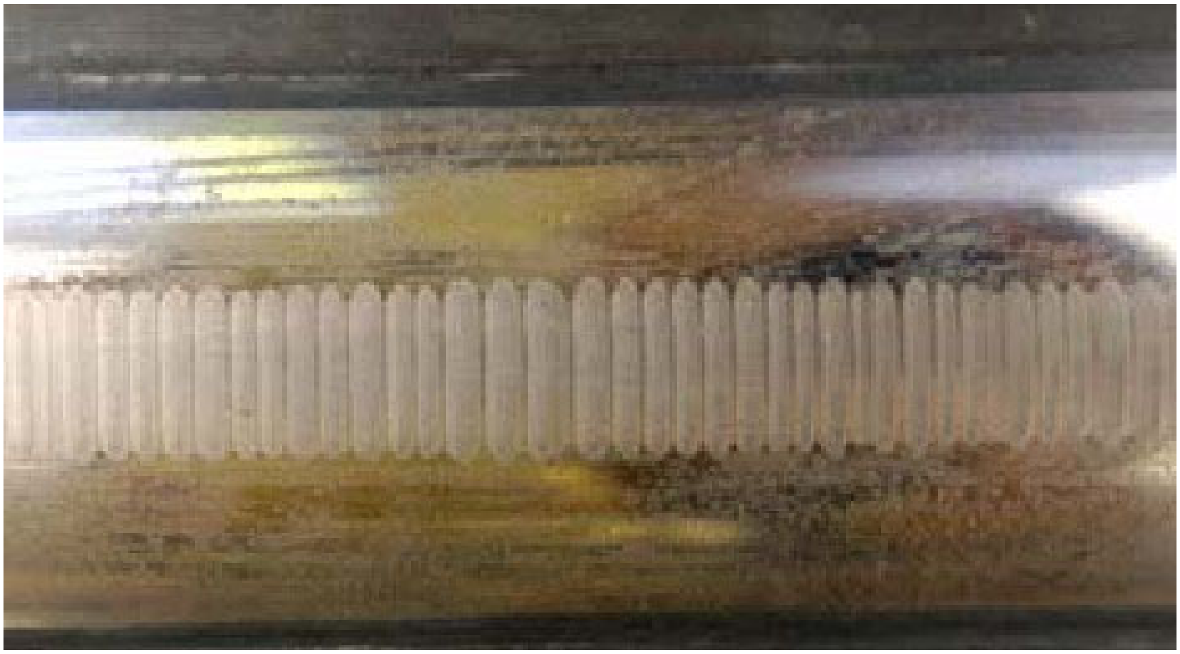

Figure 27 : Example of "fluting" due PWM VFD common mode current at the switching frequency of the VFD

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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