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The Price of Poor Power Quality

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Abstract

Electric drives, both DC drives (often called "SCR drives" in the industry) and AC variable frequency drives (VFDs), are commonplace on drilling rigs and offshore installations. Their operation can significantly degrade the quality of electric power, resulting in loss of operational capability, equipment failure with subsequent down-time in addition to presenting safety concerns. Marine classification bodies have rules to limit harmonic voltage distortion but these are rarely policed.

The quality and security of electric power are absolutely crucial to the operational integrity of any drilling rig or offshore installation, irrespective of type or class. Any failure or malfunction of equipment due to poor power quality can result in severe or disastrous consequences.

This paper looks at the main problems associated with poor power quality, including excessive harmonic voltage distortion, line notching (SCR drives) and voltage spikes attributed to SCR drives; these are all traditional 'harmonics problems'. However, the introduction of large VFDs has resulted in significant increases in 'common mode voltage' problems which can be extremely problematic; even to the point where rigs are being taken off-hire due to major equipment being deemed 'dangerous'. On another rig, the gas detection system failed when the top drive VFD was running due to this problem.

This paper will provide a practical understanding of each problem and how they can be resolved. The paper also introduces an inexpensive, yet powerful, remote power quality monitoring system which can be easily retrofitted to monitor all aspects of land-rig and offshore rig power quality, including waveforms and harmonic spectrums. The data is available locally with the capability to transmit the information via the internet to anywhere in the World.

Introduction

The paper looks at the importance of electrical power quality on drilling rigs/ships and offshore installations. It describes the more common power quality (PQ) issues including harmonics, line notching, voltage spikes and the more recent problem of common mode voltages due to AC VFD drives. Mitigation directed at attenuating each type of problem has been suggested together with an example of a remote power quality monitoring systems has been introduced.

1.0. The importance of power quality

Electrical adjustable speed drives, both AC variable frequency (VFD) and DC SCR types, are standard equipment onboard offshore drilling rigs/ships, land rigs and offshore oil production installations. Indeed, without adjustable electric speed drives many types of installation would have extreme difficulty operating.

Adjustable speed drives have many applications in the offshore sector including main propulsion, thrusters, 'drilling packages' (i.e. mud pumps (Fig 1), draw-work and top drives), compressors, fans, pumps, (especially electrical submersible types), leg racking drives on jack-up rigs, cranes, etc.

Fig 1 : Mud pumps controlled by adjustable speed drives

Fig 2 illustrates a typical DP3 semi-submersible rig with 25,600kW (~35,000HP) of 12 pulse VFDs for thrusters and around 2 x 5000kVA (~10,000-12,000HP) of 6 pulse drilling package drives. The non linear load constitutes around 85-90% of the rig electrical load.

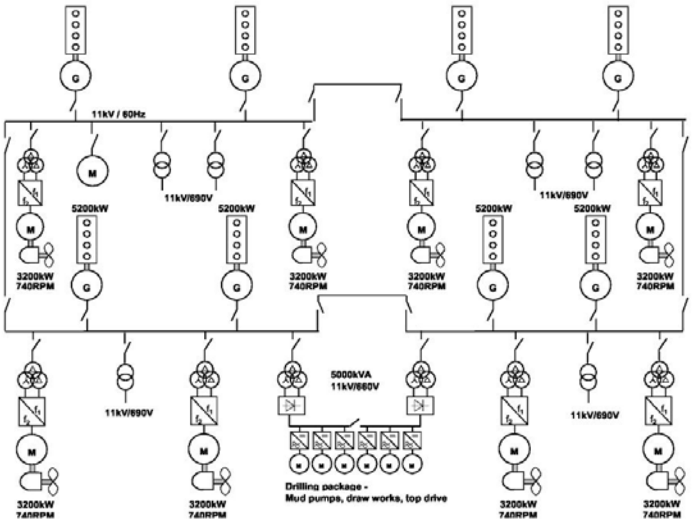

Fig 2 : Typical DP3 semi-submersible drilling rig

All types of conventional drives (AC and DC), whilst essential to many industries, including drilling and related downstream oil services, significantly degrade the quality of power on all installations, onshore and offshore. For installations which rely on generator derived power (i.e. the vast majority of drilling rigs) the resulting harmonic voltage distortion can be up to 3 to 4 times that of transformer based power supplies of the same given adjustable speed drive load. This is due largely to difference in source impedance between transformers (e.g. 5-6%) and generators (e.g. 12-25%).

The numerous negative effects of harmonics are widely acknowledged and therefore should not require any further explanation in this paper other than to state that they generally fall into two basic categories :

a) Excessive heating caused by additional I^2R losses, skin effect et al in cables and in equipment (e.g. generators, transformers, motors, etc).

b) Voltage distortion due to the harmonic currents ability to produce voltage drops in the various feeder impedances and leakage inductances of the system. In addition, line notching due to DC SCR drives can also be problematic.

Since a significant number of types of equipment use the voltage to synchronize or derive control information, the presence of harmonics can cause a wide range of failures and/or malfunctions. Consequently, marine classification societies and other bodies have rules and recommendations to limit the harmonic voltage distortion. For example, American Bureau of Shipping (ABS) now has 5% Uthd (total harmonic voltage distortion) generally and 8% Uthd for MODUs (Mobile Offshore Drilling Units). To coincide with the initial 5% Uthd rule introduced in February 2006, ABS published the document "Guidance Notes for the Control of Harmonics in Electrical Power Systems". This 240 page comprehensive guide can be downloaded from www.eagle.org, Publication 150. Other marine classification bodies, whilst not publishing any guidance notes per se also have similar voltage distortion rules. However, in the experience of the authors, no civilian marine classification bodies effectively police their own harmonics rules. This may be due to lack of knowledge, experience and independent and reliable harmonic estimation software packages but is also due to commercial considerations.

Since equipment to control harmonic currents is often seen as expensive and may not directly aid production, commercial considerations often dominate and the 'solutions', if installed, can end up providing less than ideal power quality, usually above the stipulated limits. The result is a considerable number of installations have significantly more harmonic voltage distortion than permitted. In the author's experience it is not uncommon to measure up to FIVE to SIX times the permitted limit on some installations.

The quality and security of voltage supplies are crucial to the safety and operational integrity of any vessel or installation, irrespective of class or type. This simply cannot be overstated. Any failure or malfunction of equipment due to poor power quality can result in loss of production or an incident with possible severe or disastrous consequences. The problem has been further compounded by offshore Health & Safety bodies across the world not policing the high levels of voltage distortion either; instead this is currently left to the oil companies to police themselves. Again, the lack of knowledge and experience is stated, as are financial constraints. However, this is starting to change. The Health and Safety Executive in the UK is now proactive and it is rumored that they will impose a legal 8% Uthd (total harmonic voltage distortion) on all North Sea installations in the near future. When this happens it is assumed it will be imposed throughout the industry worldwide.

There have been a number of incidents on and offshore over the World, some very serious, over the last 25 years or so. The numerous effects of poor power quality may not have been fully appreciated over this time and, as a result, it is doubtful that quality of electrical power was an issue which many considered a factor to be investigated.

Often the offshore oil industry when pressed on harmonic issues, cites the common phrase "*we never have had any problems with harmonics*". Past incidents, the more recent events, in addition to some of the information detailed in this paper and presentation may suggest otherwise.

2.0. Harmonic voltage distortion

Most conventional adjustable speed drives fed with sinusoidal voltages draw non-sinusoidal or 'non linear' current. During the conversion process from AC to DC, both DC SCR drives and from AC VFDs draw unwanted harmonic currents which are multiples of the supply frequency (e.g. 5th harmonic current is 5 x 60Hz = 300Hz) are drawn from the source.

The 'characteristic' (i.e. expected) harmonics currents are dependent on the number of three phase (i.e. 6 pulse) input rectifiers in non linear load(s) and is based on the formula :

$$I_h = n.p +/-1$$

where n is an integer, p is pulse number (i.e. 6 pulse)

Examples of characteristic current harmonics are :

6 pulse = 5, 7, 11, 13, 17, 19, 23, 25.......
12 pulse = 11, 13, 23, 25, 35, 37......
18 pulse = 17, 19, 35, 37......
24 pulse = 23, 25, 47, 49….

Note : that 12, 18 and 24 pulse drives/systems illustrated above comprises two, three or four three phase (i.e. 6 pulse) rectifiers respectively, each with an appropriate phase shift transformer.

The individual harmonic currents then interact with the system impedance at their respective frequencies to produce voltage distortion at those frequencies; this is based on Ohms Law where :

$$U_h = I_h \, x \, Z_h$$

Where U_h is harmonic voltage at a specific harmonic frequency
I_h is the harmonic current at a specific frequency
Z_h is the impedance at a specific frequency

The individual harmonic voltages are summed as follows and result is the "total harmonic voltage distortion" (Uthd) :

$$U_{thd} = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1} x100\% = \frac{\sqrt{U_5^2 + U^2{}_7 + U_{11}^2 .... + U_n^n}}{U_1} x100\%$$

Where U_5, U_7, U_{11} etc harmonic voltages 5/7/11...
U_1 is the fundamental voltage
U_{thd} is total harmonic voltage distortion

Note : 'Uthd' relates to line voltages whereas 'Vthd' relates to phase voltages.

It can be seen from above that the higher the value of non linear loading in kW, the larger the magnitude of the harmonic currents and higher the subsequent voltage distortion. Fig 3 illustrates an example line voltages distorted due to excessive harmonics currents (and capacitive VFD loads).

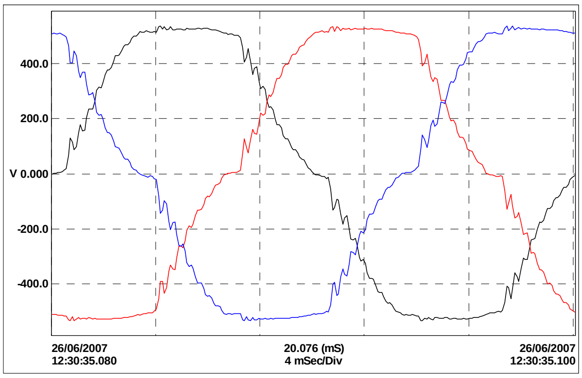

Fig 3 : Example of line voltages distorted by AC VFDs (8.8% Uthd) . Note - flat-topping at peak !

3.0. AC Variable Frequency Drives

Both AC and DC adjustable speed drives draw nonlinear current but AC variable frequency drives (VFDs) tend to produce higher levels of harmonic voltage distortion due to the capacitive load (DC bus) as seen from the supply side.

VFDs are increasingly popular on drilling rigs/ships and comprise three subsystems (Fig 4):

i) Input rectifier (diode or SCR pre-charge) to convert AC into DC for the DC bus.

ii) DC bus, which is essentially a capacitor storage system from which the output inverter IGBT (insulated gate bipolar transistor – power switches) bridge draws energy.

iii) An IGBT inverter bridge which inverts the DC bus voltage to AC variable voltage/variable frequency to drive the induction motor(s).

The VFD only draws current from the supply only when the voltage across the capacitors in the DC bus is lower than the instantaneous supply voltage. This occurs near the peak of the supply voltage waveform so the currents drawn are pulsed in nature with two pulses of current per phase as can be seen in Fig 5.

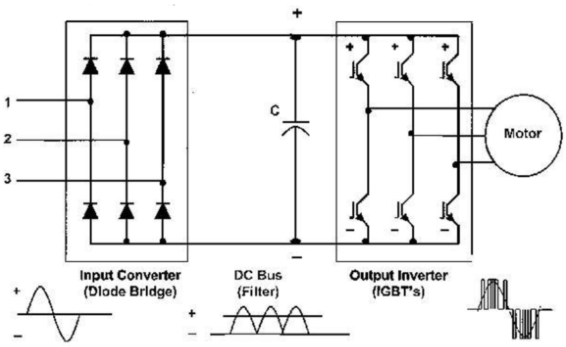

Fig 4 : Simplified 6 pulse AC VFD schematic

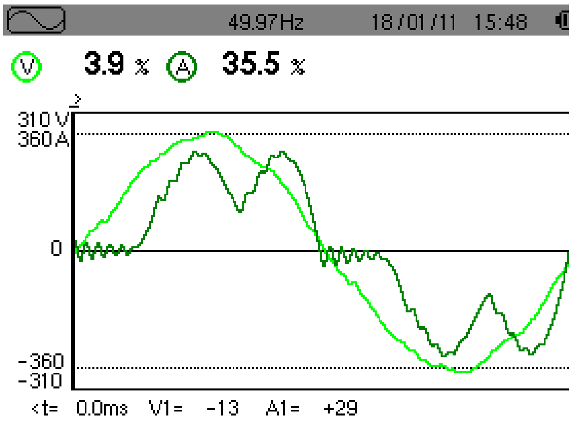

Fig 5 : One phase of VFD input (voltage and current) waveforms

Fig 6 illustrates the nonlinear phase currents drawn by a 1500HP/1100kW VFD at moderate load. The oscillations around zero were due to EMC filter capacitors downstream. Fig 7 details the harmonic current spectrum. Note the partial resonance at the 23rd and 25th harmonic due to the capacitance.

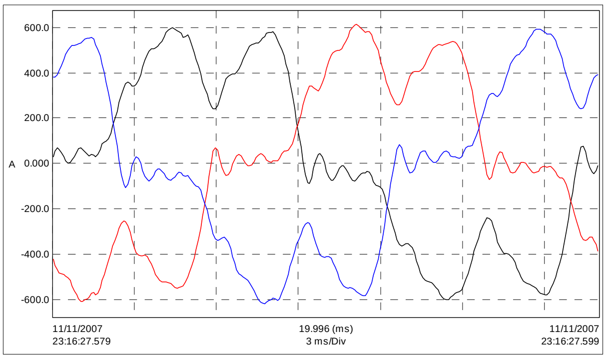

Fig 6 : Example of 1500HP (1100kW) VFD phase currents at moderate load. 34.88% Ithd.

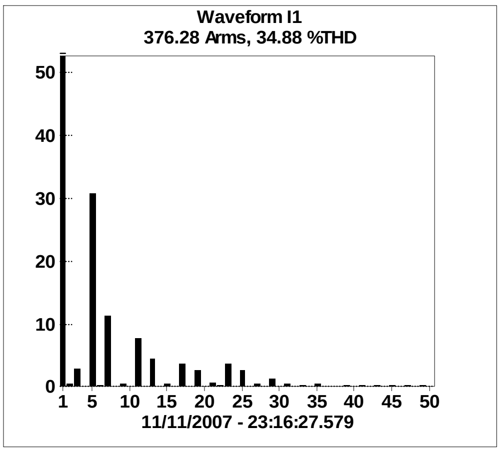

Fig 7 : Example of 1500HP (1100kW) VFD current harmonic spectrum (%). (Fundamental rescaled to 50% to show detail. Partial resonance at 23rd and 25th harmonic)

High power VFDs are often utilized for thrusters, mud pumps, draw-works and top drives either as standalone drives (as per Fig 4) our as part of a system where a number of output IGBT (insulated gate bipolar transistor) inverter bridges share common rectifiers and a DC bus. 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 8 illustrates a common DC bus system comprising two rectifiers, a capacitive DC bus (i.e. storage unit) and eight independently controlled IGBT (insulated gate bipolar transistor) PWM (pulse width modulation – common type of VFD output waveform control) VFDs inverters (which are the final output stage of a standalone VFD).

Note that this particular system uses two 6 pulse rectifiers, one on 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). The 12 pulse configuration will reduce the harmonic distortion compared to a standard 6 pulse system but optimum performance is largely determined by the loading on each rectifier, the various imbalances in the drive system rectifiers, transformer windings and supply voltages and the level of background distortion (i.e. voltage distortion due to other loads).

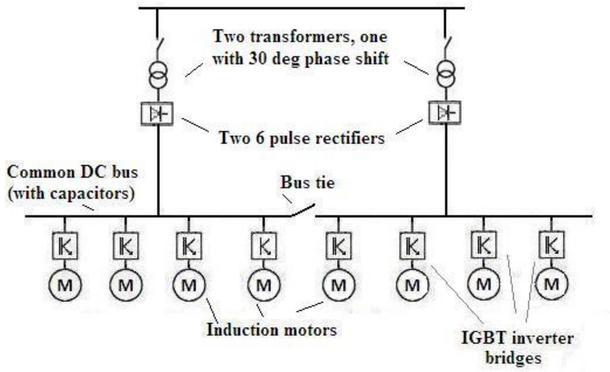

Fig 8 : Common DC bus system with quasi 12 pulse harmonic mitigation configuration

3.1. DC SCR drives

DC SCR drives are not as complex as VFDs and are essentially sophisticated DC voltage controllers where the output voltage largely determines the DC motor speed whilst the output DC current determines the motor torque.

As can be seen in Fig 9 DC SCR drives draw nonlinear current which tends to be smoother in nature than VFDs due to influence of the DC motor armature inductance. Fig 10 details a typical harmonic current spectrum of a 6 pulse DC SCR drive with additional inductance installed between the SCR drive and the supply. Unfortunately, this 'additional inductance' is often omitted on drilling rigs/ships on the grounds of cost and space. This leads to higher harmonic currents. As we shall discuss later, issues with 'line notching' and occasionally voltage spikes are the unwelcome result.

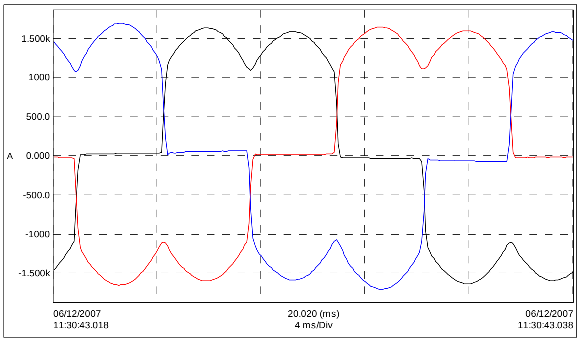

Fig 9 – Example of DC SCR drive at moderate load (31.51% Ithd)

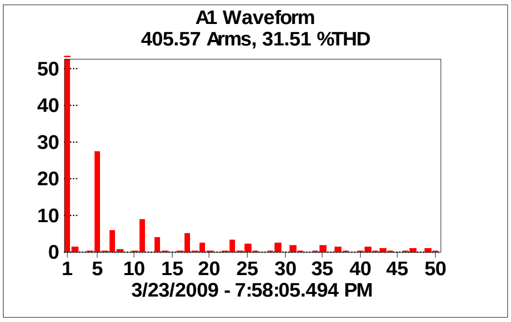

Fig 10 : DC SCR with line reactor. Typical harmonic current spectrum (%)

At relatively high speed/high torque levels the DC SCR drive will result in slightly less voltage distortion than an AC VFD of the similar kW loading. However, as the speed of the DC SCR drive reduces and a high torque demand is maintained, the resultant voltage distortion (and line notching) will increase significantly, due the control angle of the SCR devices becoming progressively phased back.

3.2. Increasing cause of concern ?

On production platforms VFDs are used for pump, compressor and other duties. A considerable number of ESPs (i.e. electrical submersible pumps) use multi-pulse VFDs (e.g. 12, 18 or 24 pulse) which utilize multiple 6 pulse rectifiers and phase shift transformers.

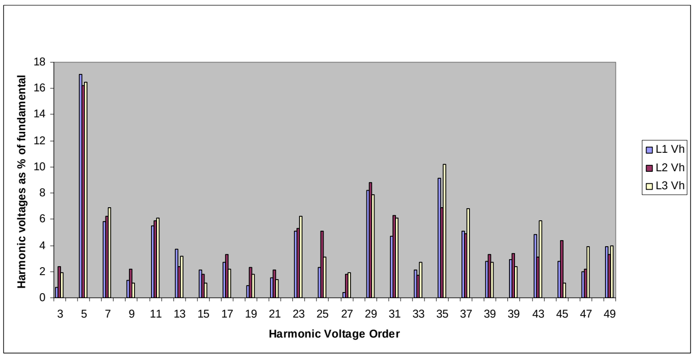

Fig 11 - Offshore oil platform harmonic voltage spectrum measured on 690V drilling package

Fig 11 shows the Uthd (total harmonic voltage distortion) captured instantaneously on a 690V drilling package with a DC SCR drilling package. The average Uthd was 25.61% of which 19.3% was >21st harmonic due mainly to large number of 24 pulse VFDs for submersible pumps connected to MV supplies. The recommended limit for harmonic voltage for the installation was 5%. The higher order harmonics are more serious due to higher frequency heating effect per amp.

It should be noted that standard LV (low voltage) fixed speed IEC (International Electrotechnical Committee – sets standards for electrical equipment outside North America) explosion proof motors are only permitted 2% background Uthd, based on Section 6 of IEC EN 60034-1 and (IEC EN 60034-12 for Type N, 3% Uthd); UL or NEMA as far as the authors are aware, do not currently have similar restrictions. What is also of significant concern is that this example is not an isolated case.

A leading US University Professor of Power Quality, who is also a World authority on the subject, recently estimated that the voltage frequency spectrum in Fig 11 would reduce the life of a motor by around 34%. However, there are significantly greater concerns regarding the level of overall voltage distortion as illustrated in Fig 11 and the effect on explosion proof motors plus, as yet, the unknown heating effect of the higher order voltage harmonics on double cage or deep bar rotors such those as used on compressors with the resultant risk of ignition should an escape of gas or vapor occur. The IEC was alerted to the problem of higher order harmonic voltages over 5 years ago but the authors are unsure as to whether any studies have progressed.

3.3. Common types of harmonic mitigation

3.3.1. Multi-pulse drives

Historically, multi-pulse drives, most prominently 12 pulse drives, AC and DC, are used to reduce the harmonic currents and thereby reduce the voltage distortion. These comprise a number of 6 pulse (i.e. three-phase rectifiers) and phase shift transformers. The pulse number (e.g. 18 pulse) determines the theoretical characteristic harmonics. For the 18 pulse configuration the characteristic harmonic currents would be 18 +/-1 = 17, 19, 35, 37, 47, 49. Fig 12 illustrates an 18 pulse VFD simplified schematic.

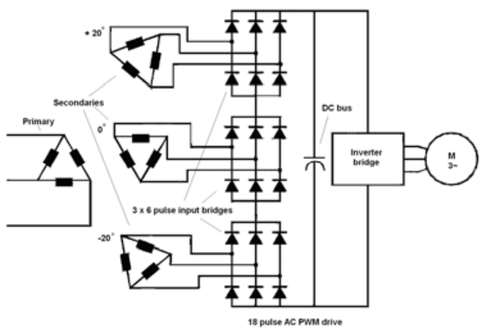

Fig 12 : Typical 18 pulse AC VFD with phase shift transformer

Multi-pulse drives under ideal conditions can offer good levels of performance. However, even moderate levels of background voltage distortion (<5% Uthd) combined with any imbalances in rectifiers, transformer windings and supply voltage seriously degrade the performance. In addition, multi-pulse drives tend be to large (due to phase shift transformers) and bulky. Due to stricter limits on voltage distortion 12 pulse versions have lost their popularity. 18 and 24 pulse VFDs are still popular for LV (low voltage) and MV (medium voltage) ESP (electrical submersible pumps) duties despite the disadvantages cited.

3.3.2. Passive Wide Spectrum Filters

Over the last 5-6 years the passive ‘wide spectrum filter’ has gained popularity within the drilling and marine sectors. These rugged and effective devices comprise a close coupled tri-limbed reactor wound on a common core and a small capacitor bank (Fig 13). The filter is connected in series with the drive load(s) (Fig 14). These devices have been installed in sizes to 3500HP/2650kW for both AC VFDs (D type) and for DC drives (T type) and are now being developed for MV (medium voltage) VFDs. Fig 15 shows 2 x 2300HP/1800kW D type (AC) wide spectrum filters during ABS compliance testing in the United Arab Emirates. These units were connected to an AC VFD common DC bus system for three mud pumps. The Uthd was reduced to below 5% to meet requirements.

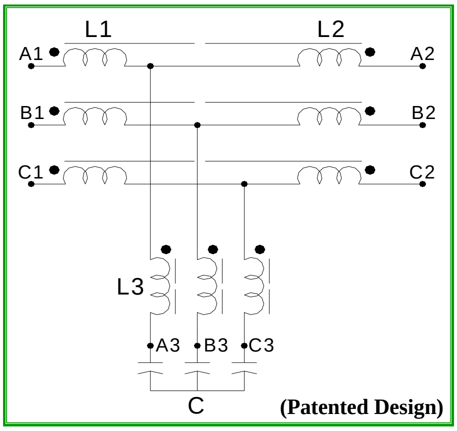

Fig 13 – Advanced wide spectrum filter schematic.

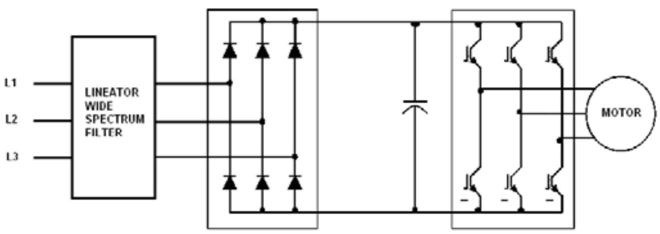

Fig 14 : Advanced wide spectrum filter connection to VFD. Can also be connected to a group of AC or DC drives.

Fig 15 : 2 x 2300HP/1800kW D type wide spectrum filters on mud pumps during ABS compliance testing in the UAE

A number of wide spectrum filters (T types) can also be used for DC SCR drives to attenuate the harmonic currents and reduce line notching (line notching is explained in Section 4). Fig 16 details the harmonic current spectrum from a 900HP/630kW 6 pulse DC SCR drive. The Ithd (total harmonic current distortion) was measured at 30.66%. Fig 17 is the same DC SCR drive as depicted in Fig 16 but connected to a T type wide spectrum filter which reduced the Ithd by 81% to 5.83% Ithd.

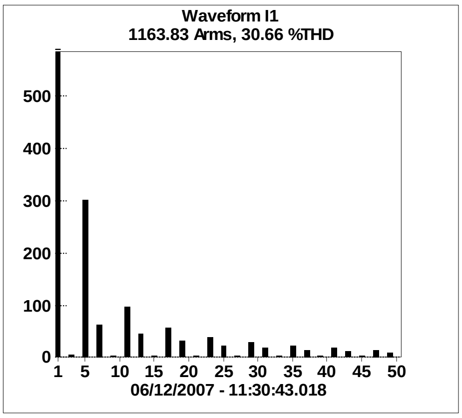

Fig 16 – 900HP/630kW DC SCR drive harmonic current spectrum. No mitigation – 30.66% Ithd

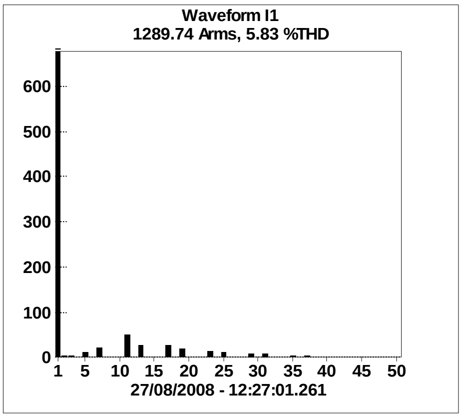

Fig 17 – 900HP/630kW DC SCR drive harmonic current spectrum (I1) in AMPS. With T type wide spectrum filter - 5.83% Ithd

For drilling and marine use, high quality wide spectrum filters with very low values <15%) of capacitance (kVAr) are essential in order to ensure compatibility with generators under all load conditions. A correctly designed wide spectrum filter is an effective and rugged device, environmentally and electrically, and well suited to the offshore and drilling applications. If applied correctly to single or multiple drive loads full compliance with classification body rules (general and MODU) can usually be provided.

3.3.3. Active filter solutions

There are several types of electronic or 'active' filter. The series active filter and the parallel active filter are shown in Figs 18 and 19/20 respectively.

Series active filters, more commonly associated with "active front ends" or "AFE" VFDs, are connected in series with the nonlinear load and operate by regulating currents into the line, correcting harmonics and displacement power factor. They are often closely integrated with motor drives as the power circuit is identical to a VFD output IGBT bridge and the vector control techniques used are identical to those used in VFD motor drives. The series active front end is a special type of active filter that is able to boost its internal DC bus voltage higher than the peak of the line-line voltages, which allows it to have unique control over the line currents to significantly reduce harmonic currents. The series active filter also can control power in both directions, allowing regenerative energy from the motor drive in many applications to be fed back to the line.

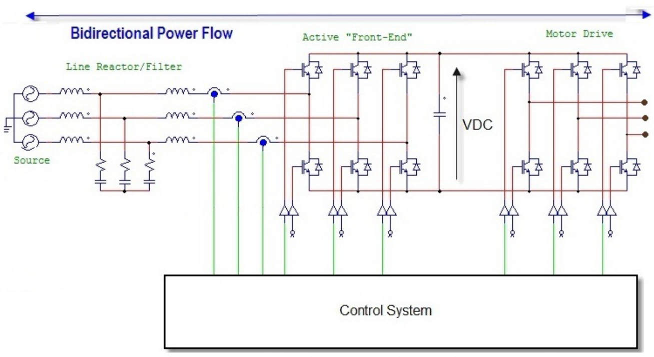

Figure 18 : Series active filter provides harmonic mitigation at input of an AC VFD (induction motor not shown)

Parallel active filters (Figs 19 and 20), are similar in technology to VFDs, as well, but are much smaller (~60-70% smaller) than series active filters as they only need to treat the harmonic currents (not total rms {root mean square} current), which are typically around 30-40% of the full rms source current value. In a correctly dimensioned system the vast majority of the harmonic currents are drawn from the active filter (Fig 19) and only the fundamental current is drawn from the generator or transformer. Parallel active filters also simultaneously supply reactive power and can maintain high levels of system DPF (displacement power factor) under all load conditions; this is important on rigs with DC SCR drives, which have low DPF during high torque, low speed operation.

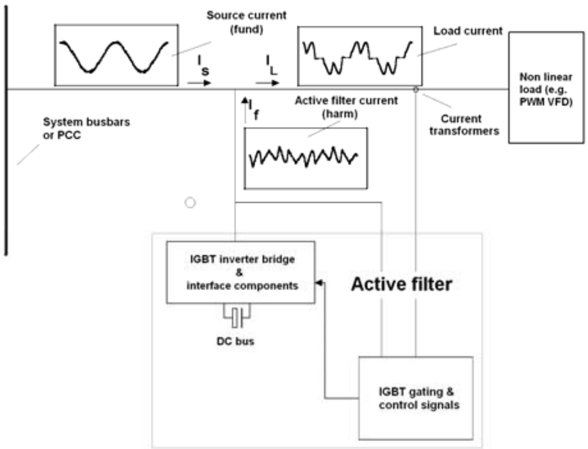

Fig 19 : Parallel active filter current waveforms

Fig 20 illustrates a schematic for one popular power circuit architectures used for parallel active filters.

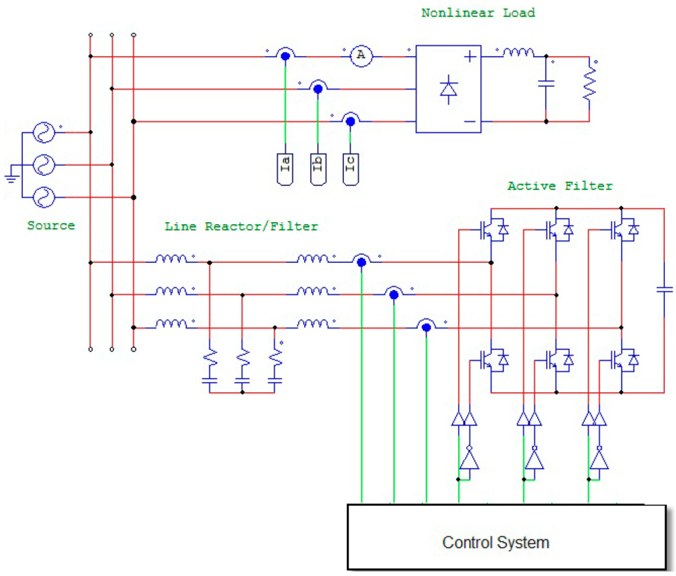

Fig 20: Parallel active filter schematic and connection

Active filters, if applied correctly, can offer excellent performance but that performance is largely dependent on the speed of response (i.e. the type) of active filter, where it is connected in the system and most importantly whether a suitable (at least 3% reactance) AC line reactor (or DC bus reactor for VFDs) exists in each drive. AC line reactors (or DC bus reactors) are crucially important for active filters.

Note that the selection of parallel or series active filters is often driven by the additional consideration as to whether or not the AC or DC motor drive system benefits from the ability to regenerate power back to the line. Many adjustable speed drive loads have significant inertia, whose energy needs to be recovered for reasons of energy costs or to provide braking to the load(s), for example. In these cases, a series active filter may be selected even though it is larger than its parallel active filter counterpart, simply because regeneration capability is a dominant requirement. The fact that it can also eliminate harmonics is an additional bonus feature.

The source impedance for the harmonic currents of an active filter is <1%. This is significantly lower than for a transformer (~5-6%) or generator (~12-25% X"d). Active filters have complex control systems, and depending on the quality and bandwidth such control system it is possible for a motor drive load (AC or DC) to draw significantly more harmonic current from the active filter than it would from the conventional transformer or generator source. This additional harmonic can be up to 200-300% more if no additional reactance (at least 3%) is existing in each drive and if the control system is not tuned properly. Even with 3% AC line reactance in each drive load the additional current can be reduced to 20-25% more.

Configuration and commissioning of active filters in a system needs to be done according to the manufacturers requirements and this is where many of today's active filters fall short, (i.e. in their inability to be deployed in the field without requiring advanced technical onsite support). It is the authors belief that once more advanced auto-tuning and external load identifying algorithms are designed and developed, these shortcomings will be overcome. However, at this time, series active filters or "(i.e. 'active front end' or 'AFE' products) are still relatively new and as the case when AFE motor drives when they first were introduced, they have some maturation time to become more easily deployed.

The retrofitting of line reactors is an issue which can foster fierce debate as it usually entails modifying the drilling switchboard busbar system to permit the reactors to be connected in series with each of the AC VFDs and/or DC SCR drives to ensure acceptable parallel active filter performance. However, similar issues apply to wide spectrum filters as they are also series devices.

It should be noted that with active filters, retrofitting can be particularly fraught with problems as the line inductances, in additional to reducing the harmonic currents, need to support very high frequency voltages resulting from the switching action of the power electronics. Consequently, placement of such active filter inductors far from the electronics can result in high levels of common mode and radiated emissions. Inductors for series active front ends need to be located as close as possible to the active filter itself to avoid promulgating interference throughout the entire power system.

Figs 21 and 22 shows the effects (Ithd and Uthd) of 1500A of parallel broadband high speed active filters on a DC SCR drilling package comprising 6 x 900HP/630kW DC SCR drives retrofitted with 3% AC line reactors. The 800HP/600kW top drive was also treated by an active filter.

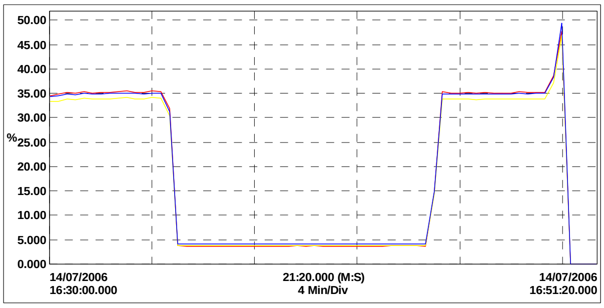

Fig 21 : Ithd on 3 x 900HP/630kW DC SCR drives without/with/without parallel broadband active filter. Ithd reduced from 35% to 3.7%

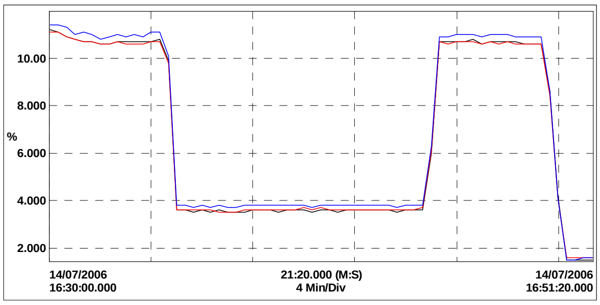

Fig 22 : Uthd on 3 x 900HP/600kW DC drives without/with/without parallel broadband active harmonic filter. Uthd reduced from 11.2% to 3.2%.

As mentioned earlier the speed of response of active filter is crucial when applied to even mildly dynamic loads. There are several subclasses of active filters :

♦'Broadband' or 'wide spectrum' active filters – all non-fundament currents are treated.

♦'Selective FFT (full Fourier Transform – a type of harmonic calculation) or 'discrete logic' – individual harmonic currents can be programmed.

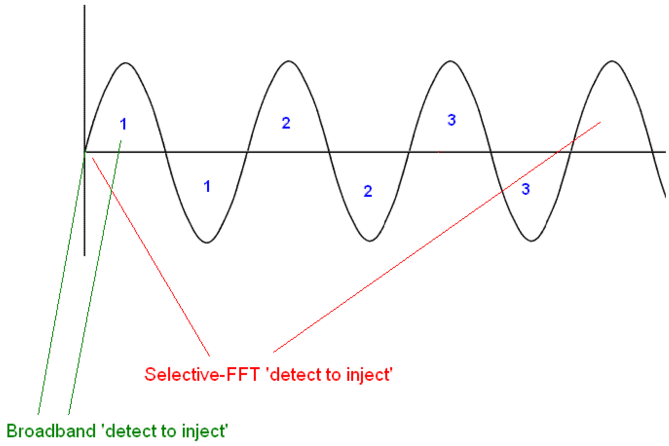

Fig 23 : Comparison of 'broadband' and 'selective FFT' active filter response times

As can be seen from Fig 23 the broadband active filter has the faster response and more suitable for dynamic loads. If the response is too slow then 'hunting' may result. On DC SCR drives where line notching attenuation is required both high speed of response and line reactors are mandatory.

4.0. Line notching

'Line notching' is usually associated with phase controlled semi-conductors such as SCRs (silicon controlled rectifiers or thyristors – power devices. Note, 'SCR' in the drilling industry is also the generic name for DC drives). These devices are used in DC drives and some types of larger AC drives such as synchronous drives and load commutated inverters. Line notching can also be seen in high powered AC drives with diode rectifiers under certain circumstances.

With reference to Fig 24 below. The line notches occurs six times per cycle on a 6 pulse bridge and is the result of the commutation of the load current from one pair of SCRs devices to another. During this process the line voltage is short circuited producing two primary notches per cycle. In addition, there are four secondary notches of lower amplitude which are 'notch reflections' due to the commutation of the other two legs of the three phase bridge rectifier.

The short circuit current duration, or 'notch width', is a function of the DC output current of the rectifier and the total inductance in the power system.

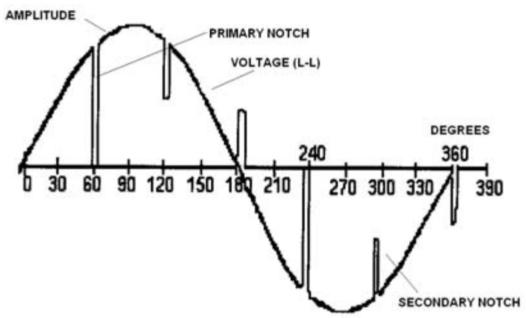

Fig 24 : Primary and secondary line notching

The notch depth is, in reality, a function on where the notch is viewed on the rig or ship power system. The further away it is seen from the terminals of the bridge rectifier, the less onerous it will seem. This can be explained with reference to Fig 25 below.

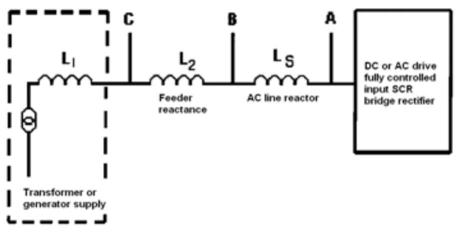

Fig 25 : Line impedance distribution and the effect of line notching

At Point 'A', the rectifier terminals (i.e. at the DC SCR drive terminals), the notching will be at its most severe, similar to that illustrated in Fig 22. However, the insertion of any additional inductance will reduce the notch depth *but will increase the notch width.* It is the notch depth which is usually the more important due to interference with equipment which relies on zero voltage crossing for operation. However, it is not standard practice to install line reactors on drilling rigs/ships. The result is that the line notches can cross the zero voltage line, often, creating false zero crossovers and disrupting equipment which require these for timing or control purposes, including other SCR drives (or active front ends that depend on line synchronizing signals). Fig 26 shows a typical voltage and current waveforms from a DC SCR drive on a drilling package.

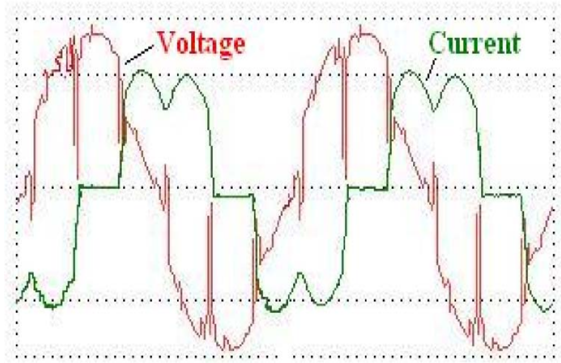

Fig 26 : Severe line notching on due to fully controlled SCR rectifiers on DC drilling package

Line notching, if excessive can cause severe problems and, as can be seen below, also lead to failures due to voltage spikes.

4.1. Reduction of line notching

4.1.1. Line reactors

As mentioned previously line notching can be attenuated by installed simple 3% or 4% line reactors in series with each DC SCR drive. Alternatively, in some cases, saturable reactors can also be used to reduce the size of the inductors. These are usually fitted inside the drive, with the voltage synchronizing connections being moved to the line side. Essentially the key requirement is that the inductor supports the line voltage without saturating for the duration of the line commutation interval. However, the attenuation level may not be sufficient.

4.1.2. Passive wide spectrum filters

Alternatively, if both harmonic mitigation and line notch attenuation is required then an appropriate wide spectrum filter (passive) should be considered. Fig 27 shows the effect of a 900HP T type wide spectrum passive filter on the line notching. The real attenuation is masked by two other DC SCR drives (700HP and 400HP, both untreated on same supply).

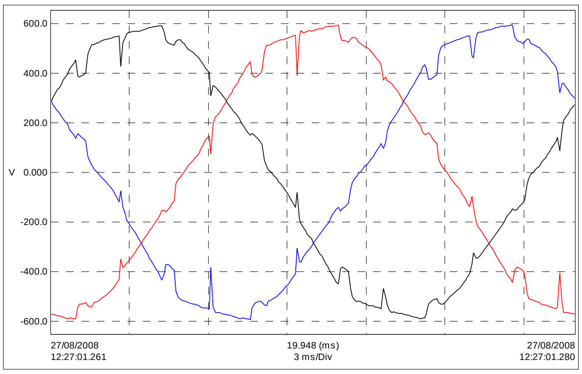

Fig 27 : 900HP DC drive line voltages with wide spectrum filter T type. Note - 1 x 700HP/500kW and 1 x 400HP/315kW untreated DC drives on same supply

4.1.3. High speed active filters

Fast broadband or other high speed active filters in conjunction with at least 3% line reactors are capable of significantly reducing line notching as can be seen in Figs 28 and Fig 29 below. The screen shots were taken from the application for 6 x 900HP/630kW DC SCR drilling package discussed earlier.

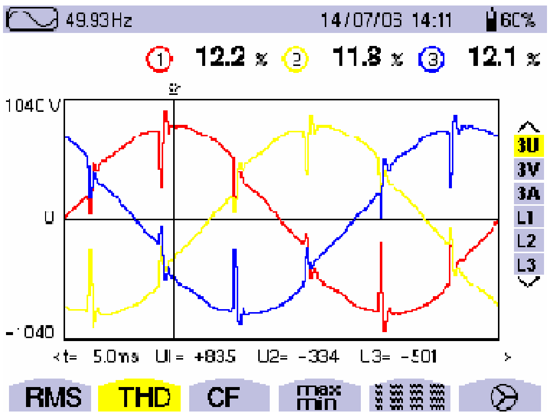

Fig 28 : 3 x 900HP DC drives voltage waveforms with 3% AC line reactors only

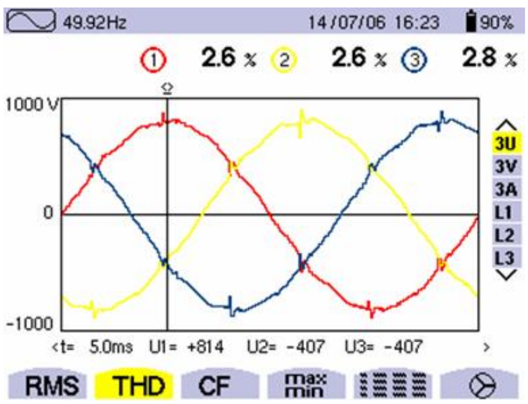

Fig 29 : 3 x 900HP DC drives voltage waveforms with active harmonic filter and 3% AC line reactors.

5.0. Voltage spikes

As the terms suggests, ‘voltage spikes’ are exactly that; spikes of overvoltage superimposed on the supply voltage. Fig 30 illustrates a typical example of voltage spikes and Fig 31, the consequences on small to medium power VFDs (e.g. shaker drives, generator cooling fan drives, etc).

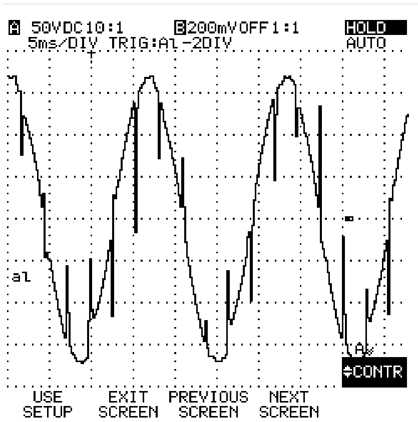

Fig 30 : Voltage spikes due to large DC SCR drives

Fig 31 : Damage due to voltage spikes on small to medium powered VFDs. Failure of rectifier devices and DC bus capacitors

Voltage spikes are commonly associated with DC SCR drive line notching and its related voltage ‘ringing’ (i.e. oscillations) are most severe during the phase back operation required for the control of DC motors at slower speeds. In order to control the DC armature voltage level, the gate firing circuit of the SCRs devices have to be varied. Line notching is more noticeable when the firing is delayed in order to achieve a lower DC voltages.

With a fully controlled SCR rectifier, the commutation notches can become severe. When the DC output voltage is lowered by delaying the thyristor firing, commutation (i.e. the transfer of current from one pair of devices to another) is also delayed until after the phase voltages have diverged. After firing, when commutation does occur, there is a potential difference between the shorted circuited phases which drives more current through the short circuit and increases the voltage drop and resulting notch.

Figure 32 shows variations in notch depths as the firing angles are varied.

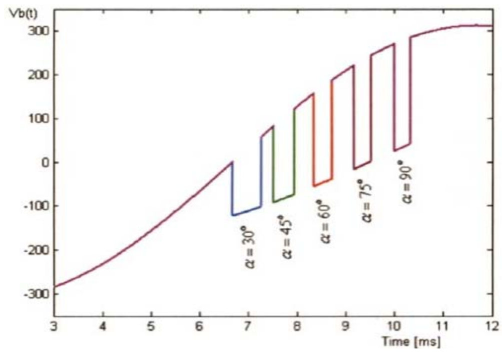

Fig 32 : Notch depth variations on firing angle changes

Since the notch has a relatively high frequency compared to the fundamental frequency, it can be excited by system resonance. If the system impedance happens to create a resonance point near the notch frequency, voltage oscillations can result (Fig 33). Often it can be stray cable capacitance and/or any EMC filters on AC VFDs that create these resonance conditions resulting in ringing and/or associated voltage spikes.

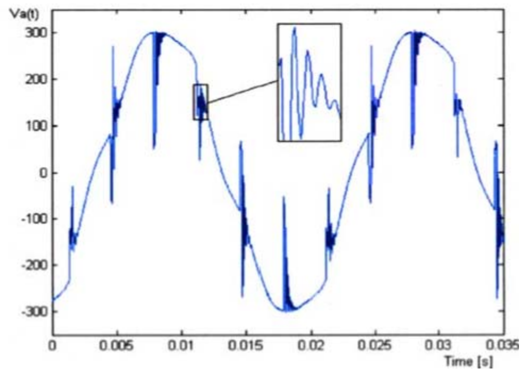

Fig 33 : Example of line notches and voltage oscillations due to delay angle of 45 deg

Voltage spikes do not only damage VFDs. The following are additional examples of the damage on one site attributed directly to voltage spikes :

- *Four off VFD EMC filters destroyed in enclosure.*
- *Multiple failures (>10 off) of 24V power supply units.*
- *Multiple AC (>12 off) thermostats destroyed.*
- *Multiple failures of Fire & Gas panel input filters.*
- *Multiple failures of fluorescent lighting across installation.*

Note that most of the above equipment have capacitor components which are obviously very susceptible to overvoltages. The overvoltages can also stress and damage semi-conductors. Most instances of voltage spikes on drilling rigs/ships tend to be due to large DC SCR drives where no additional line reactors have been installed. This practice seems to have been normal for 40 years or so (since DC SCR drive were introduced). However, before VFDs were introduced all drives were either fixed speed motors or smaller DC SCR drives; neither were affected by voltage spikes.

5.1. Attenuation of voltage spikes

There are a number of methods of addressing the voltage spike issue from retrofitting line reactors to all DC SCR drives, usually deemed impractical, to supplying the sensitive VFDs and other equipment from a separate generator or UPS (uninterruptable power supply). However, a relatively low cost and very effective solution is to install a suitable wide spectrum harmonic filter, such as mentioned in the 'harmonics' section, between the sensitive VFDs and the voltage notches. The wide spectrum filter treats the harmonic currents drawn from the supply as design but also acts as a 'blocking filter' and effectively isolates the VFDs from overvoltage and other disturbances.

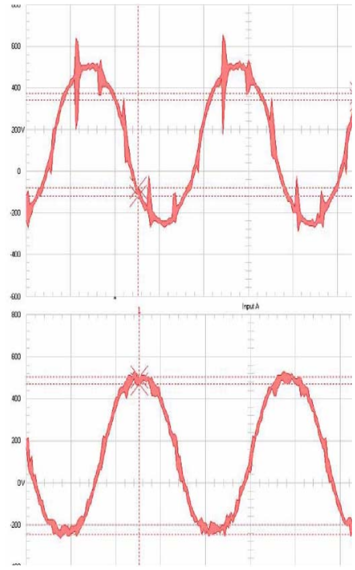

Fig 34 : The input (upper trace) and output (lower trace) to/from a wide spectrum filter on a DC drilling package. The sensitive VFDs are connected to the lower trace.

Fig 34 above illustrates how effect the wide spectrum filter type of solution can be. These are now being promoted throughout the drilling industry.

6.0. Common mode voltages

The preceding sections have all described the effects of harmonics, line notching and associated phenomena present in the line currents. However there is another, phenomena known as "common mode shift" which has equally dangerous consequences. Common mode shift originates at output of AC VFDs and is due to the non sinusoidal and high dv/dt (rate of rise of voltage) characteristic of the output voltage (Fig 35). Excessive common mode shift or the more often termed 'common mode voltage' can present a serious risk to all equipment onboard the installation.

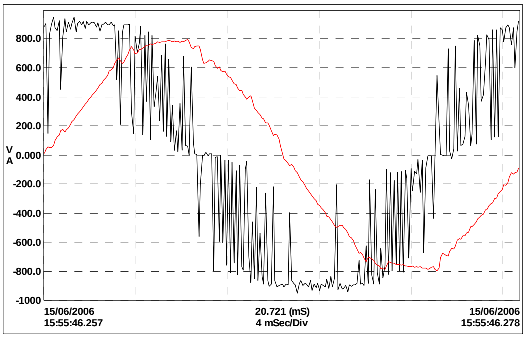

Fig 35 : Typical VFD output voltage (black) and current (red) waveforms.

Fig 36 illustrates a simplified motor drive connected to a three-phase resistive load (it could just as easily be drawn as a three phase motor). Note that the DC bus in this example is completely isolated from ground. IGBT VFD inverters can only open and close their semiconductor switches in eight possible combinations. Within the eight possible combinations of allowed switch settings, the ONLY voltages that the motor drive can enforce across it's A, B and C output lines are +DC Bus, -DC Bus and zero volts. The key point to understand is that as the motor drive modulates, these combinations can never sum to 0 volts between the neutral of the load and ground as shown at V_{NG}. This is in stark contrast to sinusoidally excited, balanced three phase loads, where the ground to neutral voltage is exactly zero, and herein lies the key difference between sinusoidal 3-phase power systems, and pulse-width 3-phase modulated systems.

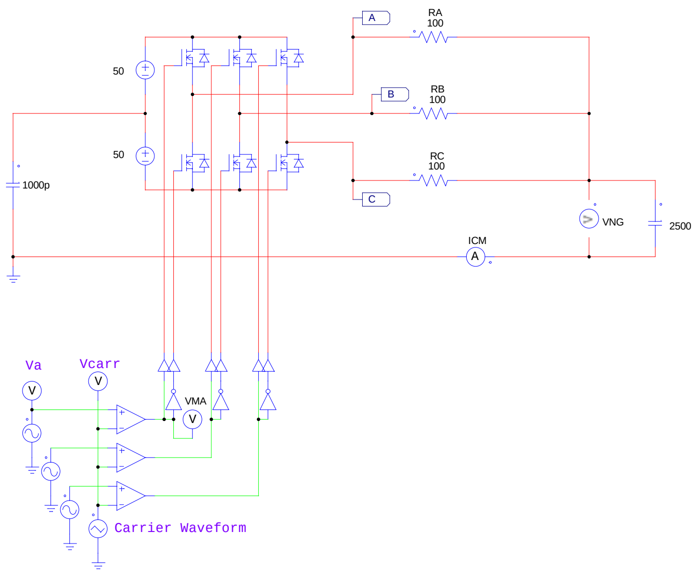

Figure 36 : Simplified circuit for common mode shift

Let us first imagine that the 1000pF (pF = picoFarad – capacitance values) and 2500 pF capacitors in Figure 36 are not present. If one were to measure between neutral of the motor and earth ground in Figure 36, they would see a complex voltage similar to the middle waveform in Figure 37. This "common mode voltage" in itself is not a problem. In this situation, the common mode current (ICM) is zero because the capacitors are zero.

However, the moment any capacitance to ground exists anywhere in the system, then ground return noise currents ICM, begin to flow as shown in Figure 38. Examples of such capacitance are i) stray capacitance in cables, ii) motor chassis to winding capacitance and iii) capacitance from the power circuit to chassis. Note that common mode currents in ii) can often find their return paths through the motor bearings. Micro-arcs in the bearings created by make-and-break operation during rotation while carrying current create pitting and can accelerate decomposition of surface smoothness creating a host of problems. One can easily visualize the high friction resulting from this type of mechanical degradation and the potentially hazardous areas where flammable gases, fluids or vapors may be present. The 1000 pF and 2500pF capacitors in Figure 36 represent ii) and iii) for example.

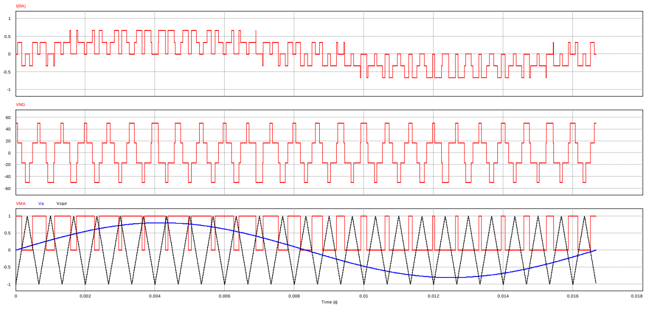

Figure 37 : Top: Motor Drive Line to neutral voltage Middle: Neutral to ground voltage Bottom: IGBT modulation on phase A, all waveforms are shown without parasitic capacitance connected

The currents are called common-mode currents because they flow on all three input lines, as well as the motor lines. (i.e. they are common to all lines, and they return through ground or hull). The exact path these currents take through ground return path is complex and unpredictable. This path is formed by the millions of parasitic capacitances between everything and anything. One can imagine that if anything is changed in a system, like a communications cable, the parasitic coupling path will change. Common mode currents are known to disrupt sensitive electronics including gas detectors, HMIs (operator inference modules), SCR drive controls and cause nuisance tripping. Common mode voltages and currents also interfere with communications and ultrasonic measuring equipment. However, because of their very nature, problems caused by common mode currents can be here today and gone tomorrow. This is why they can be dangerous.

When these currents flow, they produce even greater voltage distortion than harmonics because they are much higher in frequency than harmonics. For example, these currents have large voltage components in the 10-50 MHz range. Consequently, milli-amps of common mode currents can produce large voltage excursions in the same feeder impedances that harmonic currents see. The top waveform of Fig 38 clearly shows voltage overshoot on the motor line-line voltage that is a result of only a few thousand pico-farads to ground, and the high dv/dt of the inverter !

Again since the common mode currents are very high frequency, they couple everywhere they can find a path. Stray capacitance between the chassis walls and internal electronics of all sorts equipment in the plant can couple these currents to disrupt control electronics, whose bias and signal currents are typically easy to disrupt in the milliamp to nano-amp ranges. Worse, if these high frequencies happen to be conducted on cable lengths at multiples of a quarter wavelength they can then radiate, bringing forth radio frequency interference.

Figure 38 below illustrates real-life effects of common mode currents. ICM (common mode current - Trend three) shows how the current spikes are synchronized with the dv/dt limited step-voltage changes on VNG (phase to ground voltage - Trend two). Common mode currents and voltages are not correlated with the line frequency (they are not harmonics) and so appear as unsynchronized noise, often called “grass” in the electronics industry.

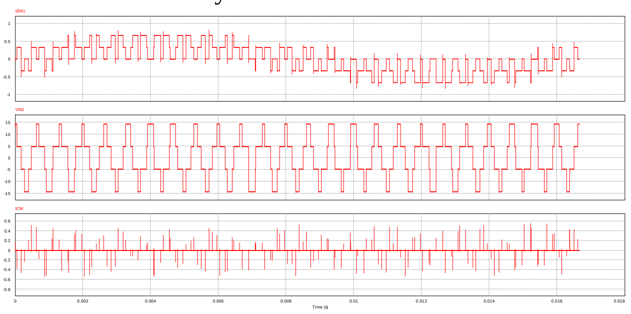

Figure 38 : Top: Motor Drive Line to neutral voltage Middle: Neutral to ground voltage Bottom: ICM ground return current. All waveforms are shown with parasitic capacitance connected

The common mode shift phenomemon is fundamentally caused by the power device switching speeds. The higher the rate of change (dv/dt) of voltage produced by the VFDs inverter power switches, the higher the common mode currents. The higher the parasitic capacitance to ground, the higher the common mode currents. The higher the common mode currents, the higher the voltage distortion. Ironically, the move to higher efficiency power devices has lead them to be designed to switch even faster than in years past, and so the common mode problem is becoming an epidemic in recent times as old drives are replaced with new.

One of the more difficult aspects of conducted common mode currents is that the ground return path these currents follow may not be stable. For example, on oil platforms and drilling rigs, wiring may be modified from time to time. When the grounding system is modified, unintended consequences can occur. For example, an installation may have a particular grounding scheme and cable layout, and a particular brand of motor drive, and it is working fine one day. However the next day for whatever reason, the cable layout is changed, or a newer model motor drive (with higher dv/dt) is added and the ground return path is changed, or a new piece of equipment is added to the system. In this scenario all of a sudden, things start to behave differently. Motor drives run with less stability, other equipment begins behaving erratically, faults circuits begin false tripping. Chaos and confusion ensues as personnel try to figure out what is wrong. This is the nature of common mode noise; Unpredictable consequences! This type of ‘here-today, gone-tomorrow’ behavior are tell-tale symptoms of a common mode noise problem.

This behavior is understood. Military standards have been created that adhere to strict design and test criterion to assure electromagnetic compatibility. This military philosophy has been engrained for many years to assure that problems cannot occur. This is the art of Electromagnetic Compatibility (EMC) at its best. In Europe, EC Directives (European Community legal Directives) are legally mandated to manage conducted emissions like common mode noise, but meeting these directives does not guarantee there will not be problems. For that to be guaranteed both the susceptibility *and* the emissions of *all* equipment at a site needs to be approved. For cost reasons this rarely happens. The philosophy in industry has been that the cost of full “EMC qualification is prohibitive” due to commercial considerations. So often the motor drive vendor and customer collectively and effectively agree to accept substandard performance, until there is a problem. However, in Europe EMC compliance is a legal requirement (since 1992).

We have discussed the background to common mode voltages. Now let us look at some examples of the practical reality. However, before we discuss these it has to be stated that many instances of excessive common mode voltage problems are due to a lack of understanding as to what is required regarding an EMC compliance system by all parties. It costs very little extra to do the job right but has frightening levels of cost (without even considering serious incidents) to do it wrong. However, what is of concern is that the marine classification bodies may not yet realize common mode voltage is a problem which needs rectifying. It is the opinion of the authors that common mode voltage and current measurements during operations should be done along with harmonics and power quality, and should form a part of any marine classification body’s annual survey. Indeed, guidance on installation of VFDs from an EMC perspective should be written into the rules. It should be noted that Military standards such as MIL-461 have already been adopted for many, many years to provide safe EMC compatible equipment for military personnel. The author’s see a stark similarity in industry today compared to the evolution of the creation of Military harmonic and EMC standards nearly 60 years ago. The common denominator is that when high power equipment is combined into small volumes (such as is the case with most military and aerospace systems), eventually the cost of poor power quality becomes intolerable. Today’s power issues with modern commercial vessels and the emerging need for appropriate power quality standards is a similar story repeating itself. As technology evolves, volumes reduce, and power levels rise, the need for strict attention to power quality quickly becomes an absolute necessity and no longer is an option.

5.1. Typical common mode problem

One example of a serious common mode problem is illustrated from a jack-up rig with a drilling package comprising both DC SCR and AC VFD drives. The red trace in Fig 39 represents the Phase 1 to ground voltage when no drilling package VFDs are assigned or running.

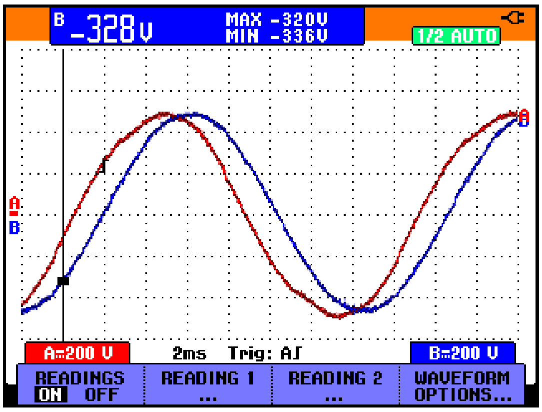

Fig 39 : Red trace represents typical Phase V1 to ground voltage when neither the draw-works and/or top drive VFDs are assigned or running

In Fig 40 below the red trace represents to Phase V1 to ground voltage when either of the drilling package VFDs was assigned or running. The consequences of this was that all deck cranes were rendered dangerous due to the common mode voltage, which increased with VFD loading, interfered with the cranes' electronic control systems. The rig was taken off hire for some weeks until the problem could be resolved; in reality the cranes were isolated from the problem, which still exists, but rig has been now drilling for 18 months.

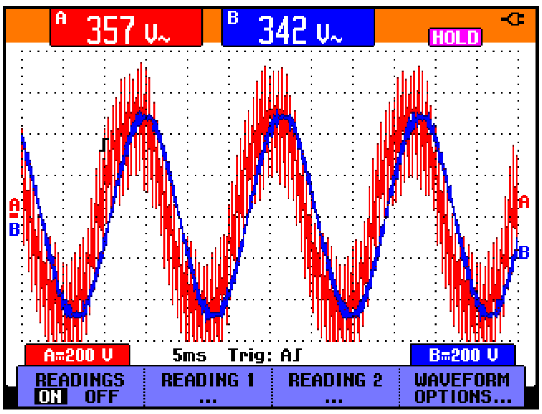

Fig 40 : Red trace represents Phase V1 to ground voltage when the draw-works and/or top drive is assigned or running

During measurements, the source of common mode voltage was established as can be seen from voltage spectrum Fig 41 below. The common mode voltage problem was due to VFD IGBT carrier frequency (1.9kHz) evidenced by 33rd harmonic, >150V to ground voltage seen below. The lesser (26V) 3rd harmonic voltage was benign and due to the paralleled generators dissimilar pitch circulating current. The problem was exacerbated by an extremely poor EMC installation.

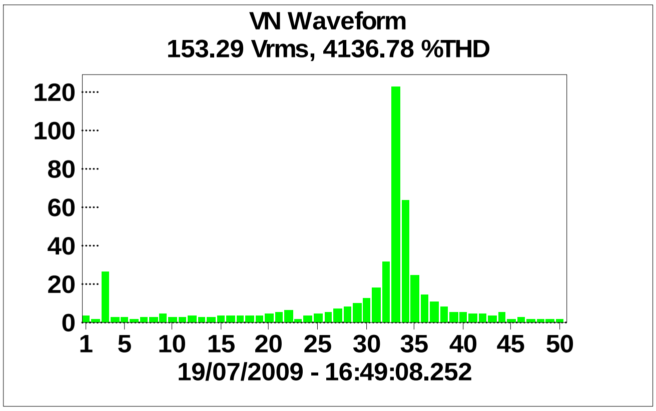

Fig 41 : Phase V1 to ground voltage harmonic spectrum (V) when draw-works or top drive VFDs are assigned or running

The above example is not an isolated case. The authors are aware of four other rigs with similar problems on cranes due to common mode voltage. The Offshore Health & Safety Executive (HSE) in the UK has also seen a dramatic rise in this type of problems since VFDs became more popular.

For comparison Fig 42 illustrates the common mode voltage on a drilling barge which followed during building, to the letter, the guidance for correct VFD EMC installation with respect to cabling, grounding, bonding et al. As can be seen, the generator 3rd harmonic voltage is significantly larger (16.5V) than any of the two VFDs carrier frequencies (6.2V, 1.26kHz – mud pumps) and (2.1V, 2.58kHz - draw-works).

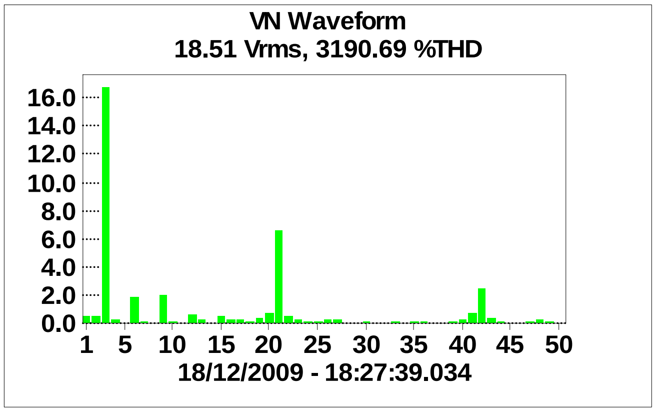

Fig 42 : Phase 1 to ground voltages on EMC compliant VFD drilling package. Note - two VFDs systems running.

5.2. Reduction of common mode voltages

Conventional VFD EMC (electro-magnetic compatibility) type filters, which disrupt the common mode return path to the drive(s), cannot be used on IT networks (i.e. power systems with isolated neutrals) as the EMC capacitors have to be connected to ground; any ground fault would destroy the EMC filter. So called 'floating EMC filters' can be difficult to apply safely.

Most VFD common mode voltage problems can be minimized by following (to the letter) the correct EMC installation techniques. Where this is not possible in situ (i.e. the drive equipment is already installed) special common mode voltage filters are available which, in conjunction with possible installation modifications, can significantly attenuate the common mode voltage.

6.0. Remote power quality monitoring

It should now be appreciated that close and continuous monitoring of power quality is essential to the safety and operational integrity of any installation.

Due to the reduction of costs of electronic equipment and the considerable advances in software over recent years it is now possible to provide small, but powerful remote power and power quality measuring/monitoring/reporting systems at relatively low cost to the drilling and offshore sectors. Systems (Fig 43) can provide data locally to multiple dedicated stations, can be interfaced with rig supervisory systems and, as are they web based, can also communicate with any PC (personal computer) connected to the intranet. They can also be interfaced to DCS (distributed control systems) systems such as Modbus, Profibus and Ethernet. Instantaneous, trend and event recording is provided.

Fig 43 : Example of physical size of remote PQ monitoring system

A remote power quality monitoring system provides continuous monitoring of all power parameters including waveforms and harmonic spectrums :

- Voltage including Uthd/Vthd
- Current including Ithd
- Frequency
- Energy - kW, kVA, kVAr, kWhr
- Displacement power factor (DFP) and true power factor (TPF)
- Harmonic voltages and currents (tables and harmonic spectrums to 63rd)

Remote power quality monitoring systems are powerful tools which can also provide the following facilities including

- Full set of recordings for up to one year.
- Adjustable event recording (e.g. SCR 1 trip) with cycles before and after the event.
- Limit values of each PQ parameter can be set and alarms initiated if required.
- Waveforms of voltage and current for trouble shooting or monitoring.
- Harmonic voltage and current spectrums at point of connection.
- If additional I/O installed, MCCBs can be monitored.

Remote power quality monitoring can provide full information on all the important power and power quality parameters (see examples in Figs 44 and 45) and may provide prior notice of some impending faults. It is connected to either the low voltage or medium voltage systems via suitable PTs ('potential' or voltage transformers) (PTs) and CTs (current transformers). The output can be direct to a laptop or pc, a local monitoring panel or to a Supervisor's office onshore thousands of miles away or to a specialist company contracted to look after the rig or company's power quality.

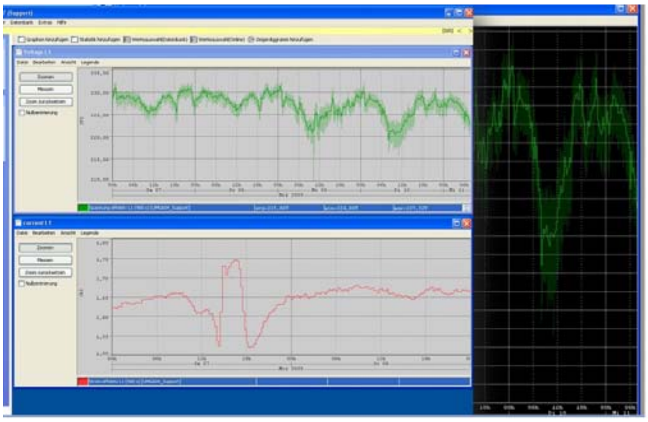

Fig 44 : Example of live trend recording with expanded view on right

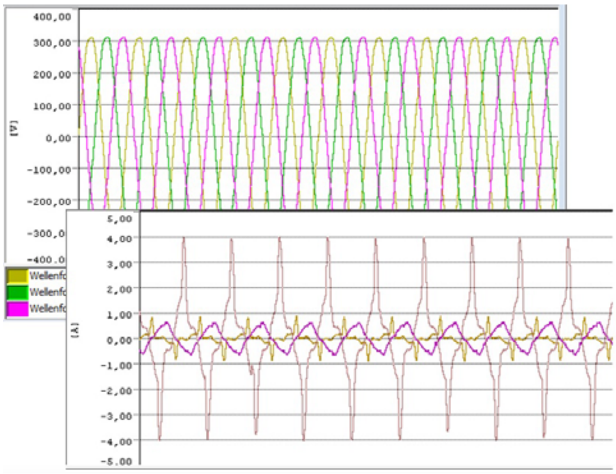

Fig 45 : Examples of live voltage and current waveforms. These can be expanded into single cycle waveforms

If any deviations from the acceptable power quality limits have been detected they can be investigated by local electrical engineers or by shore based harmonic experts.

This type of system can be used with non linear loads to compartmentalise areas of the installation to monitor power quality to ensure power is used most efficiently and that the harmonic currents and subsequent harmonic voltages are maintained at an acceptable level.

Remote power quality systems are a permanent, web based system which remotely monitors all aspects of power and power quality at relatively low cost and therefore can be a valuable tool to the oil and drilling industries worldwide.

7.0. Conclusions

1. It is clear that poor power quality is not uncommon in drilling and offshore industries and that its consequences are very expensive in terms of production and safety considerations.

2. The effects of poor power quality is generally not fully understood or recognized until it is too late. To date the industry has been lucky but maybe not as lucky as it imagines.

3. Power quality is very much taken for granted.

4. Understanding harmonics, line notching (and associated effects) and common mode issues exist to some degree with all AC and DC adjustable speed drives is an important realization that all engineers and managers need to accept and factor into calculations, including safety calculations.

5. Serious consequences exist for excessive line voltage distortion or overheating and disruption caused by harmonics, voltage spikes, or disruptive malfunctions caused by common mode currents.

6. No form of power quality mitigation is perfect; all may require compromises of some kind on site. However, if correctly applied, mitigation will reduce the risks associated with poor power quality to safe and acceptable levels.

7. Understanding and addressing these risks is the only way to ensure that disastrous consequences can be avoided, lest they remain hidden and dormant, only to expose their true effects when least expected. This requires a high level of engineering expertise, combined with an open and honest partnership with the industry and all those within it.

We need to determine where we are regarding offshore power quality and chart the way ahead such that a safe and acceptable level of electrical power quality can be assured for all in the industry, now and into the future. Let us hope this paper is a step in that direction.

Nomenclature

SCR = silicon controlled rectifier
VFD = variable frequency drive
PQ = power quality
AC = alternatively current
DC= direct current
ABS = American Bureau of Shipping
MODU = mobile offshore drilling units
HSE = Health & Safety Executive (UK)
IGBT = insulated gate bipolar transistor
kW = kilowatt
ESP = electrical submersible pump
LV = low voltage (<1000VAC)
MV = medium voltage (>1000VAC)
IEC = International Electrotechnical Committee
Uthd = line total harmonic voltage distortion
Vthd = phase total harmonic voltage distortion
Ithd = total harmonic current distortion
AFE = active front end
X"d = generator subtransient reactance
FFT = full Fourier transform
pF = pico farads (capacitance)
ICM = common mode current
VNG = voltage, neutral to ground
EMC = electromagnetic compatibility
CE = European Union Directive
MCCB = moulded case circuit breaker

References

1. Bourguet S., Guerin P, Le Doeuff R.,, *Non-characteristic harmonics generated by frequency converter*, GE44 , Laboratory, Saint-Nazaire, France, All Electric Ship 2003, Edinburgh.

2. *Guidance Notes on Control of Harmonics in Electrical Power Systems*, May 2006, American Bureau of Shipping.

3. IEC 60034-1, *Rotating electrical machines – Part 1: Rating and performance*, 2004-04, International Electrotechnical Commission IEC 60034-12, *Rotating electrical machines – Part 12: Starting performance of single-speed three-phase cage induction motors*, 2002-04, International Electrotechnical Commission.

4. Evans I C., *Are We Playing with Fire*, Electrical Review (UK), Vol. 221.No 3. Feb 1988. Page 32.

5. Mindykowski J, Tarasiuk T., M Szweda M., Evans IC., *"Electric Power Quality Measurements on an All Electric Ship with Active*

Front End Propulsion Drives", Polish Register of Shipping, Gdynia Maritime University. June 2007.

6. *Offshore Standards, DNV-OS-D201 – Electrical Installations*, January 2005, Det Norske Veritas.

7. *Rules and Regulations for the Classification of Ships*, July 2001, Lloyds Register of Shipping.

8. Evans I C., Hoevenaars A H., *Meeting Harmonic Limits of Marine Vessels*, ESTS 2007, Arlington, VA, May 2007.

9. Evans I C., Johnson J., *Practical Aspects of Applying Broadband Active Filters on Four Applications.* EPQU 2007, Barcelona, Spain, October 2007.

10. Hoevenaars A H., Evans I C., Desai B., *Preventing AC Drive Failures due to Commutation Notches on a Drilling Rig.* PCIC-2009, September 2007.

11. Evans I C., Limpaecher R., *Clean, Innovative DC Power for Marine, Offshore and Subsea Applications using AC-Link Technology*. White Paper. November 2009.