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High frequency harmonics and marine power quality - 20 Nov 2019

Ian C Evans, Principal Electrical Engineer, Harmonic Solutions Marine, a division of Sentinel Power Quality Group FZE, examines some of the issues associated with poor power quality found on vessels today.

An acceptable level of electrical power quality is absolutely fundamental to the functionality, operational integrity, safety of every marine vessel, MODU and installation, irrespective of class. Any failure or malfunction of equipment, including electrical propulsion or navigational systems, could result in an accident at sea, or close inshore, with catastrophic consequences.

High frequency harmonics - Contrary to most international standards and standard power quality analysers' capabilities, harmonic voltages and currents do not conveniently cease at the 50th order (3kHz on 60Hz supply). While these higher order harmonics usually go undetected, their consequences do not !

It will be interesting to see how the impending standard on "supra-harmonics" (2kHz to 150kHz) will be introduced into the marine industry, its resultant impact with regards emissions and immunity of equipment and enforcement are all areas of interest.

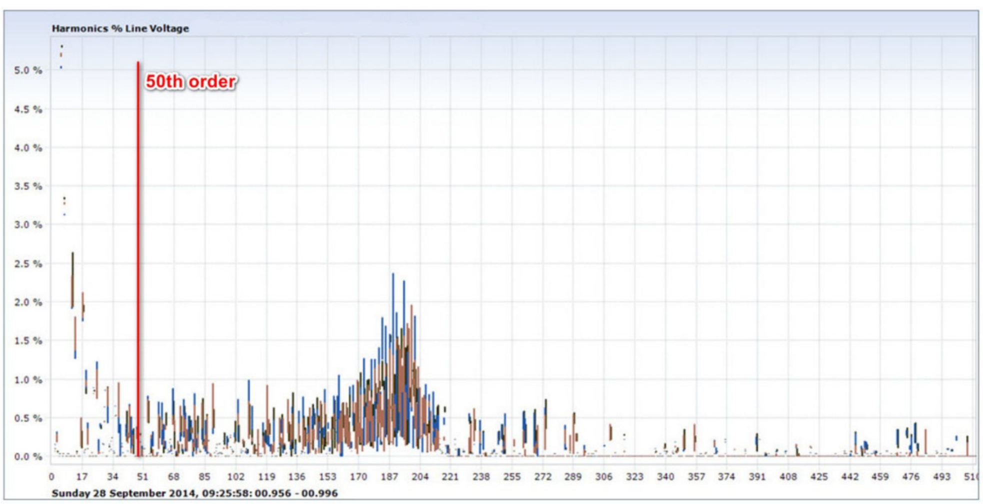

Figure 1 : Total harmonic voltage distortion (Uthd) spectrum from a 560kW variable frequency drive (VFD)

A Uthd of 26.3% (5% limit) was recorded on 600V, 19.3% Uthd of which was >21st (> 1.26kHz) order due to multiple, 24 pulse variable frequency drives (VFD) on 11kV. The spectral data was examined by PTB, Germany to determine the effect on fixed-speed EExd explosion-proof motors onboard. For 'stator critical' motors an additional rise of 24 degrees C was estimated based on harmonic voltages >21st. For 'rotor critical' machines on similar supplies, notably EExe, EExd and ExN protection concepts, hot rotors well above the temperature class and their associated affects may represent a safety risk. PTB were unable to simulate or calculate the additional heating effect on rotor critical machines,

Fixed speed explosion-proof motors – Standard AC explosion-proof motors of all protection concepts are designed and certified based on pure sinusoidal supplies. They lose this certification if the Uthd is >0% - "*they are no longer operating under the conditions envisaged when they were certified*". IEC 60034-1 Standard (electrical machines) contains requirements regarding 'harmonic voltage factor' (HVF). However, IEC-60079-1 (hazardous area equipment) does not currently have any requirement for HVF regarding temperature testing or certification for fixed speed explosion proof motors. This does not necessarily mean they are unsafe, although under certain conditions they may be (e.g. high frequency harmonics in the supply), but simply someone else, rather than the certifying authority, has to take responsibility for their safety.

Large main AC propulsion drives – Many vessels, including cruise ships, utilise electric propulsion, either direct drive or podded, including synchronous drives, usually employing phase shifting transformer solutions to reduce the resultant harmonic voltage distortion (Uthd). Most marine classification societies limit the total Uthd, usually to a maximum of 8%.

Figure 2 : Line voltage, phase voltage and current waveforms for one phase from a vessel with 24-pulse cycloconverter drives, steaming at most economical speed.

Uthd recorded was 13.59%; at higher speeds the Uthd would increase significantly. The 70% increase above the permitted Uthd limit was due to switching/notching voltage harmonics, not normally considered in the rules. A significant proportion of the Uthd impacted adversely on all voltages onboard, raising local Uthd levels and affecting sensitive equipment.

Both cycloconverters and synchronous drives comprise phase-controlled SCR input rectifiers. These have two issues. 'Line notching' due to the commutation process. (Note - the additional notches seen in Figure 2 are due to the phase shifting of the converters). In addition, the reactive power demand is dependent on the control angle of the SCR rectifiers and the motor torque demand(s). Excessive reactive power demand (i.e. low displacement power factor) increases the generator fuel costs. Many vessels employ the use of large multiple, combined passive harmonic filters/uncontrolled displacement power factor correction systems, the manually switched operation can result in generator over-excitation and blackout of the vessel, if left energised at low or intermittent loading.

PWM drives into the fray - Over recent years, pulse width modulated (PWM) VFDs have made an appearance as main propulsion drives, in addition for general purpose applications. Whilst they do not have issues with line notching and reactive power, they do have other issues of concern.

In an active front end (AFE) VFD, an IGBT rectifier replaces the normal 6-pulse diode/SCR pre-charge rectifier. Contrary to what some vendors may say, AFE have still have significant issues to overcome. Increased EMI (including common mode voltage/current), uncontrolled reactive power injection at no, light and intermittent load if multiple AFE drives are operating, causing unstable displacement power factor, harmonic currents above the 50th, lack of performance and lowest overall efficiency of all type of VFD/mitigation options are all issues which are rarely measured or considered under the rules.

Whether the VFD is 6 pulse or AFE type, the current to the motor is a synthesised sinewave. The output voltage being a modulated (i.e. chopped) rectangular (Figure 3) wave. This is the source of most VFD EMC problems.

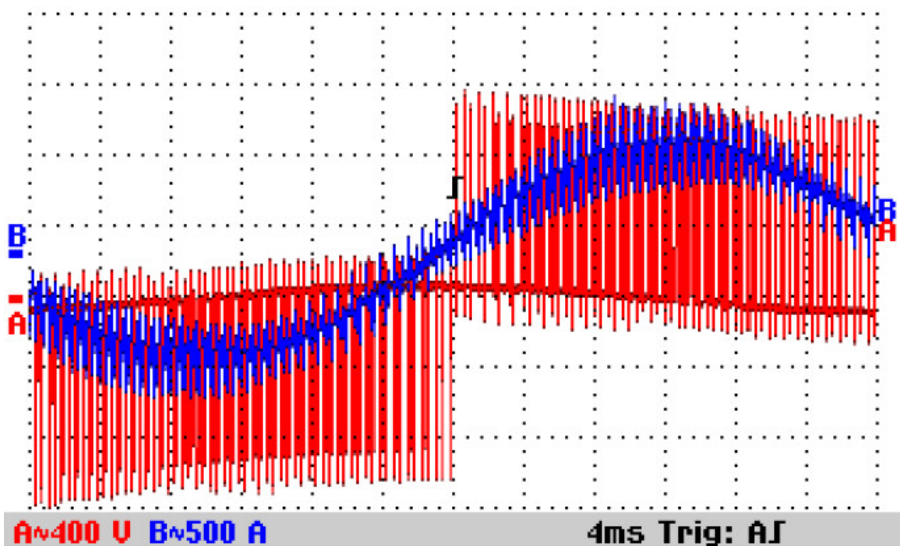

Figure 3 : The output voltage from a motor is a modulated (i.e. chopped) rectangular wave.

Harmonic voltage distortion (Uthd) due to PWM VFDs may require mitigation to be installed, as per any electric drives but there are three separate, but interrelated problems, which continue to affect VFDs:

i) Excessive du/dt (rate of rise of voltage), which can destroy motor insulation, especially on retrofit, energy-saving applications. Burnouts of multiple motors occurred recently various cruise and other vessels.

'ii) Standing waves' (cable resonance) due to long cable lengths (>30-50m). However, sinus output filters, if installed, can prevent this phenomenon.

iii) However, the most challenging aspect of VFDs, rarely mentioned by vendors, presents serious problems to all marine vessels, is that of "common mode voltage" due to the PWM output voltage switching.

Common mode voltage is between each phase and ground. If the VFD-motor combination is not installed in strict compliance with EMC recommendations, the switching frequency (1-10kHz) is superimposed on the phase to ground voltages. Every item of equipment connected to the ground (i.e. the hull) can be affected. We have involved in many marine investigations where CMV was the cause, including PWM propulsion drives failing continually (due to their own CMV) plus navigation, control, cranes and fire and gas detection systems being adversely affected.

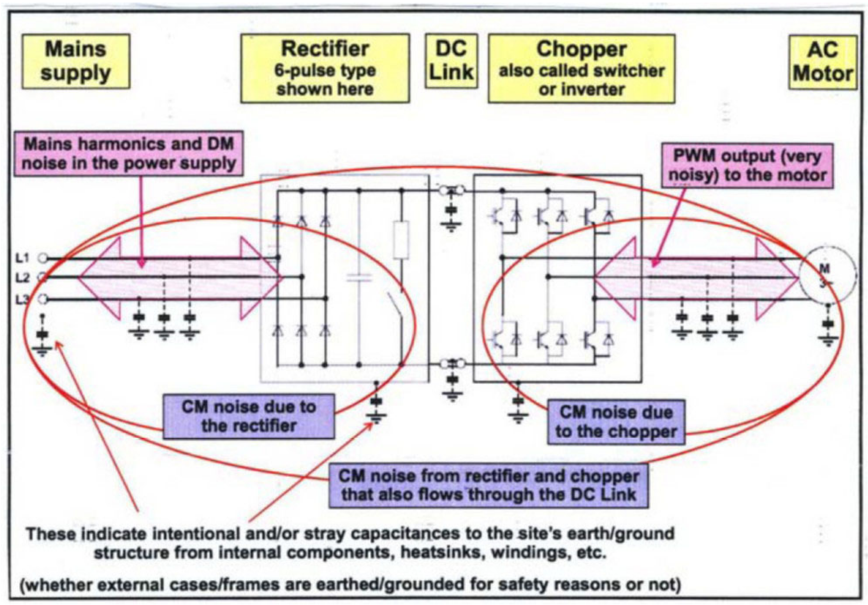

Figure 4 : multiple paths for common mode voltage (CMV) in VFDs.

CMV can be very disruptive and damaging yet not acknowledged officially by the marine authorities. Larger "multi-level" VFDs do not have CMV issues supposedly. Ongoing problems with six Type 45 destroyers, the "World's first electric warships", each having 40MW of multi-level, PWM main propulsion VFDs have up to four times the NATO STANDAG Uthd limit (5%) and CMV circulating around the hulls in kV, suggests otherwise.

CMV has an accompanying common mode current. It travels to the ground from the VFD via the motor bearings, gradually destroying them via micro-arcs of current at the VFD switching frequency. Fixed speed motor bearings in an CMV rich environment is of great concern. We are aware of multiple vessels of the same class, where EExd (flameproof) motor bearings are lasting < 3-4 months due CMV from >40MW of multi-level PWM main propulsion drives. High frequency micro-arcs of current and bearing damage occurring in a Zone 1 area is doubly concerning.

Figure 5: high frequency micro-arcs of current can lead to bearing damage

IACS Harmonic voltage monitoring - In 2017, IACS issued (UR E24) requiring all vessels with electrical propulsion and passive or active harmonic filters to have harmonic voltage monitoring. This followed the MAIB, 'Very Serious Marine Casualty' Report 28/2011', dated December 2011 published some six years earlier, which contained recommendations for power quality monitoring (not just harmonic voltage monitoring). The harmonic voltage monitoring alone it is relatively meaningless unless both voltage and current are recorded so the causes of any excessive voltage distortion can be determined and remedial action taken. In reality however, all vessels with electric propulsion and/or those with a significant electrical drive load both require continuous PQ monitoring.

The IACS directive is aimed at preventing the catastrophic failure of mainly MV passive filter harmonic capacitors. If LV active filters are included in the IACS directive, it could be argued that VFDs, which comprise an almost identical capacitive DC bus, should also be included.

This article addresses a number of issues connected with marine power quality, a subject that will only become more important in the future as more electric and hybrid vessels come into service. It is worthwhile emphasising that all the issues highlighted can resolved or prevented if the correct technical guidance is obtained. There is no reason for shipowners and ship-operators to bear the cost of poor power quality when solutions are available. We plan to discuss some of these approaches in a subsequent article in *The Motorship* in February.

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Ian C Evans is the Principal Electrical Engineer with Harmonic Solutions Marine, a division of Sentinel Power Quality Group FZE and specialises in marine and offshore power quality.

In 2004/5 he wrote the 240-page, ABS publication, "Guidance Notes the Control of Harmonics in Electrical Power Systems". He has also worked under contract for the UK's Marine Accident Investigation Branch (MAIB) and advised HSE Offshore in the UK for 7 years on offshore power quality.

Ian has written many technical papers and including previous editorials for Motorship, Naval Architect, Offshore Engineer, et al.

Harmonic Solutions Marine has many high-end marine clients worldwide.