Maritime and Coastguard Agency

MARINE GUIDANCE NOTE

MGN 449 (M)

ELECTRICAL – Potential Hazards of Excessive Harmonic Distortion of Current and Voltage of Onboard Electrical Systems

Notice to all Shipowners, Ship Operators, Masters and Officers of Ships, Ship Designers, Shipbuilders and Manufacturers of Marine Electrical Equipment

PLEASE NOTE:-
Where this document provides guidance on the law it should not be regarded as definitive. The way the law applies to any particular case can vary according to circumstances - for example, from vessel to vessel and you should consider seeking independent legal advice if you are unsure of your own legal position.

Summary

This MGN alerts interested parties to the potential hazards of excessive harmonic distortion of current and voltage of electrical systems onboard vessels.

Key Points:

- Harmonic distortion can cause various problems including; insulation system degradation and heating of machine windings.
- A good knowledge of the harmonic burden imposed by all electrical equipment is necessary when designing systems, specifying, monitoring and maintaining equipment.
- If left unchecked, harmonic distortion can greatly shorten the life of electrical equipment and cause damage to power systems, which could potentially result in fire.

1. Introduction/Background

1.1 Whilst approaching port a United Kingdom passenger ship suffered a failure of a capacitor in a harmonic filter[1] and the resulting explosion caused extensive damage to the surrounding electrical panels and a total black-out of the vessel.

[1] Harmonic filter: Variable speed motors for electric propulsion or other machinery are supplied by power converters. Switching devices used in power converters result in voltage distortion.
Harmonic filters mitigate the effects of excessive voltage distortion.

1.2 The UK Marine Accident Investigation Branch (MAIB) report[2] identified the explosion in the machinery space was triggered by the failure of a large capacitor within an 11kV passive harmonic filter and that the protection system for the harmonic filter did not work.

1.3 The investigation also identified that there is a need to improve the awareness of the potential risks of high voltage harmonic distortion.

1.4 Historically, vessels have had very few non-linear loads, because of which, harmonic distortion of current and voltage has not traditionally been an issue of concern. However, in recent years, electric propulsion with variable speed AC motors is rapidly becoming the preferred method of propulsion on several types of marine vessels. Variable speed AC motors are also becoming more common as prime-movers for various auxiliary machines. The associated problems with harmonic distortion are therefore increasing.

1.5 It is important that ships' crews gain a thorough understanding of the issue of harmonic distortion, so that they are better able to appreciate the importance of the harmonic mitigation equipment on board and take timely action if such equipment fails or shows signs of deterioration. Where the necessary expertise is not available onboard, experts should be brought in to advise.

2. What is harmonic distortion?

2.1 In simple terms, harmonics are frequencies which are usually odd multiples of the fundamental system frequency. A 50Hz signal would therefore have 100Hz (2nd harmonic), 150Hz (3rd harmonic), 200Hz (4th harmonic) and, in general, n*50 Hz (n^{th} harmonic), where n is a positive integer. In balanced three-phase systems, triple harmonics (i.e. n is divisible by 3) are much reduced or absent. In single phase distribution, third harmonic currents in a common neutral can lead to overheating.

2.2 When an AC electrical load draws non-sinusoidal or non-linear currents, it tends to distort the waveform of the supply voltage. The switching action of power electronic devices in the power converters results in non-sinusoidal currents being drawn from the generators. While the supply originally delivers a 'clean' sinusoidal voltage at the fundamental frequency of 60Hz the power converters, in drawing a distorted current, cause the supply voltage from the generators to become non-sinusoidal. This generates voltages at the harmonics of the fundamental frequency, which in turn affect all the connected loads regardless of whether they are linear or non-linear.

2.3 In marine and offshore installations, variable speed drives are the main source of harmonic distortion to current and voltage waveforms.

2.4 An effect of harmonic currents is waveform distortion (notching or deviation from the desired sine wave). This effect can occur even if the overall total harmonic distortion is within specification.

3. How do you know if you have harmonics in your electrical system?

3.1 If you occasionally experience some unexplained occurrences such as flickering lights, alarms going off, or MCBs, MCCBs, RCDs and Earth Leakage devices tripping for no apparent reason, you are most likely experiencing harmonics in your electrical environment.

3.2 Other signs are cables running hot, hot switchboards or overheating motors.

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[2] MAIB Report No. 28/2011 – RMS Queen Mary 2 – http://www.maib.gov.uk

3.3 If you are suffering frequent damage to motor bearings & insulation, it is a strong indication of the presence of harmonics.

3.4 UPS units may come into operation unexpectedly, due to waveform distortion.

4. What are the effects of harmonics in your electrical system?

4.1 Some of the common and unpredictable effects of excessive harmonic distortion on marine installations include :

- Overheating and sustained damage to bearings, laminations and winding insulation on generators, transformers and induction motors causing early life failure, which could potentially result in fire.
- Overheating of the stator and rotor of fixed speed electric motors; risk of bearing collapse due to hot rotors. This is especially problematic on explosion proof motors with increased risk of explosion, more especially with ExN (non-sparking motors).
- Failure, tripping or overheating of capacitors, filters and related equipment.
- Overheating of cables and additional risk of failure due to resonance. Harmonics also decrease the ability to carry rated current due to 'skin effect', which reduces a cable's effective current-carrying cross sectional area.
- Disruption in the operation of uninterruptible power supplies (UPS).
- Spurious tripping or failure of sensitive electronic and computer equipment, measurement and protection relays.
- Voltage resonances leading to transient overvoltage and overcurrent failures in the electrical network.
- Filters fitted to equipment for electromagnetic compatibility or transient suppression may suffer overheating or failure due to them absorbing system harmonic currents.
- Electro magnetic interference (EMI) resulting in disruption to communication equipment.
- Malfunction of circuit breakers and fuses.
- Greater than normal earth leakage current detection as a result of common mode voltages.

5. Total harmonic distortion (THD)

5.1 Total harmonic distortion (THD) of voltage and current is the ratio used to describe the distortion in the electrical power generation and distribution system. It is calculated by the ratio of the root mean square (RMS) value of the harmonic content to the RMS value of the fundamental. It is normally expressed as a percentage.

5.2 Lloyd's Register's rules on harmonic distortion of voltage state:

> *Unless specified otherwise, the total harmonic distortion (THD) of the voltage waveform at any a.c. switchboard or section-board is not to exceed 8 per cent of the fundamental for all frequencies up to 50 times the supply frequency and no voltage at a frequency above 25 times supply frequency is to exceed 1.5 per cent of the fundamental of the supply voltage.*

Some other classification societies place a limit of 5% on THD of voltage (THDv).

5.3 The Institution of Electrical and Electronic Engineers' (IEEE) Recommended Practice for Electrical Installations on Shipboard (IEEE Standard 45-2002), states:

> *A dedicated propulsion bus should normally have a voltage total harmonic distortion of no more than 8%. If this limit is exceeded in the dedicated propulsion bus, it should be verified by documentation or testing that malfunction or*

overheating of components does not occur. A non-dedicated main generation/distribution bus should not exceed a voltage total harmonic distortion of 5%, and no single voltage harmonic should exceed 3%.

5.4 IEC 60092-501, Electric Propulsion Plant states:

For the propulsion network the total harmonic distortion (THD) value of the voltage shall not exceed 10 %. If a THD-value of 10 % is exceeded, the person responsible for the propulsion system, see 4.2, shall ensure interference-free operation of all connected equipment. If the propulsion network and the ship's network are directly connected the THD value of the voltage shall not exceed the values stated in IEC 60092-101.

5.5 IEC 60034-1, Rotating Electrical Machines - Part 1: Rating and Performance, requires that the THDv for synchronous motors above 300kW output should not exceed 5%. It does not specify distortion levels for individual harmonics.

5.6 Whilst there are variations in the accepted limits for THD, keeping THD values to the lowest level on a system will further ensure proper operation of equipment and a longer equipment life span.

6. Methods of mitigating total harmonic distortion (THD)

6.1 The predominant harmonics that are expected to occur in the electrical power conversion systems are calculated at the design stage.

6.2 Keeping low THD values on a system will further ensure proper operation of equipment and a longer equipment life span.

6.3 There are several methods used to counter the effects of harmonic distortion in marine power systems, including:

- Adding of a line-reactor and/or DC bus choke.
- Active or passive harmonic filters.
- Increasing the number of pulses in power converters by using multiple phase shifted secondary windings in propulsion motor supply transformers
- Installing generators with a low sub-transient reactance.

7. Power quality measurement

7.1 Land-based utilities monitor their power quality as a matter of routine. In a marine vessel where harmonic distortion has the potential to disrupt its electrical network, possibly leading to a blackout and loss of control in restricted waters, the need for power quality surveillance is even more significant.

7.2 Regular monitoring of power quality, using a pre-determined pattern of propulsion motor loading, with a complete record of operational parameters, could help ensure that the harmonic distortion levels on board are closely monitored as the vessel and its equipment age and vessel operating profile changes.

7.3 An on-line monitoring system, that records all the parameters and can be triggered to make specific recordings of transient voltage spikes or resonances, would be invaluable in assessing the ongoing quality of power. It would also be a very useful tool to investigate the root cause of accidents caused by anomalies in the electrical network and to identify incipient faults in these systems.

8. Glossary and definitions

MCB	Miniature circuit breaker
MCCB	Molded case circuit breaker
RCD	Residual current device
Capacitor	An AC device that stores energy in the form of an electric field
Reactance	The resistance to current flow in a capacitive circuit is called capacitive reactance while the resistance to current flow in an inductive circuit is called inductive reactance
Resonance	The propensity of a system to oscillate with increasing amplitude, limited only by the system's damping characteristics. Resonance occurs only at certain frequencies and is often triggered by subtle and minor changes in the system
Single harmonic	The single harmonic content of a voltage wave is the ratio of the effective RMS value of that harmonic to the RMS value of the fundamental expressed in percent. (Ref: IEC 60092-101, 1.3.24.2)
Thyristor	A semiconductor device used to switch large amounts of electric power with a small triggering current or voltage
Total Harmonic Distortion (THD)	The ratio of the RMS value of the residue, after elimination of the fundamental, to the RMS value of the fundamental expressed in percent (Ref: IEC 60092-101, 1.3.24.1)
Transient	A short-lived oscillation in a system caused by a sudden change of voltage or current or load

9. References

IEC 60092-101, Electrical installation in ships - Part 101: Definitions and general requirements

IEC 60092-501, Electrical installation in ships - Part 501: Special features - Electric propulsion plant

IEC 60034-1, Rotating Electrical Machines - Part 1: Rating and Performance

IEEE Std. 45-2002, Table 4: Alternating current (AC) Power Characteristics

IEEE Std. 519-1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems

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