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Critical aspects of electromagnetic compatibility on board ships

V Dobref[1], I Ciocioi[2], V Mocanu[3], F Deliu[4], L Pană[2], E Dragomir[2]

[1]Professor PhD eng., Naval Academy ”Mircea cel Bătrân”, Constanța, RO
[2]Lecturer PhD eng., Naval Academy ”Mircea cel Bătrân”, Constanța, RO
[3]University Assist. PhD Candidate, Naval Academy ”Mircea cel Bătrân”, Constanța, RO
[4]Associate Professor PhD eng., Naval Academy ”Mircea cel Bătrân”, Constanța, RO

E-mail: dobref_vasile@yahoo.com

Abstract: The electromagnetic environment on board a military ship is a bounded space with disturbance sources and receivers. It is defined by the maximum disturbance levels in each interior compartment and on the ship's decks. The electromagnetic environment on board a ship is extremely complex, as it depends to a large extent on the density of equipment on board, the characteristics of the equipment installed (frequency bands, power, modulation types, etc.), the measures to prevent electromagnetic radiation pollution taken by designing the ship in such a way that the electromagnetic field strength inside the ship is as low as possible, with reduced risks to the normal operation of the equipment on board and to the personnel on board. The installation of radars in the on-board electromagnetic environment requires an analysis of the electromagnetic compatibility standards that apply to them. To prevent electromagnetic interference in such systems involves describing the composition of the environment and the interaction between different components. The paper presents a risk-based characterisation of the on-board electromagnetic environment for electromagnetic compatibility analysis.

Keywords: electromagnetic environment, electromagnetic interference, electromagnetic radiation, shielding effectiveness, noise, coupling

1. Introduction

The complex technological evolution of equipment and installations on board ships is unfortunately also accompanied by an increase in the problems created by electromagnetic interference. The effects of electromagnetic interference are disruptive not only to personnel but also to onboard installations and are often a factor in increasing costs. Tackling this complex issue involves at least two categories of activities: identifying the sources and levels of electromagnetic disturbances and interference, and comparing them with the standards and rules introducing compliance with the standards. Thus, tests, test conditions, and permissible limits of disturbances must be defined in standards to ensure compliance with the equipment to be installed. However, the issues are complex and equipment standards do not always correspond to the parameters of the environment in which the equipment will operate, because the definition of limits is most often based on adopted practices rather than on rigorous scientific substantiation.

Moreover, standards have a certain periodicity of updating, which is not fully aligned with new technological developments (e.g. use of frequencies not covered by standards, such as radars operating in the GHz range), so the rules-based approach sometimes becomes insufficient for analyzing the influences of electromagnetic interference. One approach that compensates for some of the limitations mentioned above would be the risk-based approach. The risk-based approach has been endorsed and adopted by the Register of Classification and Certification for Shipping, Lloyds [1].

It has been applied in the naval shipbuilding process of military vessels. The risk-based approach can ensure that commercially available systems could be safely integrated onboard ships, leading to lower installation costs on board seagoing vessels.

In [2], [3] and [4], the potential use of a risk-based approach to solve the problem of electromagnetic interference in complex naval systems is described. New standards are being developed to promote the use of the risk-based approach in realizing EMC, e.g. IEEE 1848 [5]. This paper details the risk-based approach and the stages of implementation. To successfully follow this approach, it is necessary to first understand the electromagnetic (EM) environment of the complex system. This paper reviews the electromagnetic environment on board modern ships as a risk-based approach to EM. To survey the discrepancies and to prepared recommendations, the paper also focuses on the determination of the electromagnetic environment on board ships, highlighting the restrictions of the standards-based approach, which is based on standards, and suggesting a risk-based assessment approach.

2. Interference on board ships - general characterisation

Interference from electromagnetic sources is a threat on board ships where several specific types of equipment are installed, such as power electronic converters, switchboards, power supply panels, dedicated digital circuits, radio navigation systems, radar antennas, etc.

In addition, long routes cable for power supply (low or high voltage) and other sources emitting electromagnetic radiation must be taken into account. Couplings between different antennas and conductors give rise to uncontrolled and unwanted fields. It has also been observed that near-field sources on board ships can affect other equipment as well as shipboard personnel, in frequency ranges between 1 KHz and 30 MHz. In many situations, even access stairs on decks, hatchways, and deck weight handling facilities can become radiating mediums that cause electromagnetic and static discharge injuries.

Throughout the life cycle of a ship, it is never fully checked for electromagnetic compatibility. Moreover, ships are frequently overhauled and repaired, so component changes, shielding modifications, additional wiring, and many connections and joints are exposed to the environment. The efficiency of insulation resistance also reduces over time.

Tests carried out by medical organizations, published in the literature, as well as work-related incidents observed during medical tests on embarked personnel have shown that some of the unexplained causes of major injuries to human internal organs are the consequences of shock or radiation effects due to electromagnetic waves. Frequencies above 1 GHz up to 33 GHz can cause serious injuries to embarked personnel, and in practice, most people on board ships work in the vicinity of such dangerous emitters, unaware of the consequences. This explains some of the injuries that maritime health specialists and occupational safety experts have regularly mentioned in scientific reports and studies.

3. Experimental evaluation of the electromagnetic environment on board ships

The electromagnetic environment of a ship can be structurally described by different subsystems, such as radio communications and navigation equipment, power generation and distribution system, propulsion system and electronic control and power converters of electric motors, high impulse power radar systems, electrical machinery control system and electrical machinery switching systems, interior communication system and digital systems, hull, mechanical, hydraulic, hydropneumatic systems, etc [6]. All of these subsystems have electrical and electronic equipment that generate signals that can potentially interfere with the normal operation of other systems, affect performance, introduce errors or malfunctions, or even cause total component failure.

Therefore, the correct location and testing of equipment on board a ship is vital for the proper day-to-day operation of the ship and for optimizing the performance of the equipment on board.

The final objective of the ship's electromagnetic environment assessment is to establish measures, technical or administrative, to reduce the impact of electromagnetic disturbances on shipboard personnel and installations, more specifically without causing unreasonable disturbances to the activities in the ship's specific environment [7]. This involves preventing high-level disruptive interference by reducing or deflecting signals that could interfere with the operation of other electronic equipment.

Shipboard disturbance interference is characterized by voltages, currents, magnetic fields, electric fields, and electromagnetic fields, transmitted continuously (including modulated) or transiently. Different areas on board ships have different signals, depending on the specific subsystems that are placed in these areas. Limits between these areas will determine how the interference levels differ and therefore impose certain solutions needed to mitigate the coupling. These zones comprise, for example, the outer bridge and the outer regions of the bridge for which lightning threats and strong EM fields from transmitters may interfere. Other areas include the regions above the deck and below the deck. Experiments carried out on board some marine vessels [8], provide the possibility of data-driven analysis of such effects so that the real state of the electromagnetic radiation spectrum on board two vessels, one for marine research and one for passenger transport, can be assessed.

Measurements for noise and field coupling were carried out using specific equipment, spectrum analyser-Agilent, range: 100KHz - 3 GHz; for the electric field ANRITSU sensors were used, range: 470 MHz -1.7GHz; for the magnetic field ANRITSU probes in the range: 1-50MHz, 5-1000 MHz; microwave amplifier Agilent, frequency range: 10 MHz - 26.5 GHz. Fig. 1 and 2 show the spectra recorded from measurements on the marine research vessel, stationary and underway respectively.

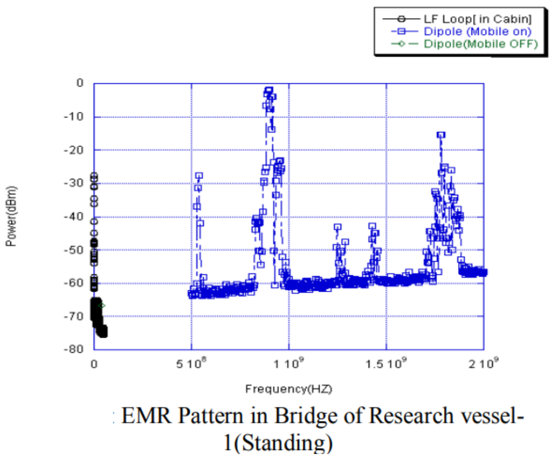

Figure 1. Electromagnetic spectrum on the deck of a stationary marine research vessel

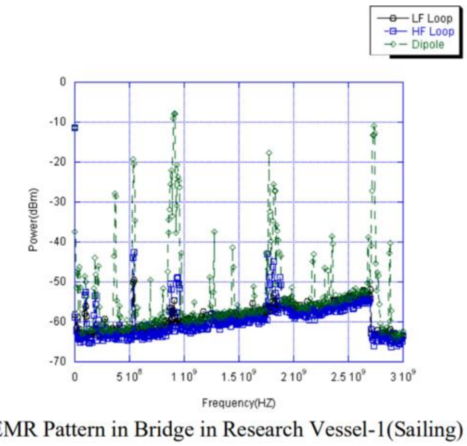

Figure 2. Electromagnetic spectrum on the marine research vessel deck measured during the voyage

Analysis of the recordings shows that the shipboard personnel on the deck of the vessel are exposed to high levels of electromagnetic radiation, mainly due to the density of electromagnetic waves produced by wireless communications and navigation signals. The recorded power levels are quite high, which leads to safety concerns for shipboard personnel.

The dominant electromagnetic radiation polluting the command deck of the marine research vessel is almost 106 times higher than the ambient electromagnetic radiation recorded in the other areas where sensors have been installed. In voyage, the radiation level can be reduced, but not more than 10 times, as shown in Fig. 2.

Measurements made [8] in the machine compartment, where the volume is much smaller, show a reduction in the contrast between the predominant and ambient radiation, as shown in Fig. 3, to only 15 dB, indicating that the dominant radiation is mainly from communication sources. In contrast, as shown in Fig. 4, near a transformer the communication sources produce higher radiation, by approx. 60 dB stronger, indicating a shielding failure.

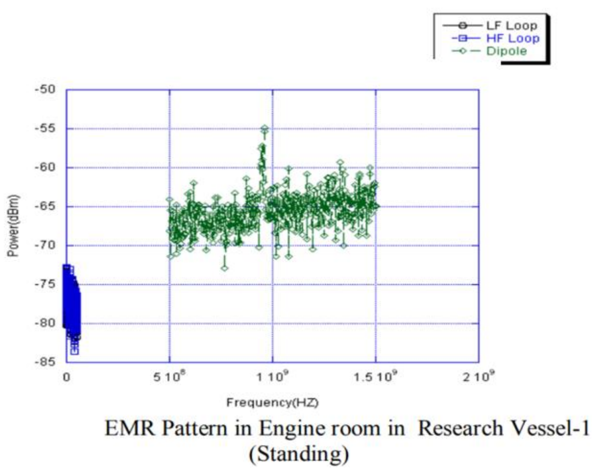

Figure 3. Electromagnetic spectrum in the engine compartment of a stationary marine research vessel

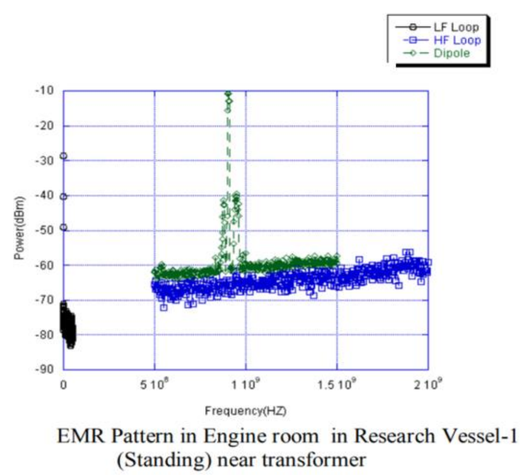

Figure 4. Electromagnetic spectrum in the engine compartment of a marine research vessel measured near a transformer

Other experiments, carried out on marine research vessels with larger displacements, have confirmed similar trends [8]. By simply switching on the equipment on the ship's deck the ambient level is amplified by 10 dBm of power, which dangerously increases the radiation level to which the embarked personnel are subjected. Experiments carried out on a passenger ship show similar trends [8]. Interestingly, however, in this case, both on the ship's deck and in the machinery compartment the radiation levels recorded are similar. Thus, it can be estimated for the radiation level to which passengers are exposed 20 dBm as a characteristic value.

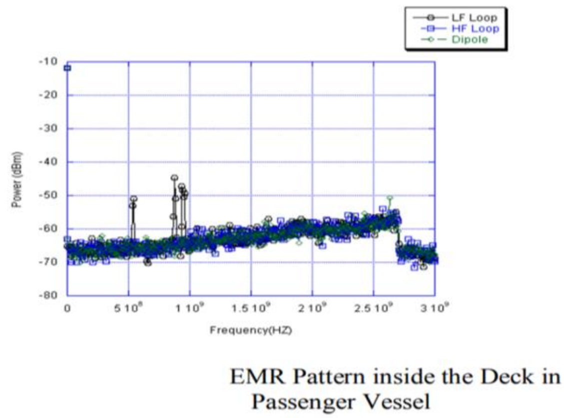

Figure 5. Electromagnetic spectrum on the passenger ship deck

The results show that the action of the radiant field can lead to injury to the shipboard personnel, through shocks or other effects on internal organs, which can range from minor inconvenience to serious consequences, or affect the normal operation of installations such as interruption of communications, interruption of electrical power supply, voltage shocks in the ship's electrical network, failure of navigational instruments, etc. It should be noted that the ships on which the experiments were carried out did not meet the requirements of any EMC standard. Navigation and communication systems are considered adequately protected if they comply with EN 50000-1-2-3 or DNV standards. We consider that a safety index of the highest level would be full compliance with DNV standards. The terms of reference were in accordance with: shielding, electromechanical devices, fuse components, wiring, and earthing. The equipment can be classified as in Table 1.

Table 1. Classification of equipment as per radiation levels

Class	Margin	Consequence of disturbance
0	0dB	No harmful effect
1	6dB	Equipment that have some consequences and harmful effect
2	10dB	Equipment which can lead to injury, effect on safety
3	20dB	Equipment with major effect on personnel, vessels safety

On such ships, there is also a need to raise the awareness of shipboard personnel of the harmful effects of microwave radiation and to raise the awareness of shipowners to ensure that measures are taken to protect seafarers against the harmful effects of electromagnetic disturbances. These effects are summarised in Table 2.

Table 2. A complete resume of biological effects of microwave damaging levels

Frequency MHZ	Wavelength(cm)	Site of major tissue effects	Major biological effects
100	Above 200	Not established- Probably whole body	General warming of exposed areas (used in Diathermy)
150-1200	200 – 25	Internal Body Organs	Damage to Internal Organs from Overheating
1000 – 3300	30 – 10	Lens of the Eye	Lens of the Eye particularly susceptible and tissue heating
3300 – 10000	10 – 3	Top layers of the Skin, Lens of Eye	Skin heating with the Sensation of warmth
10 – 100 GHZ	Less than 8	Skin	Skin surface acts as reflector or absorber with heating effects
* Damaging levels vary with frequency, ambient temperatures, and individuals. Safety criteria establish levels above 10 MW / cm^2 at any frequency as being unsafe.			

On the other hand, the experiments presented above clearly show that radiation from certified equipment was propagating due to shielding defects. In addition, there is significant radiation from unintentional sources, which can seriously affect crew members and passengers.

A ship can be subdivided into different zones in terms of electromagnetic radiation emissions. These areas are physically divided by electrically conductive materials or partitions. The material that separates the various areas can determine how the electromagnetic environment behaves in terms of radiation levels. All these areas are distinguished by various types of interference that couple to potential victims via a radiation pathway, a conducted pathway or a mixture of the two, with the interaction between an electromagnetic radiation source and a victim only taking place via a coupling pathway. Without a coupling path, there is no interference condition, therefore, interruption of this path is necessary to ensure protection against electromagnetic disturbances. The coupling path can be conductive or radiant. To achieve electromagnetic compatibility, one of three elements must be removed. For intentional sources, whose presence and normal operation are assumed to be unconditional, the elimination of the source cannot be considered and therefore the coupling path must be interrupted or the victim protected, in order to maintain the level of electromagnetic radiation at non-hazardous values, and therefore the proper operation of the vessel [9]. Mitigation can be achieved by several methods: shielding, isolation of equipment, grounding, use of shielded cables, use of filters, etc. The nature of the interference helps to determine the mitigation measures to be taken to protect personnel and facilities. In this sense, the characteristics of electromagnetic environments are described in terms of:

- Frequency bands used;
- the maximum noise level in the operational frequency bands;
- the transmitted signal power levels;
- the characteristics of the used antennas, their polarization, directivity and gain;
- the choice of distribution network (isolated, grounded, DC or AC, etc.);
- construction materials used;
- types of cables used.

Conducted emissions involve coupling interference through cables and conductors. On a ship, there are emission and reception of electromagnetic, made with power semiconductors, which produce electromagnetic emissions through switching phenomena at high frequencies, resulting in the loading of the electro energetic environment with voltage and current harmonics.

In addition, transmitters on the upper deck of a ship can also be a major cause of radiated interference because a ship is dense and compact with different sets of antennas and electromagnetic sensors for communications, navigation, detection, steering, and radiolocation. [10], [11].

Basic measures for electromagnetic compatibility include intelligent frequency selection, the use of band-pass filters, etc.

The electromagnetic environment of a maritime vessel is characterized by receivers using high frequencies (VHF) between 156-165 MHz, high frequencies in the case of operating high-power navigation radars (GHz range), long-range high-frequency (HF) communication transmitters, respectively, and high-power electrical machines. Table 3 gives an overview of some of the equipment installed on board ships and the frequency bands in which they operate. The functions of these different systems and/or equipment are presented in [12]. Communication systems and maritime radar systems are largely affected by electromagnetic compatibility issues due to the sensitivity of communication equipment.

Table 3. Overview of maritime communication systems and frequencies of operations

System/Equipment	Frequencies
Digital selective calling (DSC)	MF/HF DSC: 2187.5 kHz, 4207.5 kHz, 6312.0 kHz, 8414.5 kHz, 12577.0 kHz, 16804.5 kHz VHF DSC: VHF marine channel 70 - 156.525 MHz
Voice and data communication	1.6 MHz - 26.5 MHz
Narrowband Direct Printing (NBDP or radio telex)	1.6 MHz - 26.5 MHz
Navigational Telex (NAVTEX)	518 kHz, 490 kHz and 4209.5 kHz
VHF other than DSC	156.025 MHz - 162.025 MHz
Automatic Identification System (AIS)	156 MHz –163 MHz AIS 1 161.975 MHz AIS 2 162.025 MHz
Satellite Voice and Data Communication (UHF)	Satellite comms: 406 MHz Inmarsat C: 1626.5 MHz -1645.5 MHz Inmarsat GX 26.5 GHz - 40 GHz high capacity overlay Iridium (Pilot) Ground users – 1616 MHz – 1626.5 MHz (L-band) Terrestrial gateway 29.1 GHz – 29.3 GHz
Terrestrial communication technologies using the UHF/SHF band	4G – LTE Advanced at 2.6 GHz 5G SHF – at 6 GHz and above
RADAR SART, X-Band RADAR S-band	Radar X band - 2.9 GHz -9.5 GHz Radar S-band - 2.9 GHz -3.1 GHz

4. Standards-based approach

The standards-based approach is to use standards as guidelines, based on the assumption that meeting the requirements of a standard guarantees that no dangerous interference will occur. In the case of seagoing ships, the basic EMC standards include IEC 60533 [13], which covers electrical installations on metal-hulled vessels, and IEC 60945 [14], which describes EMC regulations for radiocommunications and navigation. In the rules-based approach, any marine electrical installation on board ship must comply with either IEC 60945 or IEC 60533 (this includes deck-mounted equipment, radio communications, and navigation equipment). These are basic standards describing emission tests and immunity tests.

However, the EMC standards mentioned above have some limitations. These limitations make them insufficient to guarantee permitted levels of the electromagnetic environment on board ships at all times, in all situations and circumstances. For example, because of the threats posed by the upper deck (outer deck) densely populated with radars, radar, and communication antennas, the levels in the standards are often insufficient and do not cover all sources of radiation. In the IEC 61000-4-3 standard for radiated immunity tests [15], there are requirements to measure radiated interference only up to a frequency of 2 GHz.

However, as shown in Table 1, there is equipment installed on board ships that operate beyond these limits, e.g. radars and satellite communications, satellite communications equipment, etc. Then, the reference standards do not fully take into account the details and continuous changes in the given environment, such as the aging of insulation, current repairs, and overhauls, evolution of technology, etc.

The new VHF Data Exchange System (VDES) standards are being developed to meet the growing need for data communication between maritime users and due to the significant increase in the number of VHF data links with the increasing use of Automation Identification System-AIS, which should provide higher data transmission speeds.

The following are some examples of the interferences in sophisticated naval systems and the main arguments why these standards are inadequate to avoid such interferences.

A. AIS reception interference.

On a modern ferry, it was not possible to acquire AIS for distances greater than 8 nautical miles [16]. Because of the disturbed frequency band, the whole onboard lighting installation was affected. To overcome the issue, the supplier was asked to provide other types of lights with other types of power sources.

B. Influence on a DGPS (differential GPS) receiver.

On a newly built ship, reception of the DGPS signal was not possible due to emissions from an air conditioner and some components in switchgear with inadequate grounding [16]. After the grounding was remedied and the air conditioner was turned off, the DGPS signal was no longer interfered with.

C. Interference of a satellite TV reception on a seagoing vessel.

A distortion of satellite TV reception was reported in [17]. The satellite reception band used was at 3.4 GHz to 4.2 GHz, while the installed radars were operating at frequencies between 3 GHz and 9 GHz. This interference is of course caused by the lack of frequency selectivity of the satellite and satellite communication equipment.

D. Initiating accidental firing of munitions from an aircraft.

In 1967, a military aircraft was exposed to interference from a naval radar, which caused the onboard weapons system to accidentally fire its ammunition, hitting another armed aircraft on the outer deck of the same ship. This accident was the result of an unfortunate case of disruptive electromagnetic interference, as investigations showed that degraded cable insulation from the first aircraft caused emissions that interfered with the radar and therefore the operation of the aircraft, causing a malfunction. Other sources reported that one of the pilots activated the aircraft's radar and then a missile was launched prematurely. Several fatalities resulted from the accident [17].

E. Effect of LED emissions on VHF reception.

There have been reports of poor VHF reception on board ships due to emissions from onboard LED lights installed in the vicinity of such receivers [18]. One such example describes how the maritime rescue coordination center in a port failed to contact a vessel involved in an incident in a traffic separation scheme, by VHF radio. The vessel in question also experienced very poor AIS reception. Other vessels in various ports reported degradation of VHF receivers, including AIS, caused by their LED navigation lights.

LED lighting installed near VHF antennas has also been shown to degrade reception. Another reported case even describes ships disappearing from radar, the event is caused by interference from LED light emissions [18]. These examples describe the context in which unsafe situations are created, as communication is essential between ships, i.e. between ships and shore.

F. Walkie-talkie interferes with the ship's steering, causing a minor accident, or minor collision. An incident occurred outside the United Kingdom (UK) in which a minor collision occurred between a supply vessel serving an offshore semi-submersible tanker.

The ship registered a sudden increase in power caused by the interaction between radio signals from a handheld VHF radio and the control joystick [19].

The incidents presented demonstrate that the rules-based or standards-based approach does not guarantee the avoidance of unwanted electromagnetic interference.. More and more organizations, such as Lloyd's in Europe, are considering the risk-based approach as a way to take into account different environmental factors.

5. Approaching problems caused by electromagnetic interference on a risk basis

The risk-based approach refers to the actual operation in the specific environment of equipment, such as high-frequency electromagnetic fields on the upper deck of the ship, or protection against indirect lightning strikes, for example. The approach involves identifying sources and victims. It defines mitigation measures where necessary and requires testing of the effectiveness of mitigation measures as well as validation of the proper functioning of equipment. In this approach, risks must be assessed and appropriate mitigation measures implemented. In [20] and [21] four main actions for implementing the risk-based approach are presented.

EMC control plan of risks and measures related to electromagnetic compatibility: contains an important part of the control of identified risks and the definition of mitigation measures. It defines best practices for risk mitigation and how to translate them into procurement specifications for the parties involved. An input to this plan is the electromagnetic threats and operational requirements from customers, combined with the specifications of the equipment to be used on board. To identify the different risks and threats, a source ”victimization” matrix is constructed.

EMC Implementation Plan: This plan explains in detail how the control plan is to be implemented. For example, it specifies details on how to lay out cables, distances to be kept in performing specific tests, correct procedures for mounting certain devices and components, etc. The reference defining the limits is given in [22], also the application limits are defined. At each boundary interface, the appropriate electromagnetic field attenuation to be implemented is applied. This can be filtering or adding a shielded cable around the circumference. Rough electromagnetic environments require shielded cables that are installed through solid metal tubes or even prohibit the use of cables in the exposed environment. This can be achieved by designing equipment so that the shielding metal structure is mounted immediately on the deck.The power supply system can be divided into several categories, such as critical subsystems, for essential missions or subsystems for non-essential ship services, crew use, etc.

The former requires an isolated power supply system with insulation condition monitoring, while the latter requires a grounded power supply system with residual current monitoring and protection, with different EMI filters for the two power supply systems.

EMC Verification and Validation Plan: This plan describes the measurement methods to be used, the voltages and currents to be measured, field strengths, frequency ranges, measurement distances, etc.

Verification includes tests carried out during the construction phase, while validation is carried out during port tests and sea acceptance tests.

It has allowed a cost-effective saturation of a ship with equipment, having a defined environment that can be established by specifying technical requirements and conducting tests performed, verified, and validated.

6. Conclusions

In order to design a complex power system, such as that of a ship, to operate with appropriate levels of electromagnetic emissions, the electromagnetic environment, the areas of potential electromagnetic risk, the components and their characteristics, and the interactions between these components must be correctly defined and understood by the designers. Examples of marine incidents are presented to support the limitations of approaches based solely on reference to the standard. Thus, the paper presents experimental and practical aspects of a ship-specific electromagnetic environment and a pragmatic model of a risk assessment approach. The risk-based approach comprises several steps understanding the environment, designing a control plan, implementation, validation, and verification.

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