EMI Aspects of Low Voltage Power Distribution Systems for Ships

Nancy Omollo
RH Marine
Rotterdam, The Netherlands
University of Twente
Enschede, The Netherlands
nancy.omollo@utwente.nl

Robert Vogt-Ardatjew
University of Twente
Enschede, The Netherlands

Jan-Kees van der Ven
RH Marine
Rotterdam, The Netherlands

Frank Leferink
Thales Nederland
Hengelo, The Netherlands
University of Twente
Enschede, The Netherlands

***Abstract*— In many mission-critical systems, such as naval vessels, the power supply system is insulated. An insulated, or unearthed, system has no connection, or via a high impedance, to earth, and often the neutral is not used. An insulated system has drawbacks with respect to electromagnetic compatibility compared to the usual earthed power supply system, mainly due to the limited use of filtering possibilities. This paper provides a qualitative analysis of the advantages and disadvantages of insulated power systems and neutral earthing and the impact on electromagnetic compatibility.**

I. Introduction

Power quality is an important aspect in the correct and efficient operation of a ship. However, due to the interaction of many installed equipment connected to the power supply, several disturbances are introduce in the system that often leads to electromagnetic interference (EMI). One basic mitigation method is earthing of equipment. To assure the continuous supply of power to mission-critical equipment often an unearthed, or insulated, power supply system (called IT, isolé-terre) without earth connection of the supply is used. This allows one short connection (fault) of a phase to earth [1] without interruption of power supply. Due to the aspect of continuity of service during a single earth fault, this system has often been used in plants and systems where continuity of service is essential, as well as in dedicated areas in hospitals, such as intensive care and operation rooms, where the isolation aspect is needed to reduce EMI towards sensitive equipment connected to patients, and for safety purposes [2, 3]. Insulated systems in ships prevents large leakage currents through the hull of a ship, which can increase the magnetic signature, and accelerate corrosion [4].

Modern systems in large electrical installations create, due to the many filters to reduce EMI, significant capacitive coupling to earth. The increased capacitance can result in increased EMI problems due to conducted interference created by the capacitive loops. Any first fault in an IT system has to be detected and the location determined, and so-called Active Earth Detection (AGD), Insulation Monitoring Device (IMD) or Power Insulation Monitor (PIM) are being used. Large capacitances in equipment are causing faulty alarms and impact the detection performance. Besides, the larger the loops the larger the magnetic signature of a ship. This can trigger magnetic mines. Furthermore the EMI filter leakage current can accelerate galvanic corrosion of a ship's hull, especially when manufactured from aluminum. In [3, 4] the impact of earthing and effect of filtering has been described with regard to insulated power system. The pros and cons of IT systems and other systems have also been described in several papers including [1, 5, 6]. The purpose of this paper is to evaluate the best power supply earthing system for ships, and to propose solution for EMI problems in such system.

The rest of this paper is organized as follows: in Section II different types of earthing systems are analyzed. Then in Section III limitation to insulated system is described. Section IV describes the remedies to electromagnetic compatibility (EMC) problems in IT systems. It is concluded in Section V that IT systems are still favorable for mission-critical systems, but measures have to be taken to deal with the adverse effects on ships.

II. Insulated vs Earthed Systems in LV Power Systems

Typically, most ships low voltage power systems have a 3-phase A.C., 3-wire and 440V design. The function of an electrical system is to safely convey the power from the source to the various equipment connected to it. The actual current return path determines the earthing system of a power system on board of ships. This involves the neutral point of the supply, which is the common point of a star-connected polyphase system or earthed midpoint of a single-phase system in an electric installation [7] . There are two distinct ways to deal with the neutral point in any power system, as given above and in IEC 60364-1 [5]. The point can be tightly connected to earth (ship's hull), earthed systems, or not effectively connected to earth like in insulated systems [8]. Often, onshore systems have an earthed neutral point whereas the offshore systems often adopts the IT systems, where there is no connection to earth. The IT system is also used in production plants where continuity of supply is important. Also highly mobile systems are often using the IT approach. In several countries the IT system is mandatory for hospitals, but in these applications the sub-grid is very small, in order of a few kVA, and highly insulated to decrease any leakage current. In some cases, the neutral is not used for distribution, so the IT system becomes a three-wire system. These different power systems have been discussed in [5, 8], illustrated in Figure 1 and reviewed below;

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No 812.790 (MSCA-ETN PETER). This publication reflects only the authors' view, exempting the European Union from any liability. Project website: http://etn-peter.eu/.

Insulated (IT) systems: IT system has no intentional conductive connection between the neutral point of the supply and earth. The protective earth (PE) connection of the installation is however locally earthed at the equipment location. This earth connection shall have a low impedance such that in case of a fault the maximum voltage on the equipment is less than 50V (touch voltage). A system may still be considered insulated if there is a deliberate connection to earth through potential measuring devices or high impedance devices (impedance earthed systems). In many cases a resistance of 1500 Ohm is installed in the star of the transformer so that the voltages will be symmetric with respect to earth [1], sometimes called neutral resistance earthing. The value of this resistance can classify the neutral resistance into either low resistance earthing or high resistance earthing as explained in [9]. This is often the case since there are installed capacitors and parasitic capacitors of the phase windings and other equipment, which creates path for leakage current, back to the supply. The earthing connection, which can be a complete ship's hull, is essential and shall be very low impedance. IT system are preferred for maximum availability because a first fault will not result in disconnection of the power, like for the other supply systems. A residual current device (RCD) shall be used in subnets for personnel safety.

To monitor any fault, or deterioration of isolation in the supply system, a PIM (or AGD or IMD) has to be used. This monitoring helps detect insulation drops before they develop into full insulation faults. EMI filters are causing often faulty readings of the PIM [3], and EMI filtering appears to be the major constraint when applying an IT system. Another issue is that if a line to earth fault happens, the IT system will continue to supply the loads. However, the other two phases will be at a higher voltage, √3 times, with respect to earth. That means special Cy capacitors (between line and earth), often not found in commercial off the shelf (COTS) filters, or in the dc (Direct Current) bus of power drive systems, need to be used. It is important that an earth-fault is detected and cleared as quickly as possible. This is to avoid a large short-circuit current on a second earth-fault on a different line, which will lead to the action of protective devices and loss of power to equipment.

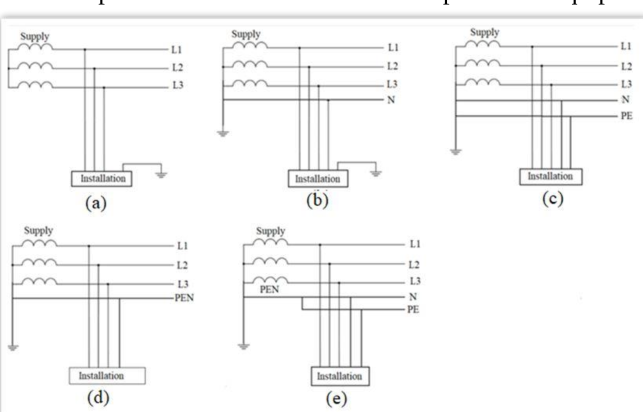

Fig 1. (a) IT system, (b) TT system, (c) TN-S system, (d) TN-C system (e) TN-C-S system.

***TT System**:* In this system, both the neutral point and the PE connection of the installation are locally solidly earthed. The neutral point near the distribution side, the PE at the installation sides. This means that each piece of equipment / installation has its own PE connection. High over voltages may occur between all live parts and between live parts and PE conductor thus leading to possible overvoltage stress on equipment insulation of the installation. It provides good safety condition since earthed conductive part must be limited to 50 V (touch voltage), and also installation of residual current device (RCD) improves safety to both humans and equipment. Several RCDs can be installed in different sections to increase availability of different equipment.

TN-S Systems: In this configuration a PE conductor is provided from the centrally earthed neutral point of the supply, separate from the neutral *(N)* conductor for the load currents. Therefore, it is a three phase five conductor system. It is the most commonly used type of earthing system in land based systems. Neutral and earth conductors are kept separate throughout the installation. This allows higher-harmonics current in distorted power supply systems to return via the neutral conductor without polluting a PE conductor. All exposed conductive parts of the installation are earthed separately, independent of the earthing at the source. In this system, residual current device (RCD) are installed to eliminate the risk of fire and ensure safety of persons. The impact of EMI filters is limited, as the RCD has to be selected, based on the number and kind of loads. Any fault or EMI filter leakage current flows back to the supply via the dedicated PE conductor. It has a low earth fault loop impedance, hence less electromagnetic interference because of well-defined current paths. On occurrence of an insulation fault, the short circuit current is high and may cause damage to equipment. This fault is cleared quickly by the installed over-current protective devices.

TN-C systems: In this installation, PE and N conductors are combined, called a PEN conductor. This conductor is connected to the centrally earthed neutral point. The EMI leakage current flows thus in the PEN, as well as harmonic currents due to non-linear loads. With many installed non-linear loads on a system, increased EMI can occur due to harmonics generated by such equipment flowing through the N conductor, but in this system is thus also the PE path. Like TN-S system, the earth fault loop impedance is low and current return paths are well defined, thus minimized EMC problems.

***TN-CS Systems**:* This system combines a TN-C system with a TN-S system. Close to the supply it is TN-C and close to the load it is TN-S. In between at a certain point the PE conductor and N conductor are merged into a PEN conductor which is connected to a centrally earthed neutral point. All exposed conductive parts of the installation are connected to the PEN conductor via the main earthing terminal and the neutral terminal, these terminals being linked together.

A summary of the advantages and disadvantages is presented in Table 1.

TABLE 1: SUMMARY TO EVALUATE THE DIFFERENT POWER SUPPLY EARTHING SYSTEM.

Criterion	TT	TN-C	TN-S	IT
Safety of personnel	+++	+++	+++	++
Safety against fire hazards	+++	+	++	++
Equipment safety	+++	+	+	+++
Availability	++	++	++	++++
EMC issues	++	+	++	++
Maintenance	++	++++	++++	+++
Installation cost	+	++	++	+++
Overall result	16	14	16	19

+ indicates poor,
++ indicates average,
+++ indicates good, and
++++ indicates excellent for the given criterion.

Although the earthing systems provide a theoretically equivalent level of protection against electric shock, they have different characteristics in terms of use, EMC, adaptability, availability, safety against fire hazards, magnetic signatures, galvanic corrosion, supervision and maintenance cost etc. as shown in the summary in Table 1. However, the implementation of EMI measures in IT systems is a major challenge.

III. LIMITATION TO INSULATED SYSTEMS.

There are several advantages of using TT or TN system, but availability of equipment and continuity of service is key, which makes the IT system favorable for low voltage ship's power system. When a single earth fault occurs (single phase shorted to earth), there is no dangerous fault current that flow back to the system, because of the high impedance of the power supply system. This will guarantee continuity of service allowing time to find and clear the fault.

The increase in size and complexity of modern ships has resulted in the installation of many equipment with integrated power line filters, line-to-earth capacitors, and increased cable lengths with a substantial amount of distributed parasitic capacitances to earth. This results in capacitive current loops in the system that can compromise safety, magnetic signature, EMI, and can cause corrosion problems.

1)Insulated systems and personnal safety

Electric shocks have two causes, namely: direct contact, i.e. a person or an animal touching an exposed live conductor; or indirect contact, i.e. a person touching the metal frame of an electrical load on which an insulation fault has occurred. To provide protection against direct contact, insulation and/or distancing measures are taken. These measures can be reinforced by additional protection in the form of a high sensitivity RCD, like in residential areas, or offices. With respect to protection against indirect contact, between an accidentally energized frame and the earth, the basic solution is to earth all the load frames. The impedance of the earth connection shall be low enough such that under a fault condition no accessible part of the equipment with have a higher voltage than 50V [5].

2)Insulated systems and fire hazards

Power systems on board ships are always designed to be reliable. On top of meeting the requirement of high availability, it should also ensure that risk to fire hazards are minimized and/or eliminated. A faulted equipment, or any fault in the system for that matter, should not bring down the entire distribution to that particular part of the system, especially if it provides essential service. However, when a short circuit occurs due to a fault, the supply is brought to a near zero resistance and thus supplies large currents. Any faults in the system that leads to the flow of excessive current has a likelihood of excessive heat and fire, which eventually leads to loss of equipment and compromises safety to personnel. This current shall be less than the current specified for all lines and earth connections.

3)Insulated systems and EMC

The increase in the size of the vessels and complexity of the system itself has resulted in an increased amount of capacitance to earth. Parasitic capacitors between line conductors and earth of shielded cables and the commutative capacitances to earth of the capacitors installed in different equipment on board ships, contribute a significant amount of leakage current. Additionally, most equipment that are installed on board ships have EMI filters. The cumulative effect of these capacitances is large enough to cause a considerable amount of leakage current through the earth system. As the IT system continues to operate during the first earth fault, a PIM is being used to monitor a fault. Old-fashioned (and improper) PIM are giving false alarms if a high (parasitic or installed) capacitance is measured [3]. Some PIMs are operating with high dc voltages which can cause damage for the Cy capacitors. Therefore, it is essential that the proper PIM is installed [3]. On board of a ship, the earth system is (assumed to be) the ship's hull. These leakage currents can result to EMI, for instance in audio and sonar systems, but also result in an increased magnetic signature and can accelerate corrosion. To reduce these interferences, the ac leakage current is controlled by limiting the amount of capacitance to earth. However, this is practically impossible with the complexity and size of modern ships. To prevent these capacitive currents flowing everywhere, and especially in the ship's hull, one can provide a return current path, for instance by using screened cables, for the power supply distribution. This defines the current paths for leakage and/or fault currents. Establishing an extensive effective contact of a screened cable at both ends ensures a low inductance loop that is effective in reducing interference. This further improves the EMC of the system effectively.

4)Insulated systems and magnetic signature

One of the most problematic wiring errors in TT and TN systems, and also the most difficult to detect, is the exchange of neutral and PE. This error causes the full load current to flow on the PE rather than the neutral. An IT system however has no neutral conductor distributed to the installation. Any fault and leakage currents thus flow through the PE conductor, or the ships' hull. This establishes a current loop with a very large loop area, which can result in magnetic coupling of hum and buzz into signal circuits. The leakage capacitive currents circulating between the main ship electric network and the ship's hull forms a current loop which is increasing the magnetic signature [10]. Therefore, the leakage currents through the ship's hull shall be minimized. Because of the classification (confidential up to secret) of magnetic signature, no further data, i.e. numbers can be provided.

5)Insulated systems and corrosion

The electrical leakage currents due to parasitic cable capacitances and the Cy capacitances in EMI filters cause currents through the ship's hull. The maximum leakage current for a steel ship shall be below 5A. However, this level shall be below 10 mA for an aluminum ship. Serious issues have been reported in [3] and more information is becoming available in publications, like in [11] where it is written 'prevent additional electrical currents on the metal parts of a boat, do not earth to the boat structure, and use an isolation transformer for shore connection'.

IV. Combining requirements

The need for continuous power supply results in the selection of an IT system. However, there are several drawback issues, with EMI and leakage currents due to EMI filters being one of the most important ones. A proper limitation of these leakage current will reduce the effect of current loops, and hence a reduction in induced voltages and current. This goes a long way in limiting conducted interference and hence a step towards achieving better EMC levels. But the leakage current path is not well defined, which is causing possible magnetic signature and/or corrosion problems. Therefore, it is suggested to upgrade the standards, like STANAG 1008 [12], and request defined earth leakage current paths. This is done by installing a protective earth conductor parallel to the power lines, or using screened power supply cables. By screening the power cable, the parasitic capacitance of the power lines is increased, but the current path will be very well defined and the loop minimized using a protective earth conductor. These measures limit the current loop areas, thus decrease the magnetic signature of the ship, and decelerate galvanic corrosion. The capacitance to earth shall be limited per power distribution group in order not to interfere with the PIM [3]. The maximum capacitance from a personal safety perspective according [13] is 70 µF. Otherwise the subgrid can be separated by using isolating transformers. This would allow different equipment to be installed and earthed accordingly to what suits their functionality. For instance, earthed grids with RCD's for lightning and socket outlet grids where there is a higher risk that someone touches a live conductor, and insulated grids where arc flash levels are really high, or very expensive equipment is destroyed when an earth fault occurs e.g. within a generator.

V. Conclusion

Insulated power systems is a solution for power systems on board ships because of the continuity of service to essential equipment and comprehensive protection of equipment and people. In a complex ship environment, this comes with a penalty. A drawback is the capacitance to earth and system impedance to earth due to EMI filters in the installed equipment, influencing the proper operation of insulation monitors. A major drawback is the flow of capacitive currents, increasing the magnetic signature of the ship and the risk of galvanic corrosion, which is especially important for aluminum ships. To reduce these currents through the ship's hull it is suggested to use screened power supply cables.

The choice of earthing system depends on the priority given to the different aspects discussed. In an optimized solution a hybrid system can be applied. In this case the insulated systems is used for the part of the ship where high reliability of service is needed. Isolated insulated sections can be made for sensitive areas, like an operation room or an intensive care (in a hospital or a ship), with low leakage currents. Personnel rooms can be supplied via RCD, to reduce personal safety hazards. And in case of commercial of the shelf equipment which cannot handle the higher voltages in IT systems, local TN system can be created via a transform, fitted with proper monitoring and protection devices, like RCDs.

References

[1] Cahier Technique Schneider Electric, "Earthing systems in LV".

[2] Dr. Dirk Pieler, "Why the IT system is often the best choice for power supply systems of all types," June 2019.

[3] P. van Vugt, , R. Bijman, R. B. Timens, F. Leferink, "Impact of Grounding and Filtering on Power Insulation Monitoring in Insulated Terrestrial Power Networks," in *EMC Europe*, Brugge, Belgium, 2013.

[4] F. Leferink, "Grounding and filtering Effect on Power Insulation monitoring in Naval Power Networks," in *MECSS*, Amsterdam, 2013.

[5] IEC 60364-1 ed. 5.0 (2005-11) , " Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions.".

[6] STANAG. 2004. 1008: (Edition 9), " Characteristics of shipboard electrical power systems in warships of the north Atlantic treaty navies. 2004.," STANAG 1008, 2004.

[7] IEC, [Online]. Available: http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=826-14-05. [Accessed February 2020].

[8] Zuhair S. Al-Sagar, Khalid G. Mohammed, Mohammed S. Saleh, "Improving the Performance of Ground Systems in Electric Distribution Network," *International Journal of Applied Engineering Research,* 2018.

[9] I. Powell, "Power Systems Neutral Grounding Fundamentals," *IEEE Industry Applications Magazine,* 2018.

[10] N. Hasril et al, "Management of Naval Vessel's Electromagnetic Signatures: A Review of Sources and Countermeasures," 2013.

[11] A. Bouvy, 20 November 2018. [Online]. Available: https://www.shapesbyhydro.com/en/material_properties/tips-to-avoid-corrosion-in-marine-environments/. [Accessed March 2020].

[12] STANAG 1008, "Characteristics of shipboard low voltgae electrical power systems in warships of the NATO Navies," August 2004.

[13] Group Schneider, "The IT Earthing system (Unearthed Neutral) in LV," Cahier technique no. 178.

[14] Bender, "Isolated Power Systems Equipment for Healthcare Facilities and Critical Care Areas," 2016.

[15] J. Prousalidis, "On investigating the influence of Zero sequence impedance in ship ungrounded electric network," *The Journal of Marine Engineering & Technology ,* vol. A18, pp. 17-30, 2010.