THE GROUNDING OF MARINE POWER SYSTEMS: PROBLEMS AND SOLUTIONS

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Abstract - Presently, most marine power systems are rated less than 600 Volts and utilize an ungrounded power distribution system. This paper discusses various types of system grounding, grounding practices and characteristics of each and shows why high resistance grounding (HRG) should be adopted as a standard for ships The grounding of medium voltage systems is discussed since many newer ships have medium voltage systems to meet electric propulsion requirements. This paper will first discuss the theory and practices of system grounding in general terms. Next, existing standards for shipboard systems are reviewed and how adoption of HRG will meet these standards is discussed. Some design considerations for HRG are discussed, including charging current, cable selection, cathodic protection, and shore connections. The appendix describes a few examples of marine applications.

Index Terms – Marine, Shipboard, arc flash, arc flash hazard, system grounding, high resistance grounding (HRG) reactance grounding, capacitance grounding, ungrounded, ground fault protection, cathodic protection, anode and cathode.

I. INTRODUCTION

Electrical systems on board a ship require some considerations that are not common on shore. Look at this situation as electricity in a metal box (for metallic hulled ships), floating in the salty ocean far from sight of land and then stick people into this box! Then add pitching and heaving and rolling from the wind and waves to create some complexity. All this needs to be added to the reason for the vessels existence, such as cargo, fishing, warfare, pleasure, research and many other functions. Every vessel has a purpose and the electrical systems on board must work to allow the vessel to achieve its purpose, even in storms, rough seas, explosions, breeches of the hull and many other problems that are not common on shore applications.

Shipboard electrical systems must be safe enough that personnel are not at risk of shock or electrocution, no matter what problems are encountered at sea. The vessel must not flounder because of a failure in the electrical system. The marine tradition has dictated that one ground fault cannot adversely affect operations. Obviously, it is not acceptable to injure shipboard personnel due to an electrical system malfunction.

A vessel at sea is wet, always in motion, isolated from help only with limited on-board tools and supplies. There are, however, shore-based facilities representative of the conditions of a ship at sea. Solutions for problems with the electrical systems on these shore-based facilities can be reviewed for answers to problems at sea.

This paper deals with the grounding of marine power systems. Proper grounding is important on board ships and vessels as with all electrical power systems. Historically, industry has determined that establishing an intentional ground on the system is important in sensing an unintentional ground. In the marine industry, this intentional ground is often times established only through a ground sensing circuit and, thus, the system is classified as "ungrounded". The question that needs to be answered is whether or not that is sufficient for a reliable and safe system. To answer the question, the available types of grounding systems need to be reviewed and the advantages and disadvantages of each need to be discussed. Finally, it must be determined whether or not the system voltage has any major impact on the type of grounding system chosen. If so, what are the constraints or limitations placed on the type of grounding system due to the system voltage level.

Many papers have been written on the subject of system grounding. Those papers have shown that there may be some varied opinions over the type of grounding system that is best for a particular application. However, the overall consensus is that there should be an intentional connection for the system ground. The use of the HRG system will be shown to provide additional benefits over any other system in the safe operation of system equipment, safety of personnel and reliability.

II. GENERAL SYSTEM GROUNDING

As a review, it should be noted that grounding of a distribution system takes on one of several forms:

- Solidly Grounded
- Reactance Grounded
- Resistance Grounded (low and high resistance)
- Ungrounded

While there is always an exception, for all practical purposes, a neutral conductor is not required for the resistance grounded or ungrounded system due to the fact that no neutral current is expected to flow. In general, the systems shown in Figs 1-4 are the options available for use.

Figs 1 and 2 show a three-wire ungrounded delta and an ungrounded wye system, respectively. Fig 3 shows a three phase, four-wire solidly grounded and reactance grounded systems. Fig 4 shows three phase, three wire, solidly grounded, reactance grounded and resistance grounded systems.

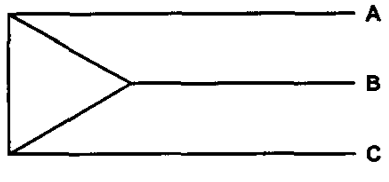


Fig. 1 Three-wire, ungrounded delta connected transformer

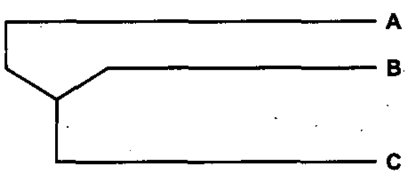


Fig. 2 Three-wire, ungrounded-wye connected transformer

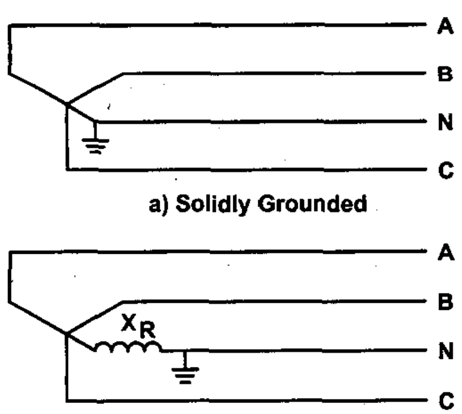


Fig. 3 Four-wire single point grounded-neutral system (Solid and Reactance Grounded)

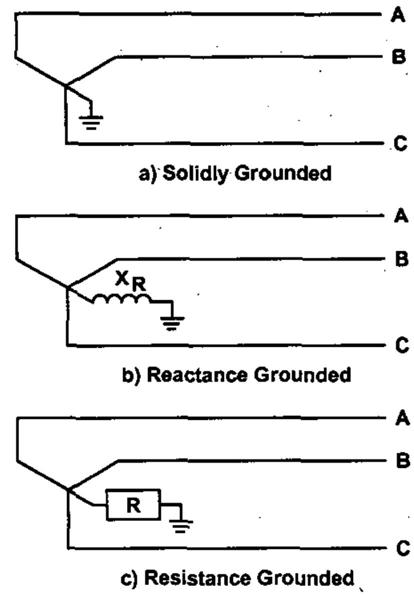


Fig. 4 Three-wire grounding – Solid, reactance and resistance

Table 1 lists the characteristics for each of the various types of grounding. Discussion of these characteristics follows:

- **Ground Fault Magnitude:**
  Tripping is required with solid, reactance and low resistance grounded systems. HRG and ungrounded systems have minimal ground fault currents which can normally be sustained without tripping
- **Fault Propagation:**
  Ground faults on HRG and ungrounded systems do not typically propagate into multi-phase faults. Solidly grounded and reactance grounded systems can rapidly escalate into multi-phase faults. Low resistance grounded systems limit the fault currents and are less likely to propagate into multi-phase faults, but can if tripping times are long.
- **Arc Flash:**
  Arc flash hazard risk for ground faults is negligible for the properly supervised and operated ungrounded and high resistance grounded systems. The arc flash hazard risk is the highest with the solidly grounded system, slightly reduced with the reactance grounded system and significantly reduced with the low resistance grounded system. This is discussed further in section IV. SAFETY AND SHORT CIRCUITS.
- **Safety Level:**
  The ungrounded and high resistance grounded systems are the two safest systems.

CHARACTERISTIC	SOLID	REACTANCE	LOW R	UNGROUNDED	HIGH R
High Ground Fault Current	Yes	Yes	No	No	No
Probability to Propagate into Multi-Phase Fault	High	High	Medium	Low	Low
Arc Flash Hazard Risk Level	High	High	Medium	Very Low	Very Low
Relative Safety Level (Equipment and Personnel	Low	Low	Medium	High	Very High
Equipment Damage Potential	High	High	Low	Very Low	Very Low
Can fault Location be easily located?	Yes	Yes	Yes	No	Yes
Continuity of Service with ground fault	No	No	No	Yes	Yes
Approximately Transient Over Voltage Level	2.5X	2.5X	2.5X	>6X	2.7X
Possible Selective Tripping	Yes	Yes	Yes	No	Yes
Alarming without tripping	No	No	No	Yes	Yes
Cable Insulation Level Requirement	1.0	1.0	1.00	1.73	1.73
Surge Protection Level	1.0	1.0	1.73	1.73	1.73

Table 1 – Characteristics associated with methods of system grounding

- **Equipment Damage:**
  For a properly supervised ungrounded and high resistance grounded system, the potential for equipment damage is minimal.
- **Fault Location:**
  Faults can be easily located on all systems with the exception of the ungrounded system. This is one of the main advantages of the high resistance grounded system over the ungrounded system. Locating grounds on ungrounded systems is done by a process of elimination. Circuits are systematically de-energized until the ground fault detection circuits are cleared. With HRG, the ground fault can be located while keeping the equipment in service.
- **Continuity of Service:**
  Electrical service can be maintained on both the ungrounded and resistance grounded systems. That cannot be said with the other systems.
- **Transient Over Voltage Levels:**
  Transient over voltages are limited on all systems with the exception of the ungrounded system.
- **Selective Tripping:**
  Selective tripping is possible on all systems with the exception of the ungrounded system.

- **Alarming without tripping:** Alarming without tripping is possible only on the ungrounded and high resistance grounded systems. All other systems require tripping.

- **Insulation Levels:** Insulation levels and surge arrester levels are the highest on the ungrounded and HRG systems.

III. OFFSHORE SYSTEM GROUNDING

A) *Earthing and Equipotential Surfaces*

On board a ship, the term "grounding" first raises concern because it generally refers to *running aground*, or no longer floating! Here, however, the concern is electrical in nature. What is an electrical ground when one is floating on water? The "earthing" connection of a facility on shore is the electrical connection to the soil, the ground or the earth on which the facility sits. This is to put the facility at an equipotential level as the ground on which a person steps when exiting the facility. Except for the time when the ship is receiving power from shore, there is no connection to true "earth ground."

So, the term "ground" takes on a slightly different meaning for marine power systems discussed here. An "earthing" connection is made on a ship by contact of the hull to the water on which the vessel floats. Nonmetallic vessels require a grounding plate to be installed along the keel, below the water line, such that it is always in contact with the water. The ship's hull or grounding plate becomes the zero potential reference for the vessel. All electrical and electronic systems on a vessel are referenced to this zero potential reference point, or "ground."

All structural parts, above and below deck, of a vessel that are welded or brazed to the ground potential (hull or ground plate) are considered as the "ground plane" so that all the portions of the vessel are equipotential and at zero potential. Connection to the ground plane must be done in such a manner that hull currents are avoided. The hull must not be a current carrying conductor except for a few well-defined applications. All metal parts of a ship that are not welded or brazed to this plane, must be bonded by bonding straps and bolted connections.

This same ground plane becomes the electrical safety ground. All electrical systems must be connected to this ground potential in some fashion. All exposed non-current carrying parts of electrical and electronic equipment must be bonded to the equipotential surface created. Power systems may be grounded solidly or through impedance to this ground plane. Even ungrounded power systems are connected to this ground through a ground fault detection circuitry as well as the stray capacitance of the system.

The ground plane is also extremely important for on-board radio systems. Antennas need a "ground plane" for reference so that the antenna pattern for transmission of radio frequencies is reasonably close to the pattern that is typical for each of the antennas used. Without a proper "ground plane" the characteristic impedance of the antenna will not be correct and the load it presents at the end of the transmission line will not allow the antenna to properly radiate.

The integrity of this ground plane must be maintained and protected against deterioration by carrions, mechanical abuse, fatiguing or any other action. Bonding of all non-current carrying metal portions of equipment to this ground must also be maintained, as must the "intentional" system grounds and ground fault monitor circuits and systems. All electrical safety of marine power system critically depends on the integrity of ground.

B) *IEEE Standard 45*

IEEE Standard 45-2002, IEEE Recommended Practice for Electrical Installations on Shipboard, covers grounding of low voltage and medium voltage systems.

Low Voltage: According to IEEE Standard 45 [4] the grounding of 600 Volts or less should be determined based on the following three considerations:

- Reduce the potential for transient over voltages
- Continuity of service for single phase-to-ground fault
- Minimize ground fault current in the hull structure

IEEE – 45 allows the use of the following grounding options:

- Ungrounded system with all current carrying parts completely insulated from ground with continuous ground fault monitoring.
- High resistance grounded system with single line-to-ground faults limited to 3 Amps (The standard assumes 1 Amp of charging current and therefore 3 Amps is sufficient. This may not always be true)
- Solidly grounded system but limited to only non-critical circuits

IEEE Standard 45 acknowledges the need to reduce the potential of transient over voltages, but allows the use of an ungrounded system. That alone appears to be a contradiction because the chance of transient over voltage conditions exists with the ungrounded system. The potential for transient over voltage is reduced by employing HRG or solid grounding.

HRG is dependent on the system capacitance. While most systems can be grounded through a resistor that limits the current to 3 Amps as required by IEEE Standard 45, it is possible that the system capacitance can be such that even a 5 Amp HRG could be inadequate on some larger medium voltage applications and that dangerous transient over voltages could still exist. So, it may be necessary to limit the size and, in particular the capacitance, of the system to meet the 3 Amp requirement.

Solidly grounded systems, by design, require ground fault tripping and therefore do not meet the continuity of service criteria. High resistance grounded systems can utilize an alarm system, tripping or a combination of the two. As such, a high resistance grounded system meets the reliability requirements (continuity of service) of IEEE Standard 45.

Medium Voltage: According to IEEE Standard 45, the grounding of medium voltage systems may be through resistance or reactance. [4] For shipboard applications, the reactance grounding does not appear to have any benefits. Reactance grounding is sometimes used by electric utilities on three-phase, four wire distribution systems where neutral currents are present. There does not appear to be any reason to have a four-wire system on board a ship.

C) Military Standard 1310G

Navy Military Standard 1310G is the "Standard Practice for Shipboard Bonding, Grounding and other Techniques for Electromagnetic Compatibility and Safety." As the title indicates, this document provides requirements and guidance for EMI prevention and safe operation of electrical systems.

The hull of a metal-hulled ship is to be considered as the ground plane as the hull is in contact with seawater. The hull of a non-metallic ship must have a ground plane installed at the lowest point of the structural hull. All ground plates on a non-metallic hulled ship must be connected to this reference ground plane.

On metal hulled ships, the structure of the hull, superstructure, decks and other metal portions of the ship are to be welded or brazed where connected to the hull and are to be considered as part of the ground plane. Where metallic surfaces are bonded together, the surfaces are to be prepped to ensure good connection. Bolts are to be welded to the metal portions (deck and bulkheads) for the lug of bonding straps.

Most of MIL-STD-1310G does concern itself with EMI (Electromagnetic Interference) and IMI (Intermodulation Interference). High resistance and high reactance connections between metal parts of a ship can have electrical potential developed from the radio and radar transmissions, and thus the great concern for those joints.

These same considerations also provide good equipotential surfaces required for safe operation in the presence of ground faults. The fabrication of the ship thus has much to do with the affects of electrical problems on the equipment and personnel on board the ship.

III. SAFETY AND SHORT CIRCUITS

For the purpose of this paper, low voltage systems are systems 600 Volts and below and medium voltage systems include systems from 601 to 15,000 Volts. Most, older shipboard electrical systems utilize a low voltage system, but newer and larger ships have utilized electrical systems above 600 Volts such as 2.4, 4.16, 6.9 and 13.8 kV.

Starting with the low voltage system, consideration on system grounding includes potentially high fault currents and potential problems with arcing faults on solidly grounded systems:

- Ground fault currents can become quite high at low voltage with relatively small transformers and generators. For example, a 500 kVA,, 120/208 Volt, transformer with a 5% impedance and a strong high side source could have fault currents approaching 50 kA. The same transformer at 480 Volts and 600 Volts would have approximately 12 kA and 10 kA available, respectively. So it can be seen that high fault currents are typically associated with a low voltage system.
- The voltage where an arc can be sustained on a system is approximately 150 Volts to ground [1]. That sustained voltage is why arcing faults are more likely to occur on systems above 260 Volts phase-to-phase such as 375, 480 and 575 Volt systems.
- At higher voltages, the fault current is limited. For example, the same 500 kVA transformer has only 1400 Amps of fault current at 4.16 kV and only 400 Amps at 13.8 kV.

Since most faults originate as a ground fault [2], limiting low voltage ground fault currents through either low or high resistance improves the safety of equipment and personnel working near the electrical equipment. Ungrounded, although commonly used in marine applications, is not recommended due to the reasons discussed in Part II – System Grounding, and in fact is not recommended by IEEE Standard 45.

With regard to safety, the ungrounded systems in the marine industry have been quite reliable and relatively safe. The HRG system proposed in the paper and commonly used in the process industries such as the petrochemical industry provides all the benefits of the ungrounded system plus two additional features discussed in Part II-System Grounding. The HRG is the safest system and the risk from arc flash is minimal. The reason is based on the following approximate statistics [2] for the origination of electrical failures:

- Phase-to-Ground >98%
- Phase-to-Phase <1.5%
- Three Phase <0.5%

Practically all faults originate as a phase-to-ground failure with a very few number of faults originating as a phase-to-phase fault. Practically no faults, except for human induced faults, originate as a three-phase fault. (A typical human induced three phase fault is erroneously closing a breaker into a set of three-phase-to-ground grounding leads.)

Medium voltage systems have many similarities in ground fault protection with low voltage systems. One of the inherent advantages to using medium voltage systems on ships is the same as that for shore side industrial plants – namely smaller conductors. As ship electrical loads become larger and larger, the increased size of the buses and cables creates difficulties. Likewise, larger motors such as those required in propulsion require higher voltage from a practical point of view. For industrial plants there is a "rule of thumb" that the voltage should be equal to or greater than the horsepower of the motor. That rule holds true onboard ships as well as in industrial plants. When dealing with medium voltage systems, the following should be considered:

- Ground currents can still be high on medium voltage systems, especially due to larger generators and transformers.

- Grounding on medium voltage systems allows the use of high resistance, low resistance, reactance and solid grounding.
- Ungrounded medium voltage systems still have the same problem of an arcing ground fault as does the low voltage system.
- The charging current, where minimal in low voltage systems, can become quite significant on medium voltage systems. In fact, charging current on 15 kV systems special attention to heat dissipation in the resistor and damage at the point of fault.

IV. DESIGN CONSIDERATIONS FOR HRG

A) Capacitive Charging Current

The reason high resistance grounding normally works so well is that the ground fault current is relatively low and does not cause damage. This is possible when the capacitive charging current of the system is low and the ground fault current is a few amps higher. However, when charging current is too high, the ground fault currents cannot be left flowing and tripping must take place.

Charging current is based on:

$$I_{oc} = V_{LL}/(\sqrt{3}(X_{co}) \quad (1)$$

Where,

I_{oc} = Capacitance charging current per phase
V_{LL} = line-to-line voltage
X_{co} = zero sequence reactance

Since X_{co} is inversely proportional to the capacitance of the system, X_{co} becomes smaller as the system capacitance increases:

$$X_{co} = (2\Pi f C_o)^{-1} \quad (2)$$

Where,

f = Frequency in Hertz
C_o = Zero sequence capacitance

Some interesting observations should be made about capacitance on higher voltage equipment. The capacitance has a tendency to be lower as the insulation level increases. For example, 500 KCM power cable has a capacitance of .215, .0920, .0685 and .0532 µF per 1000 ft for 5kV, 15kV, 25 kV and 34.5 kV systems, respectively. Likewise, recommended surge capacitance for 480 Volt, 2.4 kV, 4.16 kV and 13.8 kV motors are 1.0, 0.5, 0.5 and 0.25 µF, respectively. The capacitance on motors on a per-horse power basis tends to decrease as the motor voltage rating increases.

While the zero sequence capacitance (Xo) of a system needs to be calculated and tested in order to determine the actual amount of zero sequence charging current, a good starting point is to estimate Xo as approximately 300 Ohms. Smaller systems will have higher values of Xo and larger systems will have a lower value. Based on this approximation, the following $3I_{co}$ currents and associated power dissipated in an appropriately sized resistor are shown in Table 2:

System Voltage (Phase-Phase)	**$3I_{co}$**	**Power** Dissipation
480Volts	1 Amp	0.3 kW
2400 Volts	5 Amps	7 kW
4200 Volts	8 Amps	19.2 kW
7,200 Volts	14 Amps	59 kW
13,800 Volts	27 Amps	215 kW

Table 2

Table 2 shows the heat dissipated in a 480 Volt HRG resistor is 300 Watts. Assuming that the resistive current is just equal to the charging current, the vector sum of the currents at the point of fault is only 1.414 Amps (1 x √2). However, at medium voltages, both the charging current and the power dissipation values become significant. HRG systems work well at voltages through 4200 Volts. Above 4200 Volts, the ground fault current and power dissipation become problematic. Therefore, at the higher voltages, considerations need to given to:

- The safe dissipation of the heat from the resistor until the ground fault condition can be corrected
- Properly prioritizing the location and removal of the fault based on other operational considerations.

(It should be noted that electric utilities have successfully utilized HRG on major generating stations with voltages in the 25 kV range.)

B) Power Cable Insulation Level

Both the high resistance and ungrounded systems allow continuous service unless a second ground fault occurs on a second phase. With one ground fault, the voltage on the two unfaulted phases will increase by up to 1.73 times normal line-to-neutral values. As such, it is imperative that all equipment can withstand the higher-than-normal voltage. This is particularly true with power cables that are normally rated on line-to-neutral voltage. Table 3 shows the values that have been determined for low and medium voltage systems. Cable used on ungrounded and HRG systems should be rated for the phase-phase system voltage. Power cables are rated based on three levels. [3]

- 100 Percent Level – Cables in this category may be applied to a system where ground faults are cleared rapidly and within one minute
- 133 Percent Level – Cables in this category are applied to where the requirements of the 100 percent level cannot be met, but clearing time is still within one hour
- 173 Percent Level – Cables in this category are applied to systems where the clearing of a ground fault is indefinite.

Cable Rating	**Maximum Operating Voltage (Phase-To Ground)**
600 Volts	347 Volts
1000 Volts	578 Volts
5000 Volts	2,890 Volts
8000 Volts	4,624 Volts
15,000 Volts	8,760
25,000 Volts	14,450 Volts

Table 3

It should also be noted that the use of power cables is not recommended on systems where the X_0/X_1 ratio of the system where the cable is being used is in the range of (–1) and (–40). [3] This ratio commonly exists on systems that are ungrounded due to the capacitance of the system.

Industry has tended to ignore the over voltage limitations on power cables. Although little if any harm has been shown to be a result, theoretical problems could exist, resulting in loss of cable life.

C) Grounding and Shielding of Electronic Equipment

In the days of iron men and wooden ships, the only concern of electricity was the fear of lightning strikes. As industries have grown to have large power systems and sophisticated electronics, so have sea going vessels. With high voltage, high currents and high frequencies, sensitive electronic equipment and fragile people must be protected from potential harm.

The equipment that controls the large power systems is just as subject to EMI as are other computerized equipment on board a large ship. Over time, engineers and technicians have developed methods and techniques that allow all these various pieces of equipment and their adverse effects to work together safely. Proper grounding and shielding are a good part of the methods employed.

The basic philosophy of grounding and shielding is to provide:

- Low inductance wiring for all active circuitry
- Proper shielding and grounding
- Differential techniques to reject common mode voltages

Capacitive coupling, high Ohmic contact resistance cross talk, inductive coupling from cabling and components are all issues involved with EMI. Shielded cables come in many configurations and each one is intended for shielding against a particular type of interference [7]. Each interference type requires different methods of grounding. Some require a shield to be grounded at only one end and others require grounding at both ends.

Whatever method of grounding is used in signal, control and communications circuits they all eventually are connected to the same ground reference to which the power system is connected. The hull is the ground reference on a ship and, thus, the great concern for avoiding hull currents as they may provide interferences between systems at the grounding connections. One system can and will impact other systems, so attention to grounding of each and every system on board a ship must be considered thoroughly.

D) Cathodic Protection and Grounding

Earlier it was stated that the hull could not be used as a current carrying conductor in any electrical system, except for a few applications. The cathodic protection system is one system that can be directly connected to the hull. The purpose of the cathodic protection system is to prevent corrosion on the hull or other portions of a ship that are in contact with seawater. The rudder, propeller and shaft, cooling systems for engines on board the ship, water supplies and other portions of a ship are all subject to corrosion.

Corrosion occurs when metals are in contact with seawater, because of electrolytic cells, much like a battery, that are formed between metals of different types, or dissimilarities along a single metal surface. Zinc anodes are attached to the hull and other portions of the ship to combat this corrosion. These anodes in contact with seawater and with the metal portions of the ship form an electrolytic cell, that generate electrical currents in opposition to the normal corrosive action thus prevent the deterioration of the protected surface. Other systems use power supplies to impress a current through the hull and seawater in a direction opposite to the normal corrosive action.

When designing and installing these corrosion protection systems, care must be taken to assure that the potential developed within the hull or other surface does not create a problem in any other electrical system. Current flow in the hull means that there will be potential (voltage) difference along the flow of the current. If there are any other systems connected to the ground plane anywhere near where these protective currents flow, these may cause problems with that system's operation. Or that system could override the protective ability of the corrosion protection system.

API 14F provides a caution for any cathodic protection system operating above 50 Volts. The voltage difference between any to points one meter apart should not exceed 10 Volts.

E) Shore Connections

Where a shore connection is provided for, besides the convenient location, circuit breaker, indicator lights and phase sequence indicators, the shore connection should also provide connection of the Shore Power Feeder Grounding conductor to the same "earthing" or hull connection established for the bus to which the shore power is connected. The shore power voltage should be the same voltage as the on board generator voltage to avoid the need to back feed through any transformers to obtain higher voltages. Back feeding through a transformer can result in additional grounding problems for separately derived systems.

V. CONCLUSIONS

Although most shipboard systems are classified as "ungrounded," in fact the systems are grounded through the ground fault detection system. Therefore, there should be no objection to the HRG system since it is just another way of detecting ground faults and performs similarly to the "ungrounded" system with two major improvements over the ungrounded system:

1. The HRG system eliminates the concern for transient over voltages due to arcing ground faults.
2. A small controllable amount of fault current can be used to locate the ground fault.

Cable insulation levels on shipboard, ungrounded systems require 173% insulation level requirement. Although HRG systems will not eliminate this requirement, the HRG system will eliminate the potential of transient over voltage conditions thereby helping to eliminate further problems on the system.

Shipboard electrical systems demand extremely high reliability and safety. With reference to Table 1, the best system of grounding for shipboard electrical systems is the HRG system. Years of experience have proven that system to be far superior to any other grounding system including that of the ungrounded system, the system that is most commonly used onboard ships. It is time for the marine industry to accept that fact, change its practice of using ungrounded electrical systems and not only accept the HRG system, but start retrofitting that system on existing shipboard electrical systems. Otherwise, pardon the pun, " the industry will be missing the boat!"

VI. BIBLIOGRAPHY

[1] Dunki-Jacobs, J.R., *The Impact of Arcing Ground Faults on Low Voltage Power System Design,* GET-6098, Page 10

[2] Woodam, JL, Post Glover February 24, 2004 Symposium Notes, Page – Procter and Gamble Statistics, Based on Procter and Gamble Statistics, Page 10

[3] The Okonite Company, *Engineering Data for Copy and Aluminum Conductor Electrical Cables,* Ramsey, NJ, 1998, Page 11 [Also - Engineering reference, www.okonite.com/engineering/electrical-formula.html]

[4] IEEE Std 45-2002, *IEEE Recommended Practice for Electrical Installations on Shipboard,* Institute of Electrical and Electronics Engineers, ISBN 0-7381-3381-7, New York, NY, 2002

[5] NFPA 70E – *Advance Copy – Standard for Electrical Safety in the* Workplace, National Fire Protection Association, Quincy, Mass. 2004

[6] IEEE Std. 1584 - 2002 – *IEEE Guide for Performing Arc-Flash Hazard Calculations,* Institute of Electrical and Electronics Engineers, ISBN 0-7381-3351-5, New York, NY, 2002

[7] IEEE Std 1143-1994, *IEEE Guilde on Shielding Practice for Low VoltageCables,* Institute of Electrical and Electronics Engineers, ISBN 1-55937-141-2, New York, NY, 1994

VII. REFERENCES

[1] ANSI/IEEE Std 80-1986, *IEEE Guide for Safety in AC Substation Grounding,* Institute of Electrical and Electronics Engineers, ISBN 471-85393-3, New York, NY, 1986

[2] NFPA 70, *National Electrical Code* 2002, National Fire Protection Association, 2002, Quincy, Mass

[3] Watson, G.O., *Marine Electrical Practice,* 6th Edition, App. Index ISBN 0-750-61013-1, 308 Pages

[4] Westinghouse Electric Corporation, *Electrical Transmission and Distribution Reference Book,* Westinghouse Electric, Pittsburgh, PA 1964

[5] ANSI/IEEE Std 142-1991, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems,* (Green Book), Institute of Electrical and Electronics Engineers, ISBN 1-55937-141-2, New York, NY, 1992

[6] Shipp, D.D.; Crapps, C.O.; and Nolan, T.M.; Gr10, Grounding of Marine Electrical Systems: A True Perspective. (Draft Copy)

VIII. VITA

John P. Nelson received a BSEE from the University of Illinois, Champaign-Urbana, in 1970 and an MSEE from the University of Colorado in 1975. Mr. Nelson spent 10 years in the electric utility industry and the last 24 years as an electrical power consultant. Mr. Nelson has been active with PCIC for approximately 25 years, and has authored numerous papers typically involving electric power systems and protection of electrical equipment and personnel. Mr. Nelson is the founder and president of NEI Electric Power Engineering Inc located in Arvada, Colorado. He is a registered professional engineer in the state of Colorado and numerous other states. Mr. Nelson has taught graduate and undergraduate classes at the University of Colorado at Denver along with a number of IEEE tutorials and seminars.

David Burns received a BSEE from Mississippi State University in 1980. He spent 10 years with Chevron USA designing and installing major electrical generation/distribution systems in the Gulf of Mexico. For four years, he was located in Sumatra, Indonesia with CALTEX (CPI) working with large electrical distribution systems. The next eight years, he was vice president of engineering for Point Eight Power Inc and was responsible for designing and fabricating generator control and power switchgear for marine applications including commercial ships, US Navy and fixed/floating offshore facilities. Mr. Burns is currently a senior staff electrical engineer with Shell Exploration and Production Company. He is a registered professional engineering in the states of Louisiana and Mississippi.

Robert L. Seitz received a BSES in Electrical Engineering from the University of Alaska, Fairbanks, in 1968 and pursued postgraduate studies in Electrical Engineering and Oceanography from 1968 to 1971 at the University of Arizona and Oregon State University. Mr. Seitz spent 8 years in oceanography developing and working with shipboard and underwater systems and equipment. The last 25 years he has worked as an E/I and C Engineer, primarily in the design and construction of Oil and Gas production facilities. Mr. Seitz became active with PCIC 4 years ago, and has authored 4 papers primarily concerned with hazardous location installations. He is a registered professional engineer in Alaska. Mr. Seitz has taught in a number of tutorials and technical training sessions. Mr. Seitz is a professional engineer in the state of Alaska.

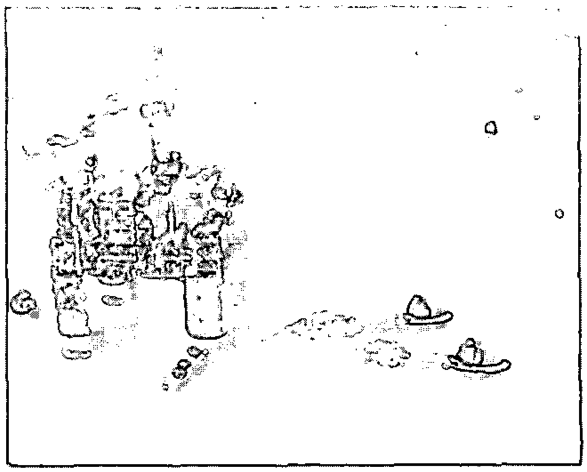
Andrew Leoni received a Bachelors of Science degree in Marine Engineering from the United States Merchant Marine Academy and a Masters in Electric Power Engineering from the University of Colorado. Mr. Leoni has held positions with General Electric and Corning Incorporated prior to accepting a position with NEI Electric Power Engineering where he is presently Vice President of Engineering. Mr. Leoni has ship board experience with electric power systems. Mr. Leoni is a Professional Engineer in the states of Colorado, Illinois, and Kansas.

Acknowledgements:

Chris Pink received a BS in Engineering with a specialty in electric power from the Colorado School of Mines, Golden, CO in 2003. He is presently working in the Master's program with an emphasis in electric power system analysis. Chris spent nine years in the Navy as a naval electrician on board nuclear submarines. He is presently and engineer with NEI Electric Power Engineering located in Arvada, Co.

APPENDIX I - EXAMPLES

GREEN CANYON AREA GC-158



The Brutus field comprises two blocks in the Green Canyon Area, GC-158 and GC-202. The blocks are located 165 miles southwest of New Orleans, Louisiana, in water depths varying between 2900 to 3200 feet. The GC 158 (Brutus) TLP is a four-column, pontoon type Hull, secured to the sea flow by twelve steel tendons, three to each column.

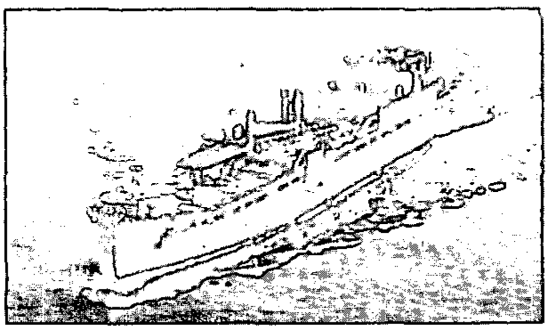
The electrical distribution system for Brutus consists of a 4160 VAC generation and distribution system and a 480 VAC distribution system. Since this electrical distribution system is located on a floating marine facility, the applicable rules from US Coast Guard and specific marine electrical standards apply.

The 4160 VAC system consists of four 4750 kW, 4160 VAC turbine generators, two of which are currently operated continuously in parallel. Each of these machines is low resistance grounded and interconnected directly to the main ANSI metal clad type 4160 Volt switchgear assembly that is comprised of vacuum circuit breakers and microprocessor, multi-function type electronic protective relays. The 4160 Volt distribution system feeds a number of large motor loads ranging in size from 100 hp to 2300 hp through several large 4160 VAC, UL 347 type motor control centers. The grounding system is conventional low resistance system through a 200 Amp resistor interconnected between each generator neutral to ground.

Ground faults at 4160 Volts are detected through the use of coordinated selective ground fault relay with zero sequence current transformers.

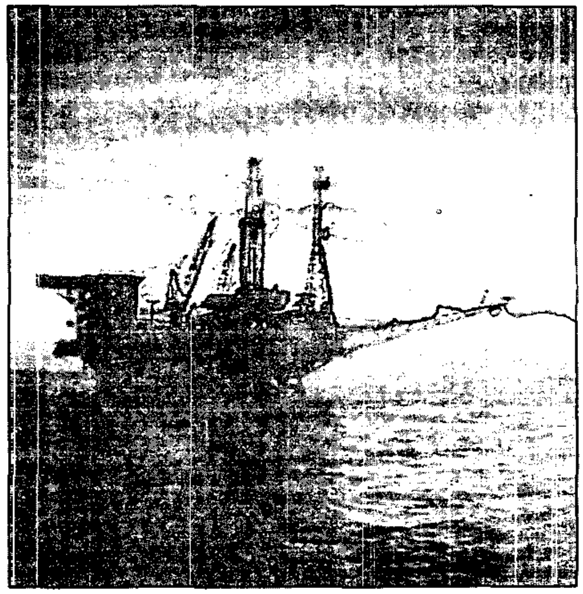
The 480 VAC distribution system is divided into three separate, high resistance grounded systems. One supports the drilling functions of the facility and is fed from one 2000 kVA oil filled transformer and feeds one main ANSI low voltage switchgear assembly. The second supplies the utility functions of the facility and is fed from one 2000 kVA oil filled transformer and feeds one main ANSI low voltage switchgear assembly. The third supplies power for all production related activities and is fed from two, 2000 kVA oil filled transformers operating in parallel and feeds two main ANSI low voltage switchgear assemblies. Each of the switchgear assemblies is comprised of low voltage power frame circuit breakers. These assemblies in turn feed many UL 845 type low voltage motor control centers. Each of these low voltage systems is high resistance grounded by interconnection of a 200 Ohm resistor between the transformer wye connected secondary and ground. Ground fault detection is not selective in this system and is provided with an over voltage relay, voltmeter, and ammeter on the grounding resistor.

BOB HOPE CLASS SEA LIFT COMMAND VESSELS



The Sea Lift Command vessels were non-combatant vessels that were used to transport military equipment to a specific location. These were RoRo vessels (roll on – roll off) and were huge floating, self-propelled parking lots. Each vessel was approximately 950 feet in length and had at least five levels for vehicle storage below decks. This yielded approximately 393,000 square feet of cargo stowage area. The electrical distribution system for each vessel is comprised of five 4000 kW 480 VAC engine driven generators of which four are operated in parallel continuously. The generator main circuit breakers were ANSI power frame breakers and the main distribution breakers were a combination of fused power frame breakers and fused molded case 400 and 800 Amp frame UL 489 breakers. These are installed in a 10,000 A, 200 KA rated generator control switchboard that was ungrounded. The primary source for the electrical loads were the hundreds of ventilation fans necessary to keep the below deck air quality acceptable. The main 480 VAC bus was ungrounded and provided with the standard ground fault indicating lights using instrument transformers arranged in a delta configuration. The normal operation of the indication lights is that they would burn at half brilliance and when one phase became grounded it corresponding indicating light would be de-energize and the remaining two would illuminate at full brilliance. Each light panel board would be provided with its own 480 – 240/120 delta/delta interconnected lighting transformer. Also, each individual secondary circuit was provided with its separate set of three ground fault indicating lights usually located on the upper portion of the panel board. This made it easy to locate and repair any and all ground faults. There were in excess of one hundred 120 VAC ground detection systems on board.

LAWIT A



Lawit A is an offshore fixed leg facility that was located on the coast of Malaysia. In this application, the engineering consultant invoked the requirements of ABS for marine electrical systems. The electrical distribution system for Lawitt A consists of a 6600 VAC generation and distribution system and a 480 VAC distribution system. The 6600 VAC consists of four 3000 kW, 6600 VAC turbine generators three of which are operated continuously in parallel. Each of these machines is ungrounded with the neutrals insulated and interconnected directly to the main ANSI metalclad type switchgear assembly that is comprised of vacuum circuit breakers and static type electronic protective relays. The 6600 VAC distribution feeds a number of large motor loads ranging in size from 600 hp to 2250 hp. The 480 VAC distribution system is fed from two, 2500 kVA oil filled transformers and feeds two main ANSI low voltage switchgear assemblies comprised of low voltage power frame circuit breakers. Each of these distribution transformers is high resistance grounded. These assemblies in turn feed many low voltage motor control centers.

The grounding for the main 6600 VAC bus was separately derived using three 6600 – 240 VAC control power transformers arranged in a wye-delta connection. The delta-connected secondary was arranged in a broken delta portion of the delta-connected secondary to limit the circulating currents present in the delta during a ground fault scenario. The resistor bank wattage requirements were calculated to allow for the full load rating of the grounding transformers. A voltage relay, voltage and ammeter were provided on the resistor assembly to provide alarming and annunciation functions. The grounding transformers were intentionally oversized to allow for approximately 8 to 9 Amps of primary ground fault current. This was significantly above the anticipated capacitive charging current for the system. The system was designed to allow for selective ground fault alarming and tripping. Each feeder was provided with a sensitive ground fault relay and a very sensitive core balance current transformer with a 1 Amp secondary. The grounding system would indicate which feeder experienced the ground fault and allow it to stay energized on the system for approximately 48 hours. At that point, if the fault were still active, then the affected feeder would be automatically tripped off line. This was one solution for a selective HRG system requirement.