DOWN TO EARTH OR EARTHING OF NAVAL MARINE POWER SYSTEMS

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ABSTRACT

Since the introduction of 440V ac systems in Naval Marine electrical power systems it has been accepted practice to adopt insulated neutral 'unearthed' systems to ensure system performance and safety. However increased capacity systems, a trend towards higher voltages, more extensive use of commercial off the shelf equipment and increased use of power electronics is challenging this practice. This article reviews current earthing practice in naval marine systems, discusses the challenges to unearthed systems and proposes a new earthing policy for low and high voltage systems.

Introduction

Traditional Naval Marine systems at 600V and below have had insulated neutrals without connection between system neutral and earth; in the case of a marine platform the earth is represented by the continuous equipotential plane provided by the hull. The reasons for adopting such an approach are founded on the ability for a system with a single fault to continue operating and the very low fire and flash hazards. The unearthed neutral approach does however mean that faults must be located and remedied quickly to prevent a phase to phase fault arising from a second earth fault.

A number of challenges however threaten the convention of unearthed, insulated systems – increased capacitance as a result of increased use of electronic equipment with EMI (Electromagnetic Interference) filters and Commercial Off The Shelf (COTS) equipment, High Voltage (HV) (1000 V ac and above) and the integrated nature of electric propulsion.

In a power system it is impossible to avoid electrical couplings between the system and earth -- in an insulated system capacitance to earth has long been the source of electrical coupling. In some cases this has been an accepted norm, as in the case of the stray capacitance between phase conductors and earth but the trend to modern electronic equipment has further increased the system's capacitive burden. In principle this capacitive earth can provide a return path for an earth fault, tripping the circuit protection device and disrupting the system. The increased capacitance also causes significant problems with earth fault monitoring systems.

Trends to higher voltages also challenge the accepted practice for insulated systems with increased touch potentials and overvoltages. While the increased insulation stress in LV systems during earth faults can be readily accommodated in HV systems the additional cost of designing the insulation to withstand the stress caused by a phase to earth fault is considerable. The additional burden of integrated electric systems and complex power electronics further challenge the use of insulated systems.

Broadly speaking, the earthing solution for a marine power system is a key part of the power system design set with the ability to impact significantly on system performance, operability, survivability, installation costs and electromagnetic compatibility.

EARTHING AN OVERVIEW

The Concept of Earth

The concept of an electrical 'earth' in power systems springs from land based practice where copper rods are driven into soil or, in larger installations, extensive metal earth grids are installed in the ground. This establishes a low impedance connection to the bulk of the earth providing a safe return path for fault currents. Equipment case work is connected to this earth to prevent the danger of electrical shock when the case work is touched during a fault. In steel ships the hull and ships structure provides a very low impedance path for power system fault current. The equivalent of earth rods are earth studs to which equipment earths are connected.

Treatment of Neutral Point

In ships power distribution schemes a number of different voltages are provided by transformers which reduce the voltage generated at the main switchboard and provide galvanic isolation. The bulk of LV power is distributed by 3 phase systems typically at 440 V and 115V. Each of these galvanically isolated sub-systems may be earthed in a different way. In general it is the treatment of the neutral point, which characterizes the earthing. However in a single phase sub ssystem one phase could be earthed. The treatment of neutral points ranges from solid earthing, through resistance earthing to the more complex Peterson coils. A mixture of earthing strategies co-exist in a number of these vessels.[i]

Safety

There is a general misconception that unearthed systems are inherently safer than neutral earthed systems in that a single phase conductor may be touched without fatal consequences. This may be true in low voltage schemes supplying small systems, however in most systems stray and intentional capacitance to earth will provide more than sufficient current to cause electrocution.

In LV systems RCDs (Residual Current Devices) trip a circuit when they detect there is earth fault current flowing. They are used in earthed neutral systems to provide a measure of personal protection. They may also provide some level of protection in unearthed systems when stray and capacitive earth currents might otherwise prove fatal. Protection in unearthed schemes is more likely to be effective the closer the RCD is to the fault or contact with the live conductor.

EARTH FAULT CURRENTS EXPLAINED

In a unearthed system the current that flows when a phase connects to earth (earth fault current) is small allowing the system to continue operating without damage. The magnitude of fault current is dependent on the phase to earth capacitance of the two healthy phases as shown in (FIG.1). If a second fault occurs in a different phase at a different location large phase to phase fault current will flow through the earth return path. The earth scheme has to be designed to withstand this high level of potential earth fault current flow.

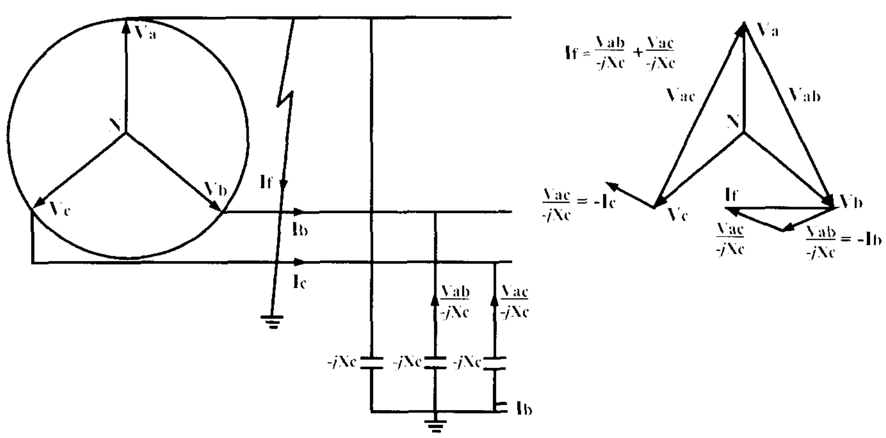

FIG. 1 EARTH FAULT ON AN INSULATED SYSTEM

The earth fault current is the sum of the currents flowing in the healthy capacitive phase connections via the fault to the faulty phase. Typical values of phase to earth capacitance for LV systems are in the range 1-5μF per phase and in naval marine applications are restricted to a maximum of 10μF per MW of installed generating capacity for 60Hz systems with resultant earth fault currents generally too small to operate earth fault relays. The analysis does however demonstrate that phase and neutral capacitive effects can impact significantly on both the hazard of a system and system protection during a single fault. Capacitive effects will be discussed in detail in the article.

The earth current returns to source by the 'easiest path'. In steady state dc current returns by the path of least resistance and spreads out widely through the ship's structure. However in ac systems (and transiently in dc systems) current follows the path of least impedance – being the combination of resistance and inductance. Thus a co-axial screen or conductor close to the faulted phase conductor is likely to carry a large proportion of the fault current. This has the benefit of minimizing the EMI (Electromagnetic Interference) produced by fault currents but the hazard of 'focussing' current in conductors unable to carry the fault current. It is therefore recommended that electrostatic cable screens are earthed at one end only to prevent fault current from damaging these low inductive co-axial paths. In the Type 45 it is intended to run drain wires close to trefoil power cable bundles to suppress potential high frequency EMI. These will be earthed at both ends and because of the low inductance of this path are liable to be melted by fault current despite the hull return path taken to be an earth plane at 2,000mm distance. Even fitting a 250mm^2 copper tape at 250mm distant from the drain wire does not appear to prevent damage to the drain wire. It is the current design intent that drain wires will be protected by fuses which will only be ruptured in the improbable event of a double earth fault. This will also prevent collateral damage to the HV power cable and safety hazard. It is intended to run some minor trial during the build of the Type 45 to confirm this theory.

Regulation

The commercial regulatory bodies including Lloyds Register of Shipping and Det Norske Veritas together with the IEE and IEEE allow the use of earthed and unearthed systems for both HV and LV systems. In most cases the system designer is required to ensure that earth fault currents are maintained within certain bounds to ensure that earth fault protection operates and insulation levels are not compromised. Defence Standard (DefStan) 08-109 2 however is rather more explicit and mandates insulated systems to ensure that important services are not disconnected by the protection system in the event of a single earth fault. Circuits fused at 10A or more are to be capable of surviving capacitive earth fault current with systems, although degraded, regarded as serviceable until the fault is repaired. Operational and safety related equipment are to work normally during such fault conditions.

Commercial Regulatory bodies are relaxed about the use of earthed systems. In particular Lloyds Rules for Naval Vessels[3] allows four wire with the neutral solidly earthed but without hull return. This reference to hull return is assumed to exclude the use of hull as the neutral return path not to exclude it as the earth fault return path. Rather confusingly this would appear to exclude resistively earthed systems however the regulations state that in 'high voltage' systems an impedance is to be used in the neutral connection to earth to limit the magnitude of the earth current to that of the three phase short circuit current.

The Hull – The most effective Earth Return?

Copper has the lowest bulk resistivity of all common metals – only silver has a (marginally) lower value. The resistivity of steel is about 10 times greater than copper. Despite this higher resistivity the ship's structure and hull, with electrical continuity throughout provided by welded construction, will provide the lowest resistance between two points on the ship structure separated by more than a few inches. It probably provides a better 'earth' than any land based installation. A typical value of steel resistivity is 20×10^{-8} Ohm m, which, implies that a 1mm thick steel plate 1 meter wide will develop 20 volts per meter along its length if 100kA amps flow. It is clearly well nigh impossible to develop high step or touch potentials in a structure where deck plates to which earths will typically be taken are at least 6 mm thick. In addition these deck plates are welded to substantial longitudinal and transverse steel beams.

Capacitive effects

The proximity of phase conductors to earthed surfaces provides substantial capacitance to earth particularly in wound components such as generators and transformers. Screened cables also provide another source of stray capacitance. As more electronic equipment is fitted EMC filters provide more intentional capacitance. These generally comprise capacitors connected between each phase and earth. This capacitance sums up across all equipment to give a surprisingly large value. In the ASTUTE class submarine project three equipment on their own provided 12μF and the figure appeared to be rising towards the figure of 70μF noted as typical of the capacitance to earth in a large system.

To avoid the hazard of undischarged capacitors during maintenance most of these capacitors will have high value 'bleed' resistors permanently connected between the phase conductor and earth. In HMS *Scott* the total of these bleed resistors reduced the insulation to earth to 25 k Ohms completely swamping the earth monitoring system. Special measures had to be taken to disconnect the earth bleed resistors during normal operation and connect them only when the equipment was, isolated ready for maintenance. Power transformers have been fitted in other classes to isolate weapons loads, which have exhibited these characteristics.

Earth Fault location (Unearthed)

The advantage of unearthed systems (that the system can continue to operate in the presence of a single phase to earth fault) only applies if there is a single fault (or multiple faults on the same phase). As soon as a second fault occurs phase to phase fault current will flow in both faulted circuits and both will be lost. As a result considerable time and effort is expended in locating earth faults. In the past this has required splitting of the system and the isolation of each circuit in turn until the fault disappears. If two faults on the same phase exist simultaneously the search processes is even more protracted.

Earth fault monitor and location equipment exists which can reduce the search time. However a comprehensive system is bulky and expensive. In the ASTUTE class submarines automatic earth fault detection is provided on the 440V, 115V and 400Hz ac and main 240V and 24 Vdc systems. Each protected circuit requires a CT in its outgoing circuit. Despite providing detection in all main switchboards and ac Load Centre outgoing circuits, manual intervention is required to detect faults on most final circuits. In the Type 45 a basic system indicates which outgoing circuit from the two main LV switchboards is faulted, below EDC (Electrical Distribution Centre) level manual isolation is required to identify the faulted circuit. On the 115 Volt system only the presence of a fault is indicated. Fault finding is again manual.

Earth faults down stream of a three phase rectifier apply the earth fault to each phase in turn and complicate earth fault detection as 'diode or' circuits in dc distribution schemes.

Earth Fault location (Earthed)

In earthed neutral schemes used commonly in domestic, commercial and industrial systems normal overcurrent protection will trip the circuit in which the earth fault occurs provided the earth return path has low enough impedance. Thus in general an earth fault announces itself by the isolation of the affected circuit. In land based systems an extra 'earth' wire is run with the phase conductors this wire is sized to ensure that there is sufficient earth return current to operate the overcurrent protection device. Where equipment case is attached to ship's structure by the normal safety earth a good earth return will be established without this third (or fourth) wire.

Cost savings in earthed LV systems

Substantial savings can be made when earthed neutral schemes are adopted. An earth fault monitoring and location system need not be fitted, both 3 phase and single phase voltage are available (usually 415/240 V) and this is frequently required in COTS equipment. In single phase distribution panels single pole switching is appropriate reducing the size and cost of these items. COTS equipment can be applied without modification to EMI suppression circuits and design skills, codes and computer packages developed for the commercial environment can be applied to the marine environment more easily.

Some issues

Solid earthing of the generator neutrals does however have some downsides[1] – the earth fault current, limited only by zero sequence reactance, is higher than phase to phase current increasing the duty and possibly size of the LV switchboards. When two generators with solidly earthed neutrals are operated in parallel third harmonic current may be circulated causing machine heating. This problem can only be overcome by special earthing arrangements or oversizing the generators. These problems do not exist in transformer fed systems where at least at low voltage the neutral point of each transformer may be solidly earthed.

As noted elsewhere neutral earthed systems cannot continue to operate with a single earth fault. It is a matter of debate how often a single earth fault occurs. However almost all essential services are duplicated and the loss of one due to an earth fault will rarely cause embarrassment.

RADICAL RETHINK OR NATURAL PROGRESSION FOR LV SYSTEMS

Having exposed the issues related to choice of earthing strategy it is clear that the norm of insulated systems could be challenged without any loss in performance, protection, operability or safety. In broad terms a move to an earthed system will remove obstacles to the selection of COTS equipment and reduce the cost of their modification to make them:

- Suitable for application in unearthed schemes.
- Reduce the cost of the installation.
- Eliminate earth fault tracing as a maintenance activity.
- Improve availability as compared to an unearthed scheme if earth faults are not traced and remedied rapidly.

The overview presented above shows that LV earthed systems have been used in the commercial marine world and are not proscribed by commercial regulations. The advantages claimed of unearthed systems are diminished by:

- The increased extent of power distribution schemes.
- The increasing use of EMC filters and capacitive coupling to earth.
- The complex earth paths introduced by 'diode or' and diode front end circuits.

It is believed that the system designer can achieve considerable cost savings by the adoption of earthed neutral LV systems without any significant impact on safety, availability or operability. It is also believed that the time spent in earth fault chasing, which will be eliminated in an earthed scheme, represents a considerable manpower saving. For the Naval marine electrical world this will be something of a radical step however the commercial world has gone ahead, at least in part, and realized the benefits of earthed schemes.

THE NEW CHALLENGE

Well rehearsed, well documented and understood, Integrated Electric Propulsion (IEP) brings together efficiency, flexibility, survivability and, perhaps most importantly, reductions in cost of ownership. Captured simply – reduced prime movers, integrated systems, a step away from the tyranny of the shaftline and the commercial precedent make it the obvious credible solution to the requirement.[4] This trend has however provided many new challenges for marine power system designers in terms of integration, performance and system stability; a key aspect of which has been a need to implement an effective earthing strategy.

The focus on earthing is a function of the higher voltages and IEP, particularly advanced converter control strategies and transformerless drives, have meant a potentially increased electric shock hazard, increased overvoltages, an array of common mode voltage and current effects, increased Electromagnetic Interference (EMI) and greater demands on protective circuits.

Discussing each of the challenges in turn:

Electric Shock Hazard

The fault currents in large capacity HV systems are potentially higher than those of an insulated LV system with currents in excess of 10mA, the notional level at which heart fibrillation and death are likely. An earthed system together with minimizing the likelihood of contact with exposed current carrying conductors will reduce the problem to an acceptable level of risk.

Overvoltages

Overvoltages are caused by a range of incidents including earth fault, failure of voltage regulation, intermittent arcing earth faults and switching operations – not all of which are attributable to the choice of earthing system. Indeed it is the potential of inductive and intermittent faults that are the most significant challenge to unearthed systems. The case of an intermittent earth fault best demonstrates the problems associated with an unearthed system. The intermittent nature of the fault results in a high unidirectional voltage as a function of alternate conduction and insulation which in a capacitive circuit leads to a residual voltage level each time the circuit is interrupted; a build up which would be prevented by a neutral earth connection. The example is oversimplified and the effects of damping and interphase capacitance would contribute to reducing the oscillatory effects and hence lower the overvoltage but it still remains a key issue.

Common Mode Effects and EMI

The integrated nature of the IEP system means that unless subject to a robust earthing strategy the system can potentially experience significant common mode voltage/current effects and unacceptable levels of EMI. The problems associated with IEP are further compounded when using a transformerless Pulse Width Modulated converter. A suitably designed overarching system earthing strategy is essential to management of such effects.

Protection Issues

The coordination of earth fault protection is a key tenet of the earthing strategy and is a trade off between rating and implementation of neutral earthing technique, the selection of earth fault protection devices and the protection of sensitive equipment.

The challenges for the power system designer clearly support the need for high voltage integrated electric systems to be earthed using a Neutral Earthing Resistor (NER) and a range of supporting earthing techniques if the earthing strategy is to be effective.

AN INDICATIVE SOLUTION FOR IEP SYSTEMS

Having made the case for an earthed HV system the following individual design areas will now be reviewed:

i. NER design and rating.

ii. Management of Common Mode Effects and EMI.

iii. Protective conductors.

iv. Earthing Architecture.

v. Earth fault protection.

NERs

NER solutions include solid, high resistance, low resistance and inductive neutral earthing and it has been shown that there is little to choose between the methods.[2] In outline the high resistance NER solution is chosen to:

- Manage earth fault current to 10 amps to allow automatic detection and isolation of a fault whilst minimizing circuit disruption.
- Prevent the build up of destructive overvoltages caused by intermittent arc faults with the resistor is sized to limit the fault current to 3 times the per phase capacitive charging current of the system.
- Minimize the potential for damage during an earth fault.
- Decouple EMI from the HV system.

The NERs are rated to withstand full system voltage and are connected to the starpoint of each generator noting that the HV system insulation will need to be sufficiently rated to account for the raised neutrals ($V_{Line}/\sqrt{3}$) experienced during an earth fault.

It is also common practice to include a Neutral Earthing Capacitor (NEC) in parallel with the NER to manage common mode voltages and provide a low impedance path for the 3rd harmonic currents that characterize a system in which dissimilar generators are operated in parallel. The NER and NEC need to be optimized to manage transient overvoltage during a fault.

Management of Common Mode Effects and EMI

The minimum recommendation for the control of common mode effects and EMI is achieved by the earthing and connection of cable screens. Able to carry full earth current regardless of fault noting that an internal earth fault to the screen. In broad terms inner screens of HV cables must be connected at one end to reduce insulation stress. Generally cable inner screens are connected at one end to relieve insulation stress and outer screens are earthed at one end to reduce voltage induced fields. The problem for converted supplies is more onerous, notably for PWM waveforms, with the solution for the inner screen to be earthed at both ends to manage potential circulating currents.

Protective Conductors

Single core power cables run in trefoil groups do not have the inherent ability to manage EMC that is exhibited by screened three core cables. A solution is therefore required to control insulation stress and manage EMC for phase conductors. The preferred solution is a multistrand protective conductor (drain wire) run together with the trefoil phase conductors. The earthing of this protective conductor needs to be considered to maintain a low impedance path and provide optimum protection from EMI.

Earthing architecture

The overarching earthing structure hinges on the integrity of the ship's hull being the accepted earth return path with a network of standard connections from equipment and systems as discussed earlier in the article. In addition, earth bars will ensure earth continuity within equipment, notably switchboards and converter cubicles.

Earth fault protection

HV earth faults are rare in the commercial marine due to the limited and protected nature of the HV system. The naval environment is however much harsher and the problem is further compounded by trends towards unarmoured cables and reduced levels of protection (a function of available space, derating issues and shock requirements). Studies have shown that the mechanical wear and tear in normal use does not justify use of armour and that no armour (or mechanical protection short of armour plating) would protect against action damage.

The co-ordination of earth fault protection is essential if the correct levels of discrimination are to be achieved and affected sections of supplies isolated.

Summary preferred design solution

In outline, the preferred design solution for the HV system is as follows:

- The ship's hull will always be the System Main Earth.
- A High Resistance Grounding System incorporating a Neutral Earthing Resistor with a Neutral Earthing Capacitor in parallel to reduce common mode voltage from the drive and to manage 3rd harmonic currents.
- Generally Cable inner screens are connected at one end to relieve insulation stress.
- Outer screens (if fitted) are earthed at one end to reduce voltage induced fields.
- Motor – Converter Cable inner screens are connected at both ends to manage circulating currents.
- Multistrand Protective conductors are run with phase conductors to provide low impedance paths to reduce EMI.
- Earth return paths are via equipment continuous earth bars, which are connected to the system main earth by suitably rated earthing studs and connections.
- Equipment earth bonds are also provided for local earth bond connections.

Conclusions

In producing this article it has been shown that the real challenge for the naval community has been how to implement an effective earthing strategy for integrated power systems. This must utilize High Voltage and extensive COTS equipment against a need to ensure new power systems are able to meet safety, operability and survivability challenges; not forgetting the statutory requirements.

Whilst the demands and requirements of the naval environment are very different to commercial practice it is clear that the accepted solutions currently in use in commercial applications are very relevant and it is the interpretation of these standards and translation to the naval environment which is key.

The designers of LV system architecture should be released (from the MoD imposed requirement to provide unearthed supplies to seek the most economic solution that meets ARM (Availability, Reliability and Maintainability) standards. Generator derived supplies at 450V will probably remain unearthed. However transformer derived supplies either lower voltage (115V) or 450V systems derived from an HV system (and there will be more of these as IEP solutions are adopted) will probably be earthed. It is believed that such measures will:

- Remove obstacles to the selection of COTS equipment and reduce the cost of their modification to make them suitable for application in unearthed schemes.
- Reduce the cost of the installation.
- Eliminate earth fault tracing as a maintenance activity.
- Improve availability as compared to an unearthed scheme if earth faults are not traced and remedied rapidly.

The issue of how to take this forward to ensure the design solutions are transferred between classes where appropriate is extremely important. Current MoD initiatives suggest that an amendment to DefStan 02-532 would satisfy any changes in LV earthing policy with the HV policy covered in the yet to be issued DefStan for HV systems.

Earthing is a discipline that crosses the bounds of the power system and must be considered early in the design process if the equipment and system selection is to be fully effective.

Acknowledgements

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