Grounding and Fault Location in Power Electronic based MVDC Shipboard Power and Energy Systems

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***Abstract*—At present there is no standardized grounding method for medium voltage direct current (MVDC) shipboard power distribution systems. This paper introduces a method for selection of a maritime MVDC grounding scheme that considers technical acceptability, maintainability, reliability, safety, and feasibility. Several candidate grounding approaches and the results of the selection process are presented. In addition to the MVDC grounding method, a potentially suitable ground fault location approach based on noise pattern analysis is evaluated. The sensitivity of this fault location approach to source-ground capacitive coupling is analyzed using a notional two-zone MVDC ship distribution system model.**

I. Introduction

As ships trend toward higher power loads, low voltage alternating current (LVAC) becomes untenable due to increased` cable size and associated circuit protection, thereby increasing weight and complexity. One method of mitigating this limitation is to use medium voltage alternating current (MVAC) as seen in the DDG-1000 and CVN-78 class ships. MVAC allows low risk implementation on naval vessels because of its widespread use in commercial infrastructure, but does not significantly improve the power distribution challenges. MVDC not only reduces cable size but allows unparalleled power conversion flexibility, simpler casualty power operation, and eliminates a majority of the emissions from the AC distribution frequency including MIL-STD-1399 [1] power quality characteristics and acoustic emissions. For this reason, the Naval Power and Energy Systems Technology Development Roadmap [2] identifies MVDC as an ideal solution for the next generation warship. However, MVDC is an emerging technology that has not been well established as a design standard, notwithstanding the recommendations provided by IEEE 1709-2010 [3], and requires further analysis before implementation.

This paper describes an analysis method to determine the optimum grounding method for a MVDC vessel. This study analyzed a number of naval and electrical engineering concerns to determine the most promising method that will further undergo hardware-in-the-loop (HIL) testing to verify the selection and determine the method's limitations. The team analyzed the grounding methods not only based on technical acceptability, but also whether the system will benefit the end user. This data will be used to create a military standard to guide the ship designer before the first MVDC ship is developed.

Techniques currently employed to locate line-to-ground faults in shipboard applications have potential drawbacks in a MVDC architecture. Increasing numbers of large power electronic converters presents challenges when measuring network impedance to determine ground fault location. The authors of [4] presented a method for ground fault location in ungrounded ship distribution systems based on noise pattern analysis. The applicability of this method to a MVDC architecture employing the selected grounding method is herein evaluated. Interactions between power electronic converters, acting as high frequency harmonic sources, and parasitically coupled elements within the distribution system create a characteristic high frequency noise that is unique to each system. This background noise is altered when a ground fault occurs, as the characteristic ringing circuit of the underlying distribution system is now changed. With careful analysis of the noise patterns associated with various fault locations, a differentiation between ground fault locations can be made.

This is a multi-phase research effort to document a MVDC grounding standard that will detail system requirements, grounding method, neutral topology, and integration of the patented fault detection and isolation method [5]. Phase 1 consisted of analyzing the problem, researching the possible grounding methods, performing initial simulation studies, creating and populating an Analysis of Alternatives (AoA), and selecting the most promising grounding method for further analysis. During Phase 2 the team will perform detailed modeling and simulation (M&S) to determine broad system limits, HIL testing will then be performed using the M&S results to determine precise system requirements, and a draft standard will be written to detail this information. Phase 3 will complete the MVDC grounding standard and will involve analysis and design of a MVDC ship.

II. Grounding Method for MVDC Shipboard Power Systems

An AoA was performed on a comprehensive data set of grounding methods to determine which should be selected for further testing. The grounding methods under review were selected from methods currently used for commercial power distribution, those used on ships, and methods that currently do not have widespread use but may be applicable. While some of

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these methods have widespread use in land-based, commercial applications, this study is for naval vessels that require unique considerations to be analyzed and tested. During the analysis, it was determined that the method of creating the DC neutral point must also be taken into account, so the analysis was expanded to include this consideration also.

A. Assumptions

Before the analysis could begin, two assumptions were made. The first was that the supply bus would be a dual rail consisting of a bipolar DC source. This was done because a single rail would require cable insulation rated to much higher voltages, high likelihood of excessive stray currents causing corrosion and safety concerns, and would experience high line-to-hull voltages. Second, was exclusion of line-to-neutral loads which would restrict the available grounding methods with a high risk of stray currents. While these loads are still possible inside of the zonal architecture, they will not be connected directly to the main distribution bus. It is also important to note that the Navy does not currently use line-to-neutral loads, so this limitation will have minimal impact to ship designers.

B. Analysis Methods

The team designed an analysis method that would determine a grounding method that is not only technically acceptable, but can also be practically applied to a naval ship for a long and reliable service life. A number of steps were taken to determine which grounding method should be explored for further evaluation and hardware testing. First the grounding methods to be studied were selected, and then analysis criteria were selected. Extensive research was then conducted for each candidate grounding method across all analysis criteria. Using the results of this analysis, along with appropriate M&S to support the conclusion from the analysis, a grounding method was selected. Nearly 50 analysis criteria were considered using known power distribution fundamentals, input from subject matter experts, known naval engineering challenges, and collective team experience. These criteria were grouped into five categories: ship design, safety, performance, implementation, and logistics. The AoA was compiled with data on each of the seven grounding methods to not only show where each method differs, but also to show where they are equivalent. The completed AoA has allowed the team to select the most promising MVDC grounding method to further evaluate via hardware testing to determine its performance limitations before incorporation into a design standard.

C. Grounding Methods

Seven candidate grounding methods were evaluated; diode, active, solidly, low resistance ground (LRG), floating/ungrounded, impedance, and high resistance ground (HRG). These grounding methods were selected from commercial applications, military applications, IEEE standards, and market research. Each method provides great benefit to the market that they are designed for, however, none of these were specifically designed for MVDC and there has been limited testing to determine their applicability.

1) Active: The active grounding method was defined as a variable resistor allowing the performance of the power distribution system to be tailored to the conditions desired. For example, a LRG can be used during peacetime operation to limit the stress on equipment during a fault and provide maximum safety to personnel, but HRG could be used during operations to ensure mission availability and fault tolerance. However, this method could require significant ship integration complexity and additional components that could affect reliability.

2) Solidly: Solid grounding is used extensively on low voltage (LV) applications. This method allows the lowest voltage rise during a fault and reduces insulation stress. However, fault current is extremely high which not only damages conductors, but is also an arc flash and ultimately an explosive hazard to a ship. Because of this, solid grounding has been primarily limited to low voltage and low power applications for sensitive electronics and in applications with direct contact to personnel.

3) LRG: LRG is primarily used on medium voltage (MV) applications that require minimal voltage rise during a fault, and cannot tolerate near infinite fault current seen in a solidly grounded system. LRG would provide many benefits to the Navy, but will not allow operation with a single line-to-ground fault which could be detrimental during an operational scenario.

4) Floating: Floating systems are the primary grounding method on most Navy ships today as LVAC in a Delta configuration. This system allows for operation with a single line-to-ground fault, and minimizes stray currents. However, it requires the highest insulation rating to withstand voltage rise during a fault and increases the hazard to personnel if chassis and the ship's hull are not bonded properly.

5) Diode: Diode grounding has been developed to solve many issues for electrified rail systems. Earlier systems were solidly grounded, but encountered significant stray currents leading to erosion of the rail and fasteners [6]. These systems then transitioned to a floating system, but a truly floating system is not practically possible and risks significant voltage differentials between the platform and train during a fault. By placing a diode between the neutral and ground, low voltage stray currents are blocked, eliminating a significant amount of corrosion. The diode breakdown voltage is selected to limit the possible platform to car voltage to an acceptable level.

6) Impedance: Impedance grounding for MVDC combines either LRG or HRG with the addition of capacitors or inductors to provide additional filtering. It is unknown how much benefit, if any, a DC system will gain from this configuration, but it was investigated as an option.

7) HRG: This grounding method provides the benefits of an ungrounded system while limiting the voltage rise during a fault. However, because the system can operate with a single line-to-ground fault, an accurate ground fault detection system must be employed to notify the operator of a fault to prevent corrosion and hazards to personnel.

D. Neutral Topology

The neutral topology plays a pivotal role in how a system will perform in all of the grounding methods except for floating. Fig. 1 shows a simplified example of a rectifier producing bipolar DC with a natural midpoint, and Fig. 2 shows a resistor divider based neutral. A natural midpoint minimizes parasitic losses experienced, but requires a more complicated generator and rectifier design to create. The resistive method can be used with standard three-phase supply and can use variable resistors to calibrate the neutral point from any drift losses, but adds parasitic losses to the electrical system. Each method provides benefits and limitations that will be further tested during Phase 2 to determine feasibility in shipboard applications.

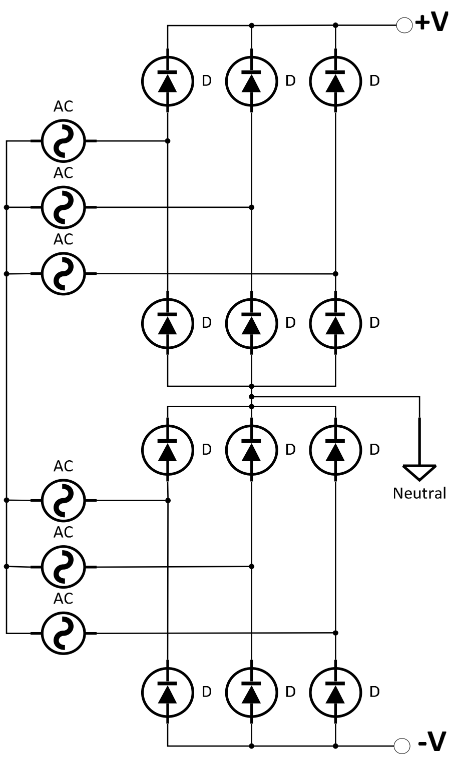

Fig. 1. Rectifier Neutral

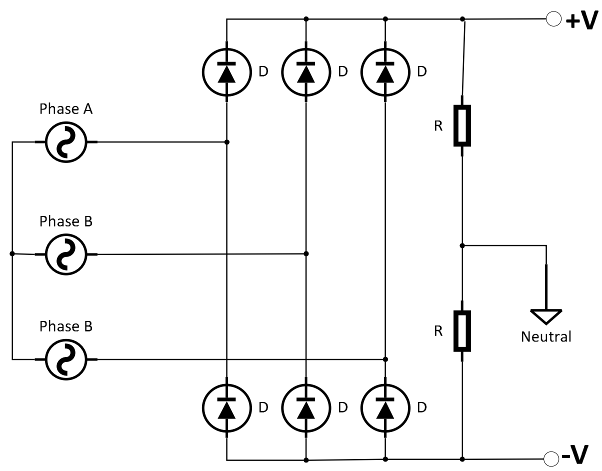

Fig. 2. Resistor Divider Neutral

E. AoA

A spreadsheet with 49 comparison criteria was composed to compare each grounding method. These criteria included typical electrical engineering and naval architecture concerns to ensure the system will provide maximum performance and ease of use to the Navy. Criteria included insulation rating, use on nonconductive ships, use on similar systems, hull currents, casualty operation, ability to backfit, and others. Each cell was populated with data and then highlighted as a positive or negative point. The result was a very clear table showing both similarities and differences for each grounding method as well as highlighting the grounding methods with the most promise. The selection of these criteria was the critical step during this study, because all stakeholders' concerns must be satisfied and the entire service life of the platform must be considered. This was accomplished by incorporating feedback from a number of different personnel with very diverse backgrounds and different focuses. The result was an exhaustive study that focused on the operational performance of the grounding system.

III. Noise Pattern Analysis based Fault Location Method

US Patent 8067942 B2 [5] provides a method for locating line-to-ground faults in DC distribution systems using a novel noise pattern analysis approach. This approach [4] differs from alternative techniques that are traditionally applied for ground fault detection, which may be less desirable in specific DC shipboard applications. No signal injection is required in this method. Rather, changes in measured noise signal patterns resulting from ground faults in the DC distribution system are utilized to detect fault location.

A. Fundamentals of Noise Pattern Analysis Approach

Oscillatory ground loops present in the DC distribution system create characteristic ringing circuits as shown in Fig. 3. During power electronic converter switching events, energy is

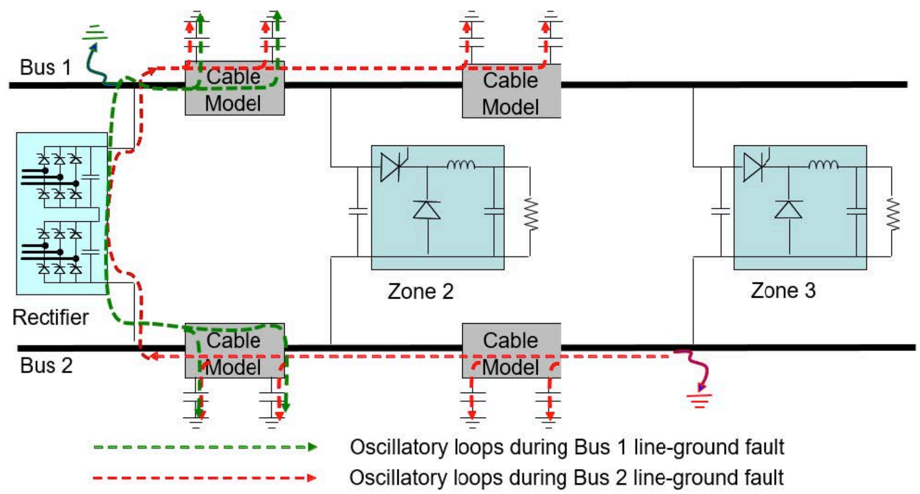

Fig. 3. Characteristic grounding loops within a shipboard distribution system

stored in parasitic elements within the circuit. This energy oscillates within the ground loops until it ultimately dissipates. When a ground fault occurs, the characteristic ringing circuit of the distribution system is altered. This fault location approach takes advantage of the characteristic noise pattern associated with each unique ringing circuit that is created when ground faults occur in various locations throughout the ship.

B. *Wavelet Multi-Resolution Analysis*

In order to differentiate between fault locations, frequency domain analysis of the characteristic noise pattern associated with each ringing circuit is required. Many different techniques are applicable for this analysis. Due to the wide range of frequencies present in the measured noise patterns, as well as the desire to represent discrete energy distributions for the purpose of classification, wavelet multi-resolution analysis (MRA) was chosen.

Wavelet decomposition has been widely applied as an alternative to Fourier analysis when it is desirable to obtain frequency characteristics of a signal while also retaining certain temporal information. Within the power systems field, wavelets are typically used in detection of high frequency signal components caused by transient events such as short circuits. In this study changes in measured noise signal patterns were analyzed using MRA with the computationally inexpensive Daubechies, or Harr wavelet [7]. In a practical implementation the fault location method must be able to quickly ascertain the correct fault location. If more computationally expensive wavelets are used, the noise signal processing time can increase considerably. The measured noise signals were decomposed into discrete frequency bands as shown in Table 1, using ten wavelet decomposition levels, and characteristic signal energy patterns emerged. As expected, during a ground fault, the noise signal energy patterns shifted in frequency and magnitude. Patterns resulting from the simulation of different fault locations within a representative system model were compared, and the results are discussed in Section IV.

TABLE 1. WAVELET DECOMPOSITION FREQUENCY BANDS

Band	Frequency
1	12.5 - 25 MHz
2	6.25 - 12.5 MHz
3	3.13 - 6.25 MHz
4	1.56 - 3.13 MHz
5	780 kHz - 1.56 MHz
6	390 - 780 kHz
7	195 - 390 kHz
8	98 - 195 kHz
9	49 - 98 kHz
10	24 - 49 kHz

C. *System Model Description*

For this study, a notional two zone distribution system model was implemented in PSCAD/EMTDC as shown in Fig. 4. The starboard and port buses are bipolar, operating at 12 kVDC. The cable models are each 100 m in length, with parameters taken from the common mode equivalent circuit model described in [8]. In order to more accurately represent the frequencies associated with this system, frequency dependent cable models were used. This cable model is essentially a distributed RLC traveling wave model, incorporating frequency dependency in each of the electrical parameters. Each DC bus is fed by two 6-pulse diode rectifiers, creating a natural midpoint for system noise measurement (see Fig. 1, and signal ‘E1’ in Fig. 4). Loads within each zone are supplied from the two DC buses through DC-DC converters (PCM1). Each PCM1 is modeled as a switch-mode DC-DC converter. These converters act as harmonic sources while switching, generating high frequency oscillations that can be measured within the distribution system. The interaction of these converters with the system's parasitic elements create a characteristic noise pattern that is distinguishable and unique when ground faults occur at different locations.

IV. Sensitivity Analysis of Fault Location Method

The noise pattern based ground fault location method extracts spectral features of voltage measurements within the MVDC system which have been demonstrated to change their characteristics measurably with different ground fault locations. The main assumption of the patented methodology until this study was that the parasitic coupling to ground within the system is dominated by cables. This assumption may not hold true if EMI filters are placed within the MVDC system or if sources and loads exhibit capacitive coupling to ground which approach the capacitive coupling of the cables. This analysis was performed to investigate the impact of additional coupling to ground at the sources by studying the maximum additional source-ground coupling that the detection method could tolerate, thus providing guidance for future naval grounding design.

A. *Description of Study*

The previously described ground fault location approach was applied to the system described in Section III. Ground faults were applied at the positive rail of Bus 1 and Bus 2, in separate time domain simulations, and the measured noise patterns were post-processed and analyzed using wavelet MRA. The goal of this study was to determine the sensitivity of this fault location method to added capacitive coupling between sources and ground at the output of the diode rectifiers, as well as to the proposed high resistance grounding scheme (Section II). The additional capacitive coupling and resistive grounding scheme are shown at the output of each diode rectifier in Fig. 4.

B. *Sensitivity to Added Source-Ground Capactivite Coupling*

To assess the sensitivity of the ground fault location method to added source-ground capacitive coupling, several simulations were performed using added capacitance connected between the two DC rails at the output of each diode rectifier. It was expected that if this added capacitive coupling began to dominate the characteristic ringing circuit of the distribution system (instead of the cable capacitances), then the noise patterns associated with different fault locations may no longer be distinguishable from one another.

Fig. 5 shows the wavelet decomposition of the noise signal measured during a ground fault on the positive rail of Bus 1. In this case, the added capacitance was at a minimum of 4.7 nF. In subsequent scenarios the capacitance was increased by a factor of 10 each time, resulting in a maximum added capacitance of 4.7 μF. The resulting wavelet decomposition from the scenario with a Bus 1 ground fault and 4.7 μF capacitance is shown in Fig. 6. As expected, the additional capacitive coupling to ground changes the system noise characteristic considerably. Most of the high frequency energy within the signal is removed, as seen by the sharp decline in signal energy contained within frequency bands 1-4. While these signal energy magnitudes are important for pattern classification, it is more important that differences in patterns due to varying fault locations be analyzed.

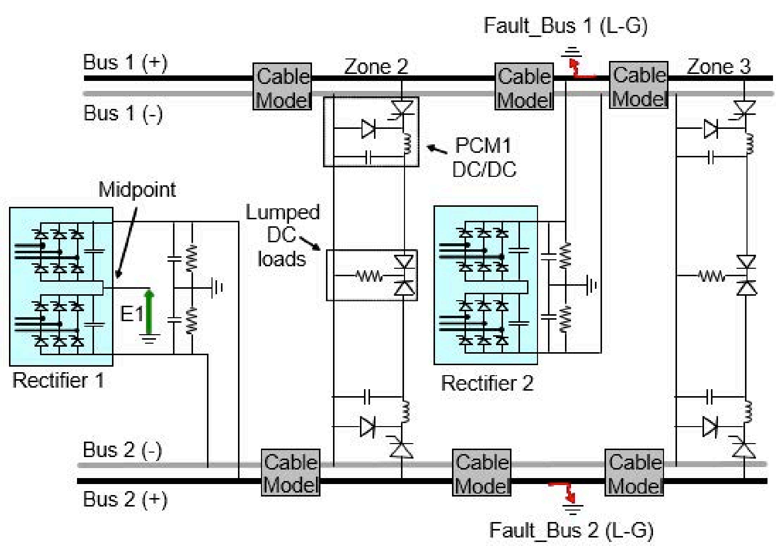

Fig. 4. Diagram of notional two zone MVDC shipboard distribution system EMTDC model used for sensitivity analysis

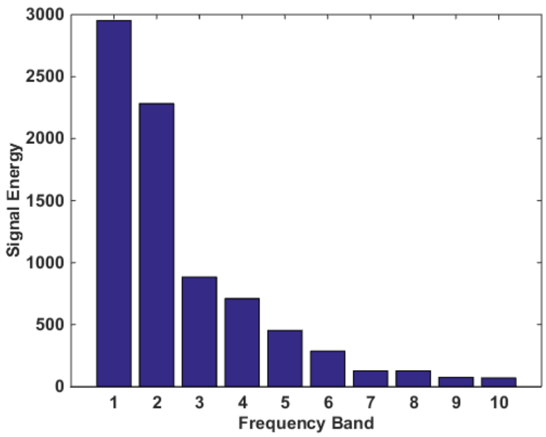

Fig. 5. Wavelet decomposition of noise signal present during a ground fault on positive rail of Bus 1; 4.7 nF C coupling

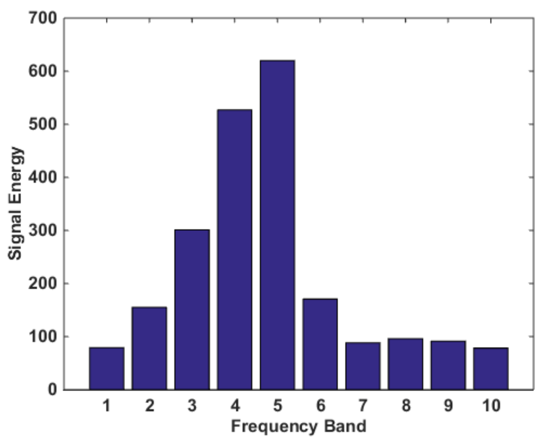

Fig. 6. Wavelet decomposition of noise signal present during a ground fault on positive rail of Bus 1; 4.7 μF C coupling

Fig. 7 and Fig. 8 show percent difference between signal energy magnitudes measured during Bus 1 and Bus 2 ground fault scenarios, for each frequency band of interest. As a convention, the Bus 1 ground fault pattern was used as the reference pattern for these calculations. For the Fig. 7 and Fig. 8 scenarios, frequency band 3 is the most useful for fault location determination. It should be noted that although signal energy in frequency band 10 appears to differ largely depending on fault location, the signal energy contained in that lower frequency band is significantly lower than many of the higher frequency bands. Therefore, it is less likely that ground fault location could be determined based on the band 10 pattern.

As capacitive coupling between sources and ground is increased further, the difference in high frequency signal energy begins to decrease. Appendix Fig. 11 and Fig. 12 show the results for the 470 nF and 4.7 μF cases, respectively. In each of these cases, frequency band 3 can no longer be used to discriminate between Bus 1 and Bus 2 fault locations. Instead the simulation results show that frequency band 6 is now the most relevant for determining whether a ground fault is located on Bus 1 or Bus 2.

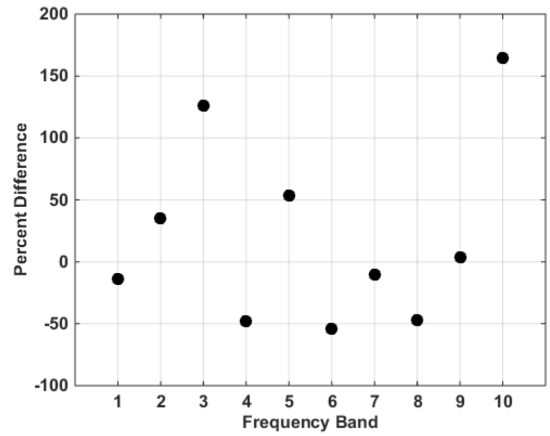

Fig. 7. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; 4.7 nF C coupling

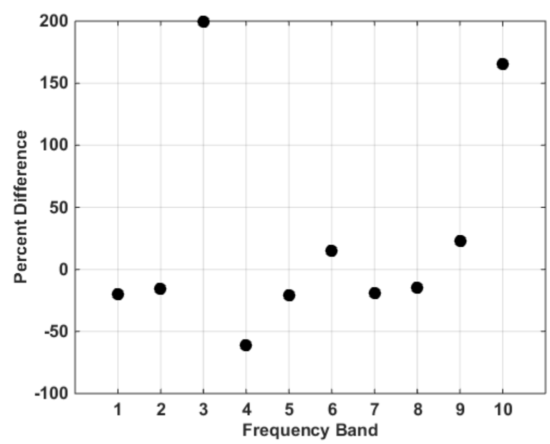

Fig. 8. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; 47.0 nF C coupling

C. *Sensitivity to High Resistance Grounding Scheme*

The same eight (8) scenarios described in the previous subsection were simulated with the addition of the high resistance grounding approach described in Section II and shown in Fig. 4. The results for the 4.7 nF and 47.0 nF cases are shown in Fig. 9 and Fig. 10, respectively. Scrutiny of the simulation results for the high resistance grounded system reveal good correspondence between the ungrounded and high resistance grounded systems when source capacitive coupling is low. However, the difference in signal noise patterns in the 470 nF and 4.7 μF cases (Appendix Fig. 13 and Fig. 14, respectively) is less pronounced. In the worst case, shown in Fig. 14, the signal energy magnitudes still differ by a maximum of approximately 50 percent. If used in conjunction with the signal energy patterns of the higher frequency bands, it is still feasible for the ground fault location to be determined using this technique.

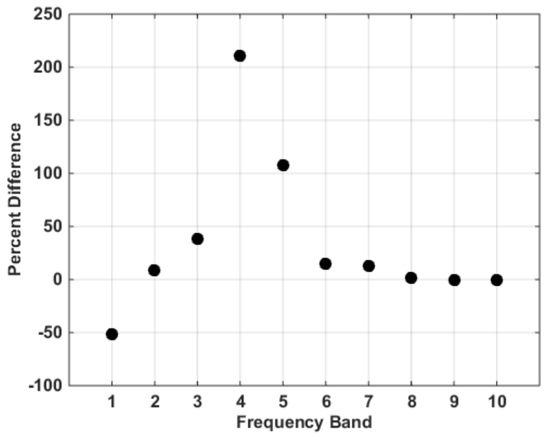

Fig. 9. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; high Z grounded, 4.7 nF C coupling

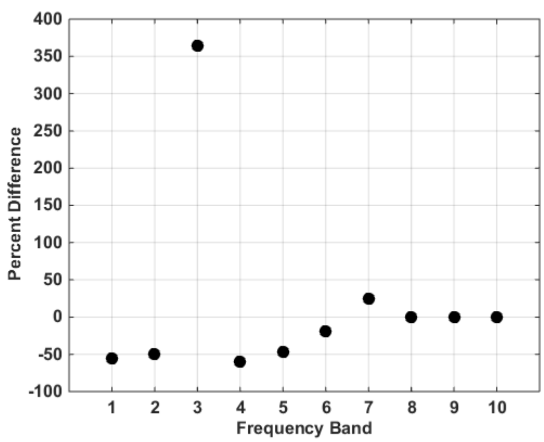

Fig. 10. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; high Z grounded, 47.0 nF C coupling

V. CONCLUSIONS

The results of the Phase 1 study were a final report detailing what was compared, the research methods, the AoA with a selected grounding method, and a Phase 2 proposal. Phase 2 will perform M&S and HIL testing on the selected grounding method using different neutral topologies and conditions to develop a performance specification. The team must determine what the system limits shall be to ensure safety and reliability of a MVDC ship. These specifications will be formalized into a military standard for public use. This standard will provide the Navy, ship designers, and manufacturers clear requirements during the acquisition of a MVDC ship. It will also reduce the amount of non-recurring engineering (NRE) costs during the development of a ship's power system by providing the design limits in advance. The initial standard will focus on a MVDC ship, but the team will structure the document such that additional applications, such as aircraft, air-cushioned vehicles (ACV), submarines, and microgrids, can be added as they become applicable.

A noise pattern-based method for line to ground fault location, based on US Patent 8067942 B2, was assessed for applicability within DC distribution systems that include increased source-ground capacitive coupling as well as a high resistance grounding scheme via simulation of a representative EMTDC model of a shipboard DC distribution system. This fault location approach, based on noise pattern analysis, was found to be sensitive to increased source-ground capacitive coupling as well as to the proposed high resistance grounding scheme. However, the analysis presented herein showed that the method is likely to be still applicable even when concentrated capacitance to ground significantly higher than the distributed cable capacitance is present at the sources. Moreover while the additional damping from resistive voltage dividers required to establish a high resistive grounded MVDC system does reduce the differences in noise patterns, the observed differences were still distinguishable. Hence it stands to reason that even with the additional damping effect caused by the proposed HRG scheme, this method is still a viable option for identifying ground fault locations in MVDC ship architectures.

ACKNOWLEDGMENT

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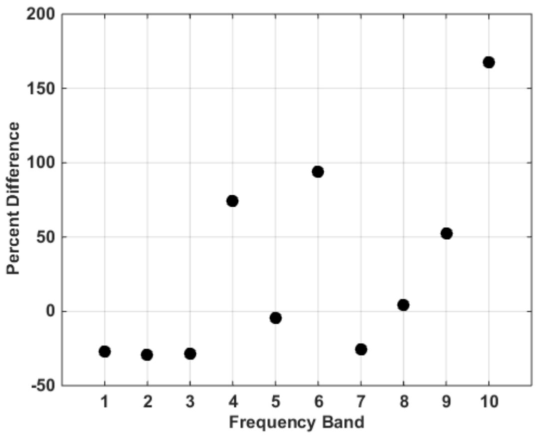

Fig. 11. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; 470 nF C coupling

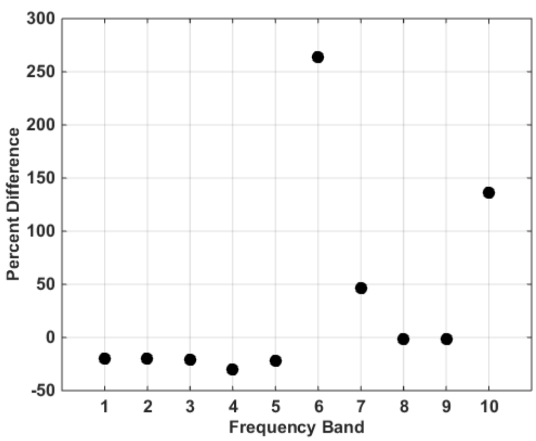

Fig. 12. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; 4.7 µF C coupling

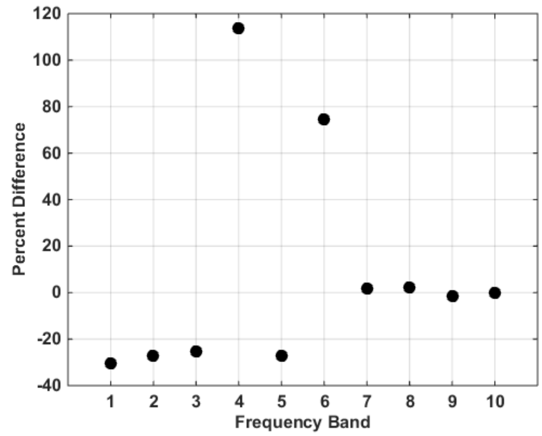

Fig. 13. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; high Z grounded, 470 nF C coupling

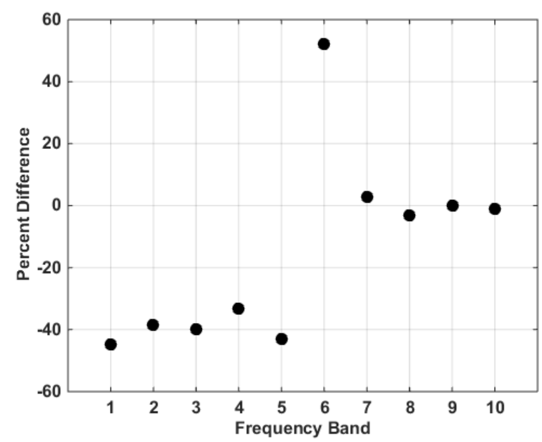

Fig. 14. Percent difference in signal energy magnitude for Bus 1 and Bus 2 ground faults; high Z grounded, 4.7 µF C coupling