Analysis and Comparison of Electric Ship Integrated Power System Architectures via Harmonic Metrics

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ABSTRACT

For the safe and efficient operation of a power system, the power quality must be maintained at a high level. In the paper, we discuss a new metric known as Harmonic Similarity (HS) which provides an understanding of the distribution of the disturbances in a system and uses that knowledge to strategically place filters at the most ideal nodes in the system. The work described in this paper focuses on the effects of applying known disturbances to three different electric ship IPS architectures developed in the new VTB Pro - medium-voltage, lower-voltage, and medium-voltage/high-frequency. After analyzing the a traditional power quality index and the new metric at various nodes of interest in each architecture, it was determined that each architecture has a unique vulnerability to the same type of disturbance, yet the proposed metric successfully indicates the optimal filter location for each of them. It is concluded that HS is a valuable tool for both proper assessment and comparison of similar power systems and for developing effective and efficient filtering schemes.

Keywords: Electric Ship, Power System, Harmonics, Filtering, Harmonic Similarity

INTRODUCTION

Maintaining a high level of power quality is essential to the safe and efficient operation of an electric ship integrated power system (IPS). The electric ship IPS has a zonal structure and is tightly coupled, which contributes to the ability of the ship to reconfigure its vital and non-vital loads for greater protection and maintainability. Unfortunately, as in any electrical power system, there are many factors that lead to the distortion of the voltages and currents in this IPS. Such potential factors include repeated pulse loads due to high-power weaponry (Domashch 2007) and multiple rectifiers and inverters for AC/DC conversion and propulsion motor speed control. Other unknown disturbance sources such as malfunctioning loads can be just as detrimental to the power quality of the IPS. In addition, the increasing use of non-linear loads such as these has made harmonic distortion one of the main issues of power quality degradation (Marinelli 2004, Manmek 2004).

Previously, metrics were proposed both to understand the flow of harmonics in a power system and to most strategically place filters in the system (Crapse 2007). In this paper, we aim to adapt the definitions of these metrics to improve their effectiveness for the electric ship IPS. The metrics employ a chosen power quality index and the similarity function known as cross-power spectral density in various mathematical combinations to assess the relationships between the waveforms at nodes of interest in a power system.

The work described in this paper focuses on applying the redefined versions of the metrics to three different IPS architectures developed in the new Virtual Test Bed (VTB) Pro simulation software. In addition, a new harmonic current source component has been developed to allow for the introduction of any harmonic profile into a system. The comparison of the power quality index and harmonic metric values in each IPS architecture reveals which architecture is most inherently invulnerable to harmonic disturbances. Finally, harmonic filters are strategically placed according to the metrics to determine the extent of their capability.

The paper will begin with an explanation of the rationale and mathematical basis for the metrics. Each of the three electric ship IPS architectures studied are then introduced. The harmonic current source component developed in VTB Pro and used to inject disturbance into the IPS architectures is then presented. In the next section, the similarities and differences amongst the architectures and application of a strategic filtering scheme based on the metrics are presented. Finally, conclusions and an analysis of whether the metrics were successful are discussed.

REDEFINED HARMONIC METRICS

To quantify the variation of a sinusoidal signal from it’s intended fundamental frequency, a variety of power quality indices have been proposed (Shin 2006). Of these indices, perhaps the most widely-accepted and used is total harmonic distortion (THD) (Heydt 1998, Kagan 2002). THD is the ratio of the power content of the harmonic frequencies of a signal to the power content of the fundamental frequency of a signal, as defined in Equation 1.

\[
THD_v = \frac{1}{|v_1|} \sqrt{\sum_{n=2}^{n=\infty} |v_n|^2}
\]
Other classical power quality indices also provide various ratios involving the fundamental frequency and disturbance frequencies, but because of its general acceptance and effectiveness, THD is used to quantify the amount of disturbance at a given node in a power system for this paper.

Though useful in their own right, THD and other power quality indices are limited in their application because they provide no indication of the relationship the disturbance at one node has with another. The only situation in which the value of THD provides this type of information is if there is a solitary source of disturbance in the power system. Unfortunately, in any real power system, there are always multiple sources of disturbance with various magnitudes. As these disturbances propagate throughout a power system, they may be constructive or destructive, limiting the effectiveness of classical power quality indices.

Attempting to perfectly track these disturbances is impossible without full knowledge of the impedance of every component in a system. That includes power sources, converters, inverters, drives, cables, and loads (weaponry, pumps, motors, etc.) to name a few. In order to remove the disturbance from a system, harmonic filters are necessary. However, depending on the frequencies to be filtered and the choice between passive and active filters, the size and cost of these filters can be substantial. The filters also must be adjusted and maintained based upon any new disturbances introduced to the system. In an attempt to simultaneously 1) provide an understanding of the relationship between the disturbance at one node and another, and 2) develop a scheme to strategically and efficiently filter harmonics in a system, a metric known as “Harmonic Similarity” has been developed.

Harmonic Similarity (HS) is the average of two sub-metrics, Harmonic Similarity in Magnitude and Harmonic Similarity in Phase. There are three factors that must be considered when seeking to relate one signal to another: 1) the frequencies of the components comprising the signals, 2) the magnitude of each frequency component, and 3) the phase of each frequency component. The Harmonic Similarity metric combines these three parameters in a unique manner to provide a measure of similarity between the disturbance at one node and the disturbance at another node.

**Harmonic Similarity in Magnitude**

Harmonic Similarity in Magnitude encompasses two of the three parameters: frequency and magnitude. Let the voltage signals, \( x(t) \) and \( y(t) \), at nodes \( X \) and \( Y \) be defined as:

\[
x(t) = f_t(t) + d_x(t)
\]

\[
y(t) = f_t(t) + d_y(t)
\]

where \( f_t(t) \) is the fundamental frequency component and \( d(t) \) is the harmonic frequency content of the disturbance. Let the Fourier transforms of the disturbance signals be defined as:

\[
d_x(t) \Leftrightarrow D_x(f)
\]

\[
d_y(t) \Leftrightarrow D_y(f)
\]

Based on these definitions, Equation 7 introduces the similarity function known as cross-power spectral density (CPSD):

\[
S_{XY}(f) = D_x(f) \cdot D_y^*(f)
\]

The CPSD is a similarity function in that it essentially amplifies the frequency components that the two signals have in common and attenuates the frequency components they do not have in common. HS in Magnitude is defined as a normalized version of \( S_{XY}(f) \):

\[
H_{Mag} = \frac{2 \cdot \int |S_{XY}(f)|df}{\int |S_{YY}(f)|df + \int |S_{XX}(f)|df} \times 100\%
\]

The normalization limits the value of the metric to be between 0 and 100 so that it may be represented as a percentage. If the two signals have identical disturbance frequency content, HS in Magnitude will be 100%. If the two signals share no common frequency components, even if they have identical THD values, the metric shows 0%.

**Harmonic Similarity in Phase**

Whereas HS in Magnitude provides a measure of how similar the frequency components are in magnitude, it does not consider the third parameter: phase. Fortunately, one of the biggest advantages of the cross-power spectral density function is that it preserves the phase information in the form of the phase difference between the two signals at each frequency (Powers 1990). This phase difference can be used to further evaluate the similarity between two signals and to decipher direction. The phase difference is implemented into the following definition that actually measures how dissimilar two signals are:

\[
H_{DisS_{Phase}} = \frac{\frac{1}{\pi} \int \theta_{XY}(f) \cdot |S_{XY}(f)|df}{\int |S_{XY}(f)|df} \times 100\%
\]
This equation is also normalized to be between 0 and 100 so that it may be represented as a percentage and also so that it may be on the same scale as HS in Magnitude. If all of the frequency components common to both signals are perfectly in phase, meaning 0 degrees of phase shift, Equation 8 simply becomes 0% and the waveforms have no degree of phase dissimilarity. If all frequency components are completely out of phase (phase shift of $\pm \pi$), the value of $H_{\text{DisS}}$Phase is $\pm 100\%$. Weighting the phase difference at each frequency by the magnitude of the CPSD at that frequency ensures that the frequencies with the largest amount of energy are given priority. The sign of the dissimilarity provides information as to which signal is leading or lagging. To convert this measure of dissimilarity into a measure of similarity and maintain the proper direction:

$$H_{\text{SPhase}} = \begin{cases} 100 - |H_{\text{DisS}}|, & \text{if } H_{\text{DisS}} > 0 \\ |H_{\text{DisS}}| - 100, & \text{if } H_{\text{DisS}} < 0 \end{cases}$$

This measure of Harmonic Similarity in Phase takes into account all three parameters, but gives the greatest emphasis to frequency and phase. The metrics HS in Magnitude and HS in Phase may be averaged together to obtain a complete measure of Harmonic Similarity:

$$H_{\text{S}} = \frac{H_{\text{SMag}} + |H_{\text{SPhase}}|}{2}$$

Other than some minor mathematical changes, the most notable difference from the previous version of the HS metric is that the fundamental frequency component is no longer included in the cross-power spectral density. It was determined that the metrics were more informative without the fundamental included since it is a relationship between the disturbances at the nodes in a system that is sought.

**ELECTRIC SHIP IPS ARCHITECTURES**

The general structure of the electric ship IPS architecture that is studied in this paper was proposed by BMT Syntek Technologies (Syntek 2003 [12]). The schematics developed in VTB Pro are intended to be virtual realizations of Syntek’s proposed one-line diagram, from the structure to the ratings of the loads and the impedance of the cables. The VTB schematic representing this one-line diagram can be seen in Fig. 1.

Power is supplied to a ring bus (Fig. 1(a)) by two main turbine generators (MTGs) rated at 36 MW and backed up by two 4 MW auxiliary turbine generators (ATGs). This ring bus supplies power to two permanent magnet motors (PMMs) and to the ship service load centers (SSLCs). For this paper, the electric ship IPS has only one SSLC and it can be seen in Fig. 1(b). An electric ship IPS may have multiple SSLCs, and each one of them would be nearly identical in structure to the next, however the load ratings may differ. The SSLC is connected to the ring bus in VTB Pro via subsystem connectors. Subsystem connectors are essentially ports with invisible wires connecting one schematic to another. This ability makes it easier to view and understand large, complex systems such as the electric ship IPS.

The SSLC architecture is intended to be zonal in structure, with each SSLC characterized by reconfigurable AC and DC zones. The load centers receive 450 V AC from the ring bus at two locations via transformers. One location supplies power to the starboard side of the load center and one to the port side. Internally, each load center also has an auxiliary power unit (APU) which allows for back-up power should the power from the ring bus be lost for any reason. The non-vital and vital
loads are powered directly from the starboard and port buses, as seen in Fig. 1(b). The AC power is then converted to DC via AC/DC rectifiers on each side of the ship. This DC power is provided to each of the DC loads and is also inverted back to AC for additional loads if necessary. The AC loads are modeled as pure resistive and as resistive-inductive (motor) loads. The DC loads include a pump motor and a DC/DC converter feeding a resistive load.

In Fig. 1(b), nodes of interest have been labeled with a number between 1 and 11. The nodes permanently associated with the starboard side of the ship are nodes 1-4 and are highlighted in bright green. The nodes permanently associated with the port side of the ship are nodes 8-11 and are highlighted in pink. It is noted that the vital loads are the loads that have the ability to draw power from either the starboard or port side of the ship via transfer switches. They are labeled as nodes 5-7 and are navy blue. For this study, nodes 5 and 6 are connected to the starboard side of the ship and node 7 is connected to the port side of the ship. These vital loads require the most attention when it comes to power quality.

Three different electric ship IPS architectures will be analyzed in this study (Clayton 2007):

**Medium-Voltage Architecture:** The MTGs and ATGs in the medium-voltage (MV) architecture produce 13.8 kV at 60 Hz. The highlighted transformers feeding the PMMs are necessary and have a 13.8/4.16 kV ratio. The SSLC transformers have a 13,800/450 V ratio. The 13.8 kV is on the high end of the medium voltage classification. This higher voltage allows for lower current levels at increased power levels.

**Low-Voltage Architecture:** The MTGs and ATGs in this lower-voltage architecture produce 4.16 kV at 60 Hz. The voltage 4.16 kV is actually still considered medium-voltage, but for the sake of distinguishing this architecture from the 13.8 kV architecture, we will refer to this architecture as the low-voltage (LV) architecture. At 4.16 kV, the highlighted transformers in Fig. 1(a) are not necessary and the motors are powered directly from the ring bus. The transformers feeding the SSLCs have a 4,160/450 V ratio.

**Medium-Voltage, High-Frequency Architecture:** This architecture maintains the 13.8 kV medium voltage on the ring bus, but it is produced at 240 Hz rather than 60 Hz; therefore we will refer to it as the high-frequency (HF) architecture. The transformers for the PMMs are necessary, but the increased frequency means a reduction in the size and weight of the transformers, generators, and harmonic filters. It also allows for increased acoustic performance. However, higher frequency also introduces such challenges as a high number of poles being required for generators and adapting the loads and cables to a new frequency (Doerry 2007), just to name a few.

**HARMONIC CURRENT SOURCE**

Any periodic signal can be broken down into a series of Fourier coefficients. Considering this and the fact that a harmonic disturbance in a power system may be modeled as a harmonic current source (Dugan 1996), such a component was developed for VTB Pro. This harmonic current source component takes as input the fundamental frequency, the peak value of the fundamental frequency component, the phase value of that component, and the order, magnitude, and phase of any harmonics that are desired. Its icon in a VTB Pro schematic and the pop-up window allowing for full customization are seen in Fig. 2.

![Figure 2. Harmonic Current Source Component in VTB Pro.](image_url)
nent to make it easier to input a traditional harmonic current profile. This component will be used to inject known disturbance in each electric ship integrated power system.

**COMPARISON AND ANALYSIS**

With the three architectures modeled in VTB Pro, this study will seek to achieve the following objectives:

1. Determine which architecture (MV, LV, or HF) is most inherently immune to particular disturbances, and
2. Determine if the Harmonic Similarity metric can be used to strategically locate the optimal harmonic filter location.

To introduce disturbance into the IPS, a Harmonic Current Source (HCS) component was attached to both the starboard and port buses, as shown in Fig. 1(b). In order to test the metrics, each HCS was given two different harmonics. The starboard HCS was given 3rd and 9th harmonics, and the port HCS was given the 5th and 7th harmonics of the appropriate frequency. Military standards state that the THD of the voltage waveforms at the interfaces in a ship IPS should not exceed 5% (DON, 1987). However, because the standards were devised for a 440 V, 60 Hz system before electric ships were being developed, we looked to Syntek’s IPS description for a standard directly applicable to the IPS being studied. One of the important factors noted by Syntek in their description of the IPS is that the THD of the AC voltage at the SSLC AC/DC rectifier inputs should not exceed 15% (Syntek 2003 [13]). To obtain a common basis for the disturbance introduced to the three architectures, the disturbance current levels were input so that the phase A rectifier voltage on the MV architecture (chosen because it is a compromise between the other two architectures) had a THD value of just under 15%; the same ratio of the magnitude of the current input to each bus to the magnitude of the disturbance current injected was used for the other two architectures.

The electric ship IPS is designed such that the AC loads in each SSLC are in parallel and powered directly from either the starboard bus or the port bus, which are both supplied by the ring bus. Therefore, the most logical filter location candidates to have the greatest impact on the largest number of nodes are the ring bus, the starboard bus (node 1), or the port bus (node 8). Rather than monitoring the ring bus at various locations, the secondary phase A voltage of the transformers feeding the load centers are monitored on the starboard (node 2) and port (node 9) sides.

**MV Architecture**

Fig. 3(a) shows the THD values for each node of interest in the MV IPS architecture after introducing the HCS disturbances to both sides of the ship. Consistent with Fig. 1(b), the bright green bars (light colored in gray scale) represent the starboard nodes 1-4, the navy blue (dark colored) bars correspond to the vital loads 5-7 that can optionally be connected to either side, and the pink (diagonal patterned) bars represent the port nodes 8-11. It is noted that the two noticeably higher THD values occur at nodes 1 (18.01%) and nodes 8 (19.74%), which are the phase A voltages of the actual starboard and port buses respectively. Another point of interest is the high THD value at node 6. The protection of the vital loads at nodes 5-7 is of premium interest, and the large amount of distortion particularly at node 6 (THD of 11.86%) is of great concern. However, judging from the THD values only, it is difficult to determine where best to place the harmonic filter(s) to efficiently protect this node. If a location were to be chosen based purely on this traditional power quality index, the optimal location would have to be node 8, the port bus, which has the highest THD value.

To contrive a more intelligent solution to this problem, it is necessary to understand which bus is providing the disturbance most similar to the disturbance at the node we most want to protect, node 6. Because the electric ship IPS SSLC is designed to be reconfigurable, and because both the starboard and port buses are tied together via the ring bus, it cannot be assumed that a vital load is more associated with one bus than another. Fortunately, regardless of the configuration of the IPS, the Harmonic Similarity metric will help determine which bus disturbance is most similar to the disturbance at vital node 6 and therefore which bus is the optimal candidate for the placement of a harmonic filter.

From Fig. 4(a) it is apparent that the disturbance at node 6 is most similar to the disturbances at the nodes on the starboard side of the ship (nodes 1-4). It is also clear that disturbance at node 6 is much more similar to the disturbance at the starboard bus (node 1) than to the disturbance at the starboard SSLC transformer (node 2). Along with the fact that the THD at node 2 is nearly negligible, this indicates that the optimal filter location is on the starboard bus itself. Fig. 4(b) displays the magnitudes and phases of the normalized harmonics at node 1 in the frequency domain computed via the Fast Fourier Transform (FFT). The 3rd and 9th harmonics are most prevalent because of the HCS tied into its bus.

Following the indication of the HS metric and the information from the frequency spectrum, the harmonics on the starboard bus are filtered. After filtering, the THD is again evaluated at each node of interest and shown in Fig. 3(b). The distortion at vital node 6 has been greatly attenuated from 11.86% to 1.01%. In addition, because the optimal location was chosen, the disturbance at nodes permanently associated with the starboard have been attenuated as well. Had the port bus been chosen, as was the indication from THD alone, the THD at node 6 would have still been 11.51%, offering almost no protection to the vital load.
Figure 3. THD values at the nodes of interest in the MV architecture before and after filtering.

Figure 4. HS of the nodes of interest to node 6 and the frequency spectrum of the disturbance at node 1 in the MV schematic.

LV Architecture

For comparison, the nodal THD values for the low-voltage schematic can be seen in Fig. 5(a). Again, the ratio between the current input to the starboard and port buses and the harmonic disturbance current introduced was kept the same as in the MV schematic, and will be kept the same for the HF schematic. For the LV architecture, the THD values prior to filtering are now noticeably higher on the port side than the starboard side. Further study has shown that this is partially due to the direct connection of the PM motors to differing levels of inductance when the identical transformer models were removed. Therefore, for the same percentage of applied disturbance, the LV architecture tends to alleviate the disturbance on the starboard side, but creates a greater burden for the port side.

Once again, the vital load at node 6 is under great duress. Studying only the THD values, it is even more convincing that the proper, optimal location for a filter is on the port side. The THD values at the SSLC transformers are once again negligible, so the ring bus is ruled out. For proper assessment, the HS between each of the nodes of interest and node 6 can be seen in Fig. 6(a). The similarity of node 6 to the starboard side of the ship is as drastic as it was for the MV architecture, and it is much less similar to the port side. It is again concluded that the proper action is to place a harmonic filter on the starboard bus rated for
The THD values at the nodes of interest after filtering are shown in Fig. 5(b). The disturbances have been greatly reduced on the starboard side of the ship and at node 6, as intended. The THD value at node 6 has been reduced from 11.15% to 0.20%, offering near complete protection from the disturbance.

The THD values at the nodes of interest after filtering are shown in Fig. 5(b). The disturbances have been greatly reduced on the starboard side of the ship and at node 6, as intended. The THD value at node 6 has been reduced from 11.15% to 0.20%, offering near complete protection from the disturbance.

HF Architecture

Finally, the THD values for the HF IPS schematic before filtering are shown in Fig. 7(a). Since the fundamental frequency is set to 240 Hz from 60 Hz, the harmonics are four times as high in frequency as well. The higher frequency will lead to the inductive loads having a higher impedance and therefore drawing a smaller amount of current because the voltage level is fixed. The different amplitudes and phases of the harmonic components combine differently at the higher frequencies as well. Whereas the distortion was considerable on the two bus nodes for the previous architectures, the harmonics have become more constructive on the buses leading to even higher levels of distortion.
As before, node 6 still has the highest level of distortion amongst the vital loads and must be protected. And again, the HS between the nodes of interest and node 6 seen in Fig. 8(a) points to the starboard bus as the optimal bus for placing a filter. However, whereas the HS between node 6 and the starboard bus (node 1) was greater than 90% for the previous architectures, it is only 75% for the HF architecture. This drop can be attributed to the more constructive combination of the higher frequencies that also caused the THD to become higher on the starboard bus than on the port bus, again altering the previous trend. The normalized disturbance harmonics shown in Fig. 8(b) were once again properly filtered at the starboard bus. As expected, Fig. 7(b) shows that the distortion greatly decreases at the starboard loads, and more importantly, at the vital load at node 6. The distortion at node 6 dropped from a THD value of 15.11% to 0.69%.

CONCLUSION

This paper simulates three possible architectures of an electric ship IPS in VTB Pro, and studies the effects of applying a known disturbance to the main starboard and port buses on the ship. The end goals are a more effective and efficient strategic filtering
strategy and an understanding of the harmonic vulnerability of each architecture.

The classical power quality index known as THD is used to quantify the amount of distortion at each node of interest in the systems. The revised metric known as Harmonic Similarity is used to determine the optimal location for placing the required harmonic filter(s). The three architectures studied were a medium-voltage (MV) architecture, a lower-voltage (LV) architecture, and a medium-voltage, high-frequency (HF) architecture. After applying the harmonic disturbances, the THD values at the various nodes on the starboard and port sides of the MV architecture were fairly similar, whereas the the THD values were noticeably higher on the port side for the LV architecture. The distortion values were again similar for both sides of the HF architecture, but the starboard and port buses themselves had much larger distortion values than the rest of the nodes.

Though the different architectures were vulnerable to the disturbances in unique ways, the HS metric consistently pointed to the starboard bus that was most significantly damaging the vital load at node 6. The information from the HS metric allowed for proper, intelligent placement of the harmonic filter in each architecture, which led successfully to the protection of the intended vital load. Instead of simply placing filters at the nodes of highest distortion (THD) value or excessively and inefficiently placing filters at every load, HS provided a strategy for efficient filter placement. To fully verify the effectiveness of the HS metric, more studies need to be carried out in the future. The HS metric needs to be adapted to determine similarity amongst transient disturbances as well harmonic disturbances. Also, the electric ship IPS is a reconfigurable system with a network of switches and breakers. This means that the structure of the system can change at any time. A new structure could introduce new and/or different disturbances to loads and zones that were previously unaffected. Because the HS metric does not depend on architecture, but rather uses only the voltage signals to indicate the similarity of one node to another, it is believed to be effective on any structure. This will be verified with the electric ship IPS and other types of power systems in the future.

ACKNOWLEDGEMENT

The work reported in this paper was supported by the U.S. ONR Electric Ship Research and Development Consortium under Grants N00014-02-1-0623.

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