

# The Application Of Wavelets to Shipboard Power System Protection

H. Douglas, P. Pillay, *Fellow, IEEE* and T. H. Ortmeyer, *Fellow, IEEE*

**Abstract** – The proposed Integrated Power Systems (IPS) of Navy ships is based on an ungrounded system. However the natural capacitance of the cable and the EMI filters provide ground paths to the ship’s hull. There is thus a “Virtual Ground” between the modules of the IPS. The fault current is very low for a single line to ground fault in this ungrounded system allowing continuous operation but also making fault detection difficult. In this paper a method of ground fault detection using wavelets is introduced. The ground fault conditions are simulated using PSPICE and fault detection implemented with Daubechies wavelets. It is shown that ground faults can be detected by wavelet analysis of the line to line voltages.

**Index Terms**— Integrated Power Systems, shipboard, ungrounded system, wavelets, protection, fault detection

## I. INTRODUCTION

The Intergrated Power System (IPS) is ungrounded to allow operation during faults yet cable capacitance and filters provide stray paths to the ship’s hull. The fault current is very low for a single line to ground fault in an ungrounded system and the line to line and phase voltages are unchanged. This ensures a high continuity of service which is the Navy’s motivation for installing ungrounded systems in ships. These systems are however subject to high transient overvoltages to ground and consequently are a potential hazard to equipment and personnel. These faults also cause insulation stress and lead to failures and more severe faults [1-5].

In this paper the output line to line voltages are used as the medium for fault detection. A line to ground fault is defined as a single connection between an output phase voltage and the ship’s hull. PSPICE is used to generate the line to line voltage data for the various faulted conditions. A wavelet analysis using Daubechies wavelets is then applied voltages [6-15]. The coefficients of the detailed scales are examined to determine the location and duration of the fault.

The IPS consists of a 3-phase generator, 3phase transformer, bridge rectifier, a one-quadrant chopper and a three-phase inverter as well as ungrounded ship loads as shown in figure 1. These modules are coupled to the ship’s hull through filters and the cables’ capacitance.

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The system is fed by generation rated at 4160V, 3phase 60Hz with capacities ranging from 3.75MW to 21MW. The voltage is stepped down to 430V ac using the transformer modeled in figure 2. The transformer is coupled to the ship’s hull or ground via a series resistance and capacitance. The transformer’s output is connected to a three phase bridge rectifier. This is connected to the smoothing capacitor via the line impedance. The rectified DC voltage across the smoothing capacitor is 1000V. This rectification module is also capacitively coupled to the ship’s hull as shown in figure 3.

The 1000V DC voltage is then stepped down to 800V DC by means of the one quadrant chopper shown in figure 4. The switching frequency of the chopper is 4KHz with a duty ratio of 0.8. The 800V dc link voltage is converted into a three phase PWM waveform using the three phase inverter shown in figure 5. The PWM waveform is generated using sinusoidal PWM with a modulation index of 0.9. The switching frequency is 4.5KHz and a frequency modulation index of 75 is utilized.

Figure 6 shows the line impedance, PWM filters and balanced three phase loads. The filtered output voltages are coupled to the ship’s hull through the EMI filters. A single line to ground fault between Phase C and the ships hull is indicated by the dashed line.

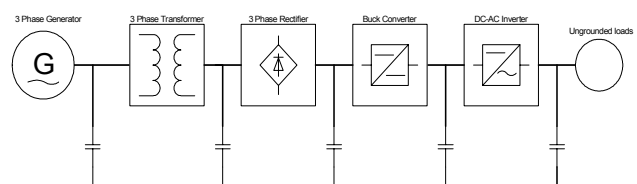


Figure 1. A typical integrated power system.

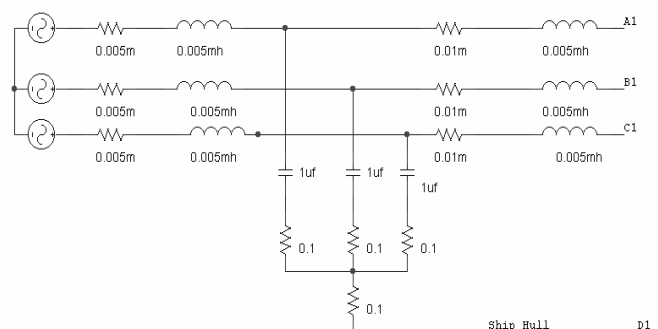


Figure 2. Generator and transformer of the IPS.

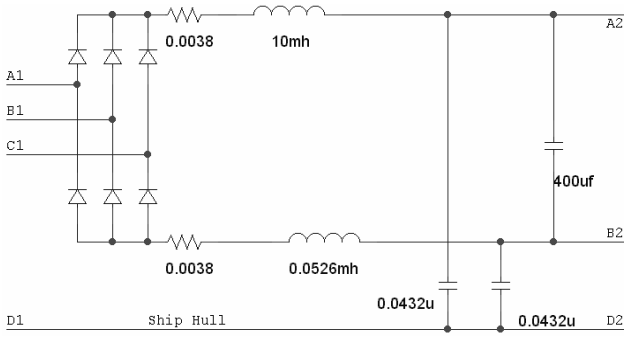


Figure 3. The rectifier, line impedance and filter.

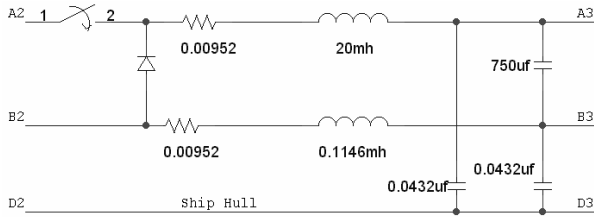


Figure 4. The One quadrant chopper.

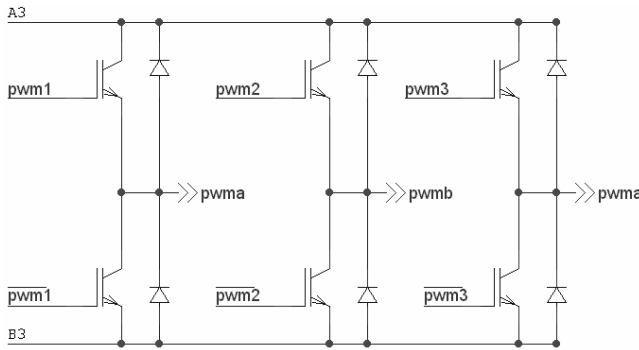


Figure 5. The three phase Inverter.

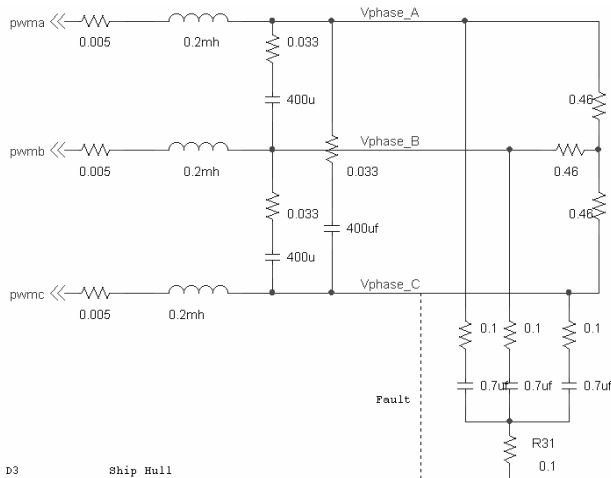


Figure 6. The line impedance, PWM filters and ship load.

## II. WAVELET THEORY

The orthogonal basis functions used in Wavelet analysis are families of scaling functions,  $\phi(t)$ , and associated wavelets,  $\psi(t)$ . The scaling function,  $\phi(t)$ , can be represented by the following mathematical expression:

$$\phi_{j,k}(t) = \sum_k H_k \phi(2^j t - k) \quad (1)$$

where,

$H_k$  represents the coefficients of the scaling function,  $k$  represents a translation,  $j$  represents the scale.

Similarly, the associated wavelet  $\psi(t)$ , can be generated using the same coefficients as the scaling function.

$$\psi_{j,k}(t) = \sum_k (-1)^k \sqrt{2} H_{1-k} \phi(2^j t - k) \quad (2)$$

The scaling functions are orthogonal to each other as well as with the wavelet functions as shown in (3), (4). This fact is crucial and forms part of the framework for a multiresolution analysis.

$$\int_{-\infty}^{\infty} \phi(2t - k) \cdot \phi(2t - l) dt = 0 \quad \text{for all } k \neq l. \quad (3)$$

$$\int_{-\infty}^{\infty} \psi(t) \cdot \phi(t) dt = 0 \quad (4)$$

A discretized signal can be decomposed at different scales as follows:

$$f[n] = \sum_{k=0}^{N-1} a_{j,k} \phi_{j,k}(t) \quad (5)$$

$$= \sum_{k=0}^{N-1} a_{(j+1),k} \phi_{(j+1),k}(t) + \sum_{k=0}^{N-1} d_{(j+1),k} \psi_{(j+1),k}(t) \quad (6)$$

The coefficients of the next decomposition level,  $(j+1)$ , can be expressed as

$$a_{(j+1),k} = \sum_{k=0}^N a_{j,k} \int \phi_{j,k}(t) \cdot \phi_{(j+1),k}(t) dt \quad (7)$$

$$d_{(j+1),k} = \sum_{k=0}^N a_{j,k} \int \phi_{j,k}(t) \cdot \psi_{(j+1),k}(t) dt \quad (8)$$

$$a_{(j+1),k} = \sum_k a_{j,k} \cdot g[k] \quad \text{and} \quad d_{(j+1),k} = \sum_k a_{j,k} \cdot h[k] \quad (9)$$

The decomposition coefficients can therefore be determined through convolution and implemented by using a filter. The filter,  $g[k]$ , is a lowpass filter and  $h[k]$  is a highpass filter.

$$y[n] = \sum_{k=1}^N h[k] \cdot x[n - k] \quad (10)$$

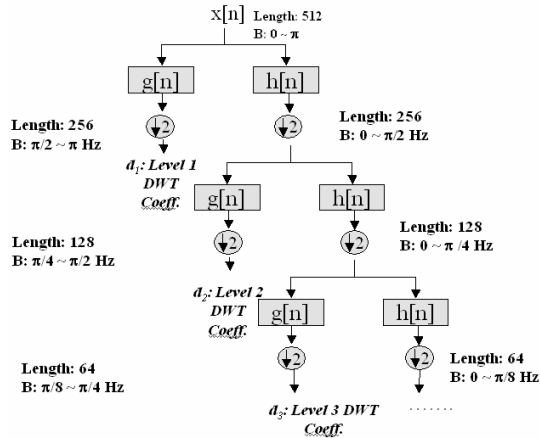


Figure 7. A three level multiresolution decomposition.

### III. THE DETECTION ALGORITHM

It is desired to be able to detect a line to ground fault by analysing the output line to line voltages. Figure 8 shows the line to line voltages for an unfaulted condition. Figure 9 shows the three line to line voltages with a 100ms fault on phase A which occurs between 0.15 and 0.25 seconds. By comparing figures 8 and 9 it is difficult to detect if a fault has occurred, which phase is faulted as well as when the fault has occurred.

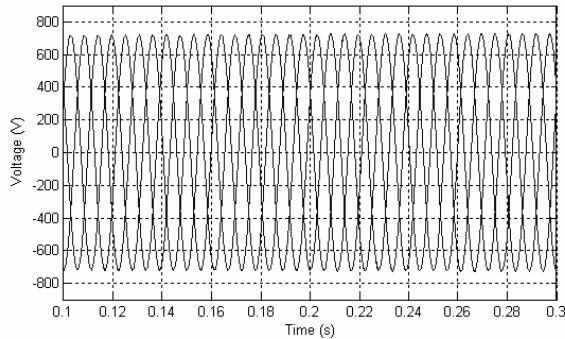


Figure 8. The unfaulted line to line voltages

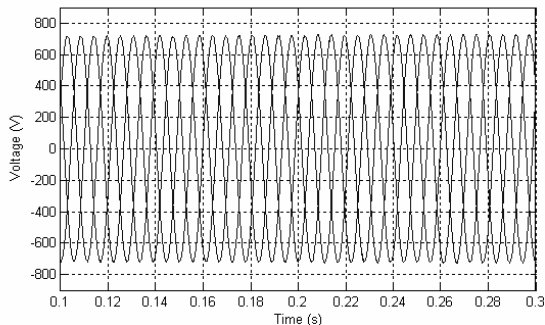


Figure 9. The output line to line voltages with a fault on phase A

#### A single line to ground fault on phase A

The resulting wavelet decomposition for line voltages, AB, BC and CA are shown in figures 10-12. The 3<sup>rd</sup> and 4<sup>th</sup> detail scales of the line voltages AB and CA, clearly indicate that a

disturbance has occurred. Figure 11, shows that the decomposition of line voltage BC does not have any significant changes in the coefficients during the fault. It is therefore evident that the disturbance is only found in the decomposition of the common phase i.e. phase A is common to AB and CA. This fact can be used to unambiguously detect the faulted phase.

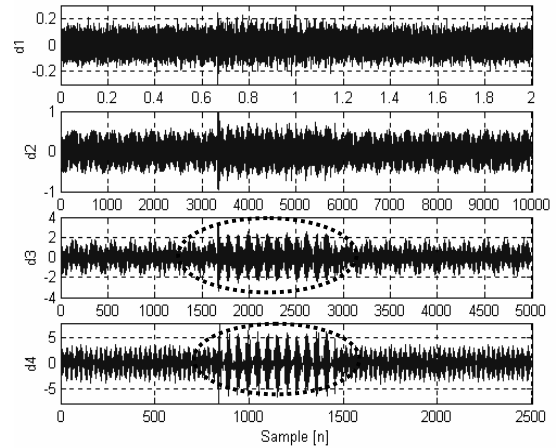


Figure 10. Wavelet Decomposition of Phase AB

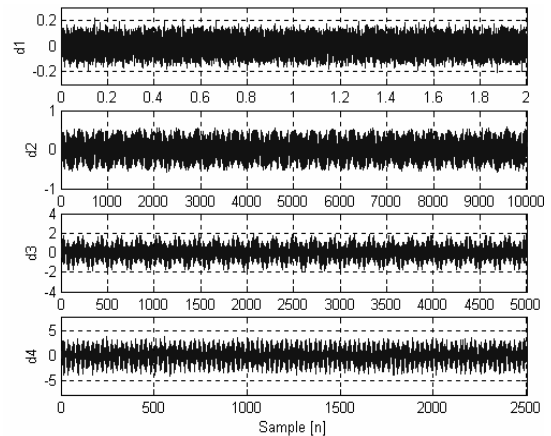


Figure 11. Wavelet Decomposition of Phase BC

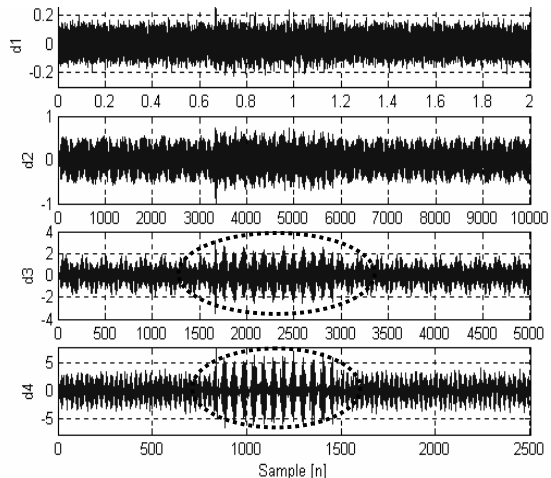


Figure 12. Wavelet Decomposition of Phase CA

*A single line to ground fault on phase B*

Figures 13, 14 and 15 show the wavelet decomposition for a fault on phase B. The presence of a disturbance is indicated by the encirclements. The disturbance is common to phases AB and BC, therefore the fault is on phase B.

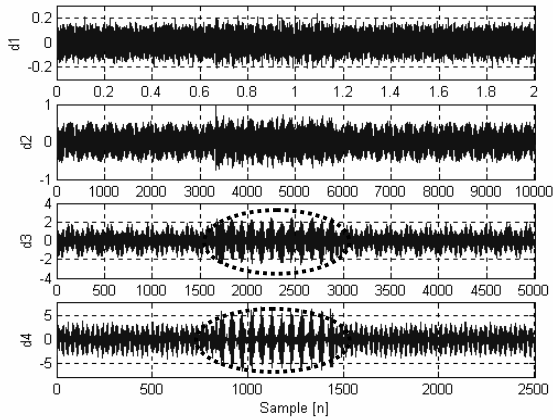


Figure 13. Wavelet Decomposition of Phase AB

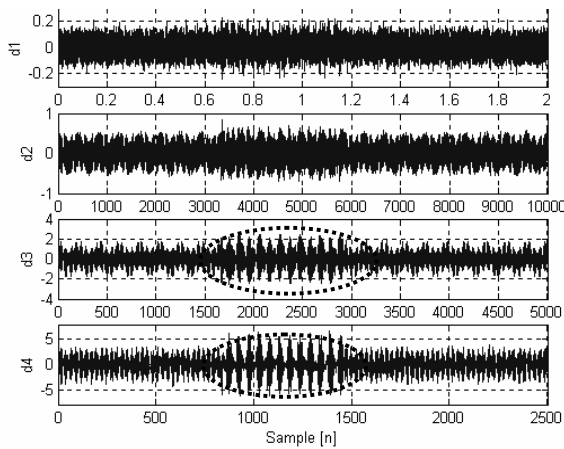


Figure 14. Wavelet Decomposition of Phase BC

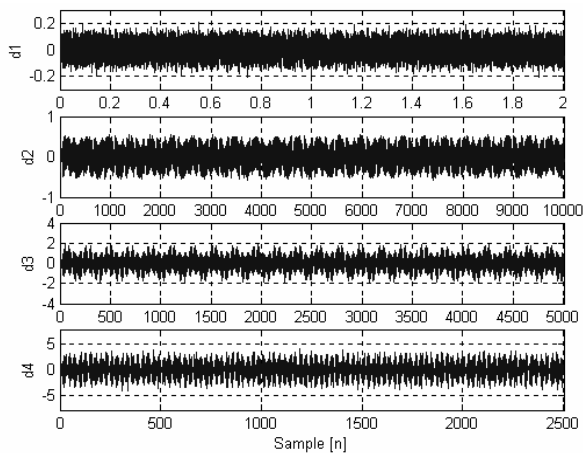


Figure 15. Wavelet Decomposition of Phase CA.

*A single Line to ground fault on phase C*

Figures 15, 16 and 17 show the wavelet decomposition for a fault on phase C. The presence of a disturbance is indicated by the encirclements. The disturbance is common to phases BC and CA, therefore the fault is on phase C.

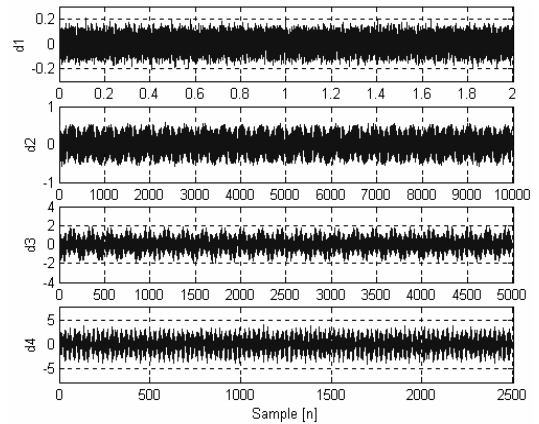


Figure 16. Wavelet Decomposition of Phase AB

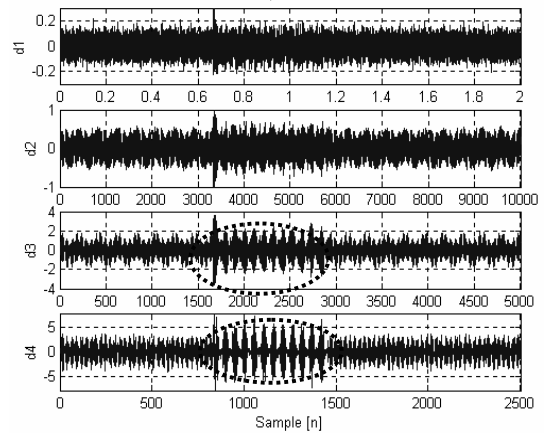


Figure 17. Wavelet Decomposition of Phase BC

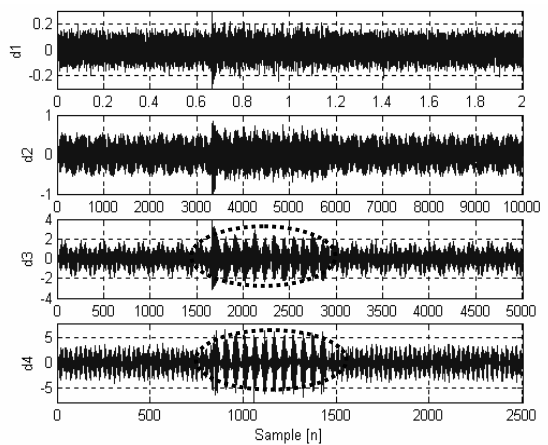


Figure 18. Wavelet Decomposition of Phase CA.

Phase AB	Phase BC	Phase CA		Fault on A	Fault on B	Fault on C
0	0	0		U	U	U
0	0	1		U	U	U
0	1	0		U	U	U
0	1	1		U	U	<b>1</b>
1	0	0		U	U	U
1	0	1		<b>1</b>	U	U
1	1	0		U	<b>1</b>	U
1	1	1		U	U	U

Table 1. Truth table for faulted phase discrimination

In table 1, the disturbances observed in the coefficients for a phase is represented as a 1 and no change is represented by a 0. The U represents an unfaulted condition. A fault is identified by a common disturbance on two phases. This logic can be integrated into a fault detection system. In the final paper we will add a variance function that will analyse the disturbances and an analysis of the line to line and three phase faults will be presented.

#### IV. CONCLUSIONS

In this paper the discrete wavelet transform is applied to the shipboard Integrated Power System for the detection of faults in an ungrounded system. It has been shown that wavelet analysis can be used to detect line to ground faults. A method of fault discrimination that determines the fault location is presented and applied to the identification of all three single line to ground fault scenarios.

#### ACKNOWLEDGMENTS

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