Fault Detection and Harmonics Mitigation in Diesel Electric Ships Using IIOT Edge Devices

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Abstract— **Diesel electric ships have been identified by the various marine classification societies to be at operational risk due to power quality problems. To deal with power quality issues, the industrial internet of things (IIOT) provides a framework for monitoring, fault detection and harmonic mitigation in the electric power systems on board. This involves collecting electrical sensor data on the vessel and using FFT analysis to decompose the signals into its frequency components. We calculate the positive, negative and zero-sequence components of the three phases. This information is used for fault diagnosis and reduction of the total harmonic distortion by the use of active filters applied in parallel to the load. In this paper, we present an architecture and framework for implementation of the fault diagnosis which is an integral part of a Condition based Health system for marine applications.**

***Index Terms*—Condition based Health Monitoring, Marine Vessels, Power Quality, Variable Frequency Drives, Total Harmonic Distortion, Harmonics, Active Filters.**

I. INTRODUCTION

In this paper, we extend the concept of Condition based Health Monitoring of marine vessels to include electric power issues especially with respect to harmonics. Harmonics are any deviation from the pure sinusoidal voltage or current waveform typically generated by an ideal voltage source with linear loads. With the increased use of Variable Frequency (Speed) Drives, there is recognition of the negative effects of harmonic pollution on the overall power grid leading to failures of critical electrical equipment [1]. In a diesel-electric ship power system, the main source of harmonics is usually the diode rectifier stages of Variable Frequency Drives (VFDs) for controlling the propulsion motors. Marine classification bodies are rightly concerned with the problem of harmonic distortion and its effect on shipboard installations. Therefore, they are introducing strict limits for this disturbance in order to ensure the reliability of marine electric equipment and the safety of crews [2]. There is sensitivity to other electrical issues beyond harmonics in the marine context including voltage and frequency deviations, transients, voltage imbalance and fault detection and diagnostics [3].

The Industrial Internet of Things (IIOT) framework provides a model for implementing the identification and mitigation of the various fault scenarios anticipated in a marine diesel electric system. The electrical signals are recorded and processed in real time with a variety of signal processing steps including Fast Fourier Transform, Wavelet and Component Sequence parameters being calculated. The calculated information is used for fault detection, diagnostics and anomaly mitigation by interfacing directly with the electric and control systems on board the ship. Thus, IIOT in combination with Artificial Intelligence, can monitor for anomalies in operation of motors or VFDs, and can predict when maintenance needs to occur or when failure is imminent.

II. MARINE ELECTRIC PROPULSION

Electric propulsion systems have become the technology of choice for a variety of marine vessels including Navy destroyers, cruise ships, FPSOs, ferries and large bulk carriers. The classification societies like American Bureau of Shipping (ABS), DNV, Lloyds Registry and Bureau Veritas provide the regulatory and mandate standards to be met for safe operation of marine vessels. This includes the electric grid on board a vessel including aspects like redundancy. The prime mover can be a gas turbine or a diesel engine. Here, we present here the different elements with their layout of a twin shaft diesel-electric propulsion system on board a marine vessel as shown in Fig. 1 and Table I.

Since these are relatively small power systems, they have more distorted voltages and currents as compared to the on-shore power plants, due to the high percentage of non-linear loud units interfaced through diode/thyristor rectifiers. In the configuration here, there are two shafts with motors driven by variable-frequency drives drawing power from a power grid fed by four diesel-generators. The main loads and busbars in diesel-electric ships are three-phase and three-wire systems.

Table I: Description of various elements present in Marine Diesel Electric Propulsion system

A	Diesel engines + alternators
B	Main switchboards
C	Variable speed drives/frequency converters
D	Electric (propulsion) motors
E	Gear boxes if needed
F	Propellers

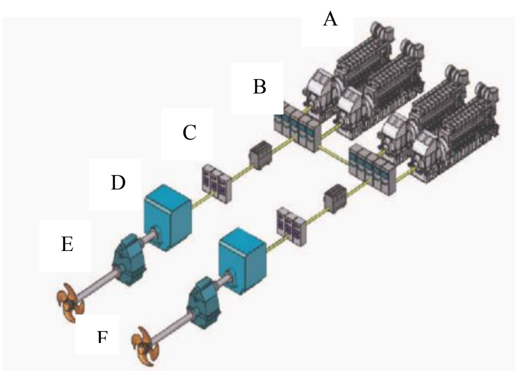

Figure 1: Marine Diesel-Electric Propulsion

III. SYMMETRICAL COMPONENTS AND TOTAL HARMONIC DISTORTION

To develop the framework for fault detection and diagnosis of the electrical system, in this section, we present the theoretical basis for electrical system analytics. The variable frequency drives in the two shafts present themselves as non-linear loads and generate multiple harmonics. Fortesque's approach of symmetrical components is used to calculate and categorize the harmonics that are propagated due to the non-linear loads in three phase systems. Fundamentals of symmetrical components approach start by defining an operator **a** which corresponds to a counter-clockwise phase shift of 120°. The $\mathbf{a}^2$ operator performs a 240 degrees counter-clockwise phase shift. A three-phase unbalanced set of currents called sequence currents I_+, I_- and I_0 can be calculated from the three phase currents I_A, I_B and I_C using equations from (1) through (3):

Positive Sequence Component:

$$I_+ = \frac{1}{3} (I_A + \mathbf{a} I_B + \mathbf{a}^2 I_C) \quad (1)$$

Negative Sequence Component:

$$I_- = \frac{1}{3} (I_A + \mathbf{a}^2 I_B + \mathbf{a} I_C) \quad (2)$$

Zero Sequence Component:

$$I_0 = \frac{1}{3} (I_A + I_B + I_C) \quad (3)$$

Substituting Voltages for Currents in the above equations would give us the equivalent expressions for voltages V_+, V_- and V_0.

A fully balanced system only has positive sequence currents. In an unbalanced system, the negative sequence currents will rotate in the direction opposite to that of the positive sequence currents (original direction). Typically, for an unfaulted three phase system there are no zero-sequence currents.

In a three-phase power system, the 3rd harmonic and all of its integer multiples (collectively called *triplen* harmonics) generated by 120° phase-shifted fundamental waveforms, are not generated since they fall perfectly in phase with each other. The non-triplen odd harmonics, however will additively add to each other according to the mathematical Table II which has an interesting pattern with regard to the rotation or sequence of the harmonic frequencies: Harmonics such as the 7th, which "rotate" in the same direction as the fundamental, are mapped to the *positive sequence*. Harmonics such as the 5th, which "rotate" in the opposite direction as the fundamental, map to the *negative sequence*. Triplen harmonics do not "rotate" at all are mapped to the *zero sequence*.

This pattern of positive-zero-negative continues indefinitely for all odd-numbered harmonics, and has been listed in Table. II up to the 47th harmonic.

Table II: Harmonic Numbers (<50) Rotation Sequence

+	with fundamental	1	7	13	19	25	31	37	43
0	Does not rotate	3	9	15	21	27	33	39	45
-	anti-fundamental	5	11	17	23	29	35	41	47

Harmonics in the electric power system combine with the fundamental frequency to create distortion. The level of distortion is directly related to the frequencies and amplitudes of the harmonic current. The expected harmonics of a VFD drive depends on the number of pulses/diodes as per the Table III.

Table III: Harmonics expected for a VFD drive

Source	**Expected Harmonics**
6 pulse/diode	5,7,11,13,17,19…
12 pulse/diode	11, 13, 23, 25…
18 pulse/diode	17, 19, 35, 37….

The contribution of all harmonic frequency currents to the fundamental current is known as Total Harmonic Distortion (THD). THD is calculated as the square root of the sum of the squares of all the harmonics divided by the fundamental of the composite waveform signal. This calculation arrives at the value of distortion as a percentage of the fundamental (V_1).

$$THD = \frac{\sqrt{\sum_{n=2}^{50} V_n^2}}{V_1} \quad (4)$$

The THD value is expressed as a percentage of the fundamental frequency component magnitude. THD values of over 10% are reason for concern.

ABS has issued Guidance Notes on Control of Harmonics in Electrical Power Systems [4]. It references IEEE 519 [5] and IEC60092-101[6], to set a 5 % limit for the Total Harmonic Distortion (THD) in voltage supply, with no individual harmonic greater than 3% of the fundamental voltage, no matter what the harmonic order, for ship distribution systems.

IV. CBM EDGE DEVICE FOR ANALYTICS

The Industrial Internet of Things (IIOT) framework provides a model for the identification and alarming of the various electrical fault scenarios anticipated in a marine electric propulsion system. The traditional IIOT model [7] has various sensor data pushed to the cloud where calculations and analytics are performed, and alerts and corrective actions are sent back to propulsion system on ships. In a marine environment it is difficult to have connectivity to push data to the cloud. Also, because of cybersecurity concerns, there is now an increased push to have edge devices which directly connect to the sensors and controls systems to enable implementation of computations and analytics locally.[8]

Therefore, to deal with connectivity issues and cybersecurity concerns, we have implemented the edge device using the National Instruments compact RIO (cRIO) embedded control and acquisition system as shown in Fig. 2. The cRIO 9065 with the 9023 Analog Input modules samples electrical signals (voltages and currents) with high fidelity (sampling rate of 8khz per signal) which is processed in real time with a variety of signal processing including Fast Fourier Transform, Component Sequence contributions and the total harmonic distortion. The system have the capability to compute Wavelet transforms which can be used when there are time-varying features in the frequency domain. The calculated information is used for fault detection, diagnostics and anomaly mitigation by interfacing directly with the electric and control systems on board the ship.

Fig 2: NI cRIO used as an edge device

Thresholds for alarming and alerting are configured on the NI edge device which interfaces with the onboard control systems for annunciation and advisories. Further, to calculate and alarm values are made available to other onboard and off-shore systems using the MQTT protocol. MQTT is a publish/subscribe bidirectional and stateful protocol that allows edge-of-network devices to publish to a broker. Clients connect to this broker, which then mediates communication between the two devices.

The IIOT Edge device can therefore be used for identifying a variety of faults, and for alerting the operators of anomalous conditions with harmonic pollution which can cause damage to both electrical and mechanical components. Further, having an edge device can be used to correct the harmonic imbalances by selecting a variety of methods like tuned passive filters, active filters or a hybrid combination of the two. In the next section, we present an Active Filter approach for mitigating excessive harmonics.

V. MITIGATING HARMONICS WITH ACTIVE FILTERING

This main source of harmonic currents in a diesel-electric ship propulsion system are the motor drive rectifier loads. Since we are now calculating the harmonics on the edge they can be mitigated by injecting harmonic components selectively. This is done using active filtering using our system which has high sampling frequency and a fast response closed loop control system driving a power converter.

Aardal and Skjong [9] have examined various configurations of Active Filtering and Model-predictive control schemas for harmonics mitigation.

Active Filters based on Current Conditioning are flexible enough to be programmable to correct a single harmonic order or a combination of harmonic orders without any change in the hardware. Moreover, since the filter is connected in parallel therefore it is easily connected or disconnected from the VFD.

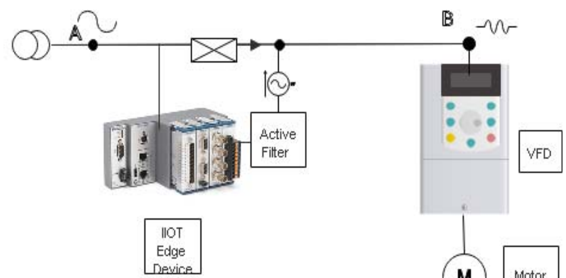

Figure 3: Harmonics suppression with Active Filter

The issue of harmonic distortion is addressed by the use of an Active Filter (AF) applied in parallel to the electric drive load. The common practice in active filtering is to use the AF for local compensation by applying a current reference equal to the harmonic and reactive current components of the non-linear load. The algorithm is to actively sense harmonics and to inject equal and opposite currents to cancel harmonic currents. Implementation of such AF is shown in the next section in the form of a case study.

VI. Case Study of Harmonic Mitigation with Active Filters

We simulated a three phase system electrical network with a 12-diode VFD as shown in Fig. 3. When no active filter connected at the common coupling point of the VFD, the input current will have harmonics in its waveform as shown in Fig. 4 where three phases of the current show the distorted waveform. Harmonics present in the current waveform is due to power electronics based VFD controlling the motor.

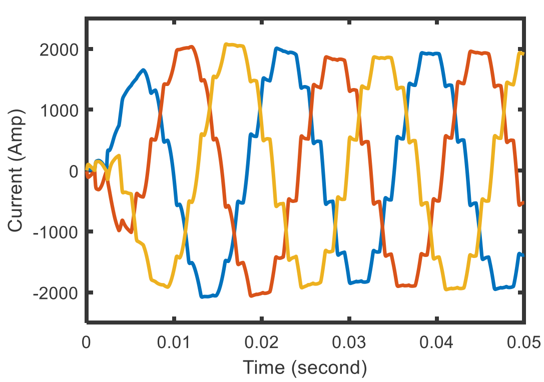

Figure 4: Three phase current waveform at the load point B of 12-stage VFD without an active filter

The spectrum in Fig 5 shows the 11th and 13th harmonics due to the VFD normalized to the fundamental component magnitude with a computed THD of 9.4774% or -30 dB. The application of the active filter injects counteracting currents based on the harmonics within one cycle which counteracts the THD to an acceptable level. The overlay of the spectra with and without the active filters shows the suppression of the harmonics in Fig. 5..

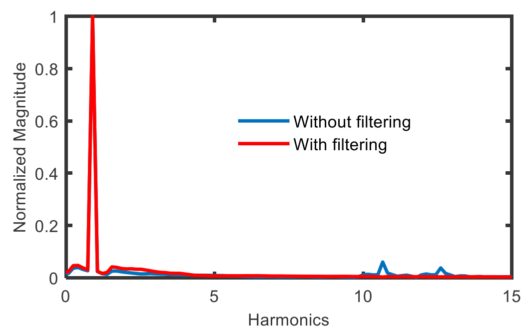

Figure 5: Harmonics with and without Active Filter

The three phase current signal is restored to normal sinusoidal shape within one cycle after the application of the active filter as shown in Fig. 6.

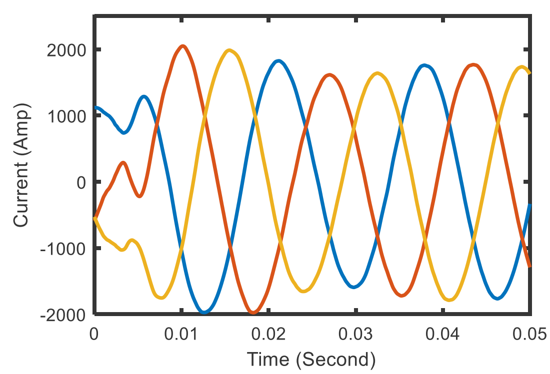

Figure 6: Three phase current waveform at the source point A with Active Filter

VII. Conclusions

This paper has investigated how alarms associated with high harmonic levels and other "faults" in marine electric power systems can be triggered using an edge IIOT device, and escalated on the onboard HMI systems. Since most marine vessels are bandwidth constrained they are unable to bring their sensor data to the cloud for alarming and alerting. Having an edge device with the computation and escalation logic connected to the plant's Alarm Management system solves this problem. Further, real time mitigation of the problems is implementable by having a closed loop feedback scheme to the control and electrical systems being monitored.

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