NILM - A Smarter Tactical Decision Aid

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***Abstract*—This paper presents results of Nonintrusive Load Monitoring (NILM) aboard an active US Coast Guard vessel. The NILM system monitors ship electricity consumption at centralized points in the ship's electrical distribution network. The NILM analyzes the electrical consumption data to extract operational information about individual equipment through automated signal processing and transient identification techniques. In contrast to a distributed load sensor network, the NILM enables lower-cost and more robust monitoring of the shipboard electrical system loads. Data collected by this NILM system during at-sea ship operations was used to develop new applications in energy scorekeeping, fault detection, and tactical decision-making. Specifically, this paper discusses NILM use for monitoring and analyzing load demands of the ship's service diesel generators, verifying theoretical Electric Power Load Analysis (EPLA) load factors using the disaggregated load information, and condition-monitoring of ship subsystems.**

I. INTRODUCTION

Today's military and commercial ships employ "optimally" manned crews just fractions of sizes of those on legacy assets [1]. This shift to smaller crew sizes derives from the aim to increase efficiency, decrease costs, and reduce at sea risks. However, with smaller crews comes increased reliance on automated processes for ship operation. In order to ensure overall ship robustness and resiliency, these automated processes in-turn require automated monitoring for tracking operation and detecting anomalies in ship machinery.

The Nonintrusive Load Monitor (NILM) [2]–[4] provides a low-cost, rugged, and easily-installed mechanism useful for automated ship monitoring. A NILM system, as shown in Fig. 1, employs voltage and current sensors to monitor electrical consumption at centralized points in the distribution network, e.g. distribution panels or electrical service generators. Using automated signal processing of this electrical data combined with transient-based recognition algorithms, the NILM "non-intrusively" detects and logs the turn *ON* and *OFF* events of downstream loads. This is in contrast to "intrusive" monitoring, where sensors are installed directly on each load of interest. Further processing of the logged data allows the NILM to record load and ship subsystem operation, track energy consumption by load, and monitor the machinery condition.

The specific NILM system involved in this study uses the sinefit spectral envelope preprocessor [5] to extract power harmonic envelopes from the raw current and voltage data. This processed data is stored in a computer local to the monitor in a custom database, NilmDB [6]. This data is accessible for viewing and further processing via a web-based user interface, NILM Manager [7]. By processing and storing the data at the physical meter, data is only transmitted when queried, resulting in lower network bandwidth requirements and increased data security.

Many signal processing algorithms are available for detecting and disaggregating individual equipment load information from the aggregated power stream. For example, recent studies have used neural networks [8], clustering algorithms [9], and finite state-machine models [10] for such purposes. The NILM system used in this study relies on a correlation-based technique [6], [11], which essentially matches electrical transients in the aggregate data to transient "exemplars" of specific ship loads. The main advantage of this method is that it does not require significant pre-recorded data for training the algorithms. It should also be noted that while this technique can stand alone for load disaggregation, it can also be integrated as a load "feature" into more complex

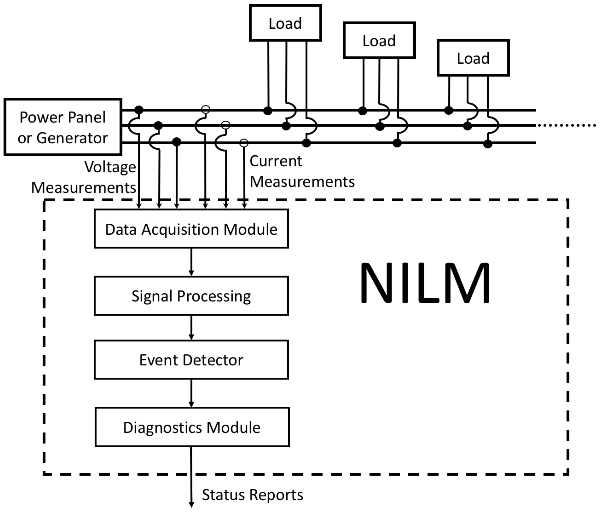


Figure 1: Conceptual Diagram of a NILM system

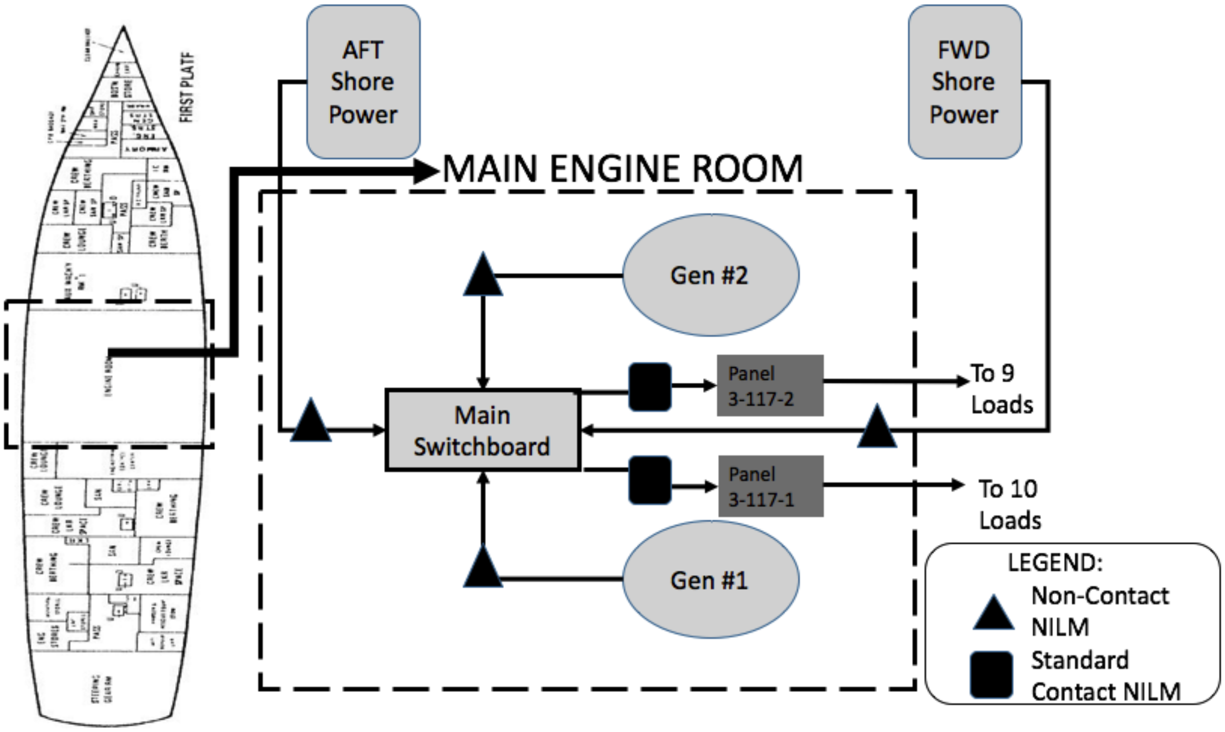


Figure 2: Placement of NILM meters onboard the Coast Guard vessel

and data-intensive techniques such as those described in [8]–[10].

In collaboration with the US Coast Guard (USCG) and US Navy, this NILM system was installed on the 270-foot USCG Cutter SPENCER for operational testing. This vessel maintains an operational tempo of 185 days away from homeport per annum and performs a host of Coast Guard missions, including environmental stewardship, law enforcement, fisheries protection, and national security. It hosts a 100-person crew and a machinery plant that comprises a complete microgrid fully capable of producing propulsion, power generation, and hospitality loads to support the crew.

To fully monitor this vessel, six NILM meters were installed as shown in Fig. 2. Two "contact" NILMs were installed at the input to two main engine room subpanels. These panels feed a total of 19 mission critical loads in the main machinery compartment. These "contact" NILMs are described as such because they require Ohmic contacts for voltage measurements. "Non-contact" NILM meters [11]–[13] were installed on each of the four main electrical feeders supplying the ship's main switchboard. Two of these feeders provide electrical power from the ship's service diesel generators (SSDGs), while the other two provide electrical power from shore when inport. Thus, these NILMs provide whole-ship monitoring capabilities regardless if inport or at sea. Further, these non-contact NILMs use novel electrostatic and hall-effect sensors to detect conductor voltages and disaggregate individual phase currents from the outside of insulated cable bundles. This means they require no interruption in service to install and keep technicians on the "safe-side" of the electrical system.

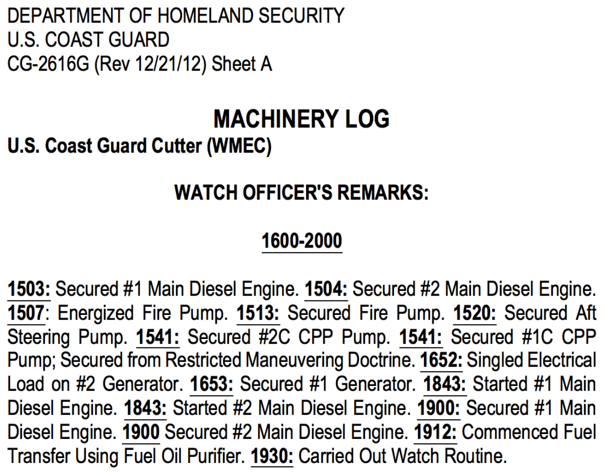
These NILMs provide three immediate opportunities for decision support systems:

- As a "Shipboard Automated Watch Stander" (SAW)
- As an energy scorekeeper and EPLA Load Factors assessment tool
- As an automated condition based monitor

The remainder of this paper demonstrates such application developments through analysis of operational data gathered while monitoring vessel operations, both at sea and inport.

II. HUMAN ACTIVITY MONITORING

With the ability to disaggregate equipment level data, the NILM can serve as a Shipboard Automatic Watchstander (SAW). This is an imperative shipboard function and a legal requirement. Currently, crews log the operational state of important machinery including propulsors, power generation gear, fuel transfer equipment, and hydraulic pumps. The NILM Manager interface provides the ability to upload custom code to the NILM for automating this machinery log generation.



DEPARTMENT OF HOMELAND SECURITY
U.S. COAST GUARD
CG-2616G (Rev 12/21/12) Sheet A

MACHINERY LOG
U.S. Coast Guard Cutter (WMEC)

WATCH OFFICER'S REMARKS:

1600-2000

1503: Secured #1 Main Diesel Engine. **1504:** Secured #2 Main Diesel Engine. **1507**: Energized Fire Pump. **1513:** Secured Fire Pump. **1520:** Secured Aft Steering Pump. **1541:** Secured #2C CPP Pump. **1541:** Secured #1C CPP Pump; Secured from Restricted Maneuvering Doctrine. **1652:** Singled Electrical Load on #2 Generator. **1653:** Secured #1 Generator. **1843:** Started #1 Main Diesel Engine. **1843:** Started #2 Main Diesel Engine. **1900:** Secured #1 Main Diesel Engine. **1900** Secured #2 Main Diesel Engine. **1912:** Commenced Fuel Transfer Using Fuel Oil Purifier. **1930:** Carried Out Watch Routine.

Figure 3: Example of log generated by a custom script designed in the NILM Manager software suite. Using disaggregated data collected by the NILM meter, the script generates a machinery log complying with standard maritime requirements.

A. *Log Generation*

The proposed SAW analyzes energy consumption under different operating conditions and acts as a tracker. Through logs, the operation and sequencing of specific machinery can be translated into an operational status (i.e. inport, at sea, at a heightened state of readiness). This key knowledge relates directly to human activity monitoring, operational tempo, and crew fatigue. As previously described in [14], logs can be generated to match current standard practice. An example of an automatically generated log is shown in Fig. 3. These logs allow an operator to verify proper operation of the plant. Moreover, because this log is generated in real-time, it allows multiple personnel in different departments to view the same data. Therefore a technician in the control room can verify that the engine start has occurred, but the bridge deck or even command cadre can view the same readings concurrently. These logs are critical to prompting maintenance actions, tracking machinery use and human activity, and tracking machinery failures over time. Complete and thorough logs are lenses through which the past operation can be inspected. They act as official records for investigators and help to pinpoint failure causes and revise best practices for the future.

B. *Procedural Checks*

This logged data also allows for procedural checks of crew actions to ensure operators follow the correct order of operations. For example, in the water purification system, specific valves must be opened in a specified order to ensure that over-pressurization does not occur. The NILM can identify missed steps and prompt watchstanders to re-check procedures and rectify neglected actions.

For example, the Main Propulsion Diesel Engine (MPDE) relies on a lubrication system which circulates oil through the engine via a gear pump when the engine is running. However, when the engine is secured, heaters and an electric prelube pump energize to heat the oil and force it through the prime mover to maintain temperature, lubrication, and thus, operational readiness. When this securing occurs, the NILM should “see” two distinct transient events: the heaters turning *OFF* followed by the electric prelube pump turning *OFF*. This correct procedure is shown in the top plot of Fig. 4, which depicts measured real power (P1) and reactive power (Q1) during an engine start sequence. Time segment *I* shows the heaters securing, segment *II* shows the electric lubrication pump securing, and segment *III* shows the final state with both loads secured. If this pump is not in “automatic mode”, e.g. following servicing the crew leaves the pump in the off or manual position, or there is a malfunction preventing it from performing automatically, the pump will remain *ON* causing unnecessary wear and energy use. The bottom plot of Fig. 4 shows this faulty operation where in phase *II* the lubrication oil pump does not secure as expected.

III. Energy Scorekeeping

The NILM system can provide metrics of power demand on the full-ship and zonal systems. These metrics can relate to EPLA load factors, generator health, and fault mechanisms.

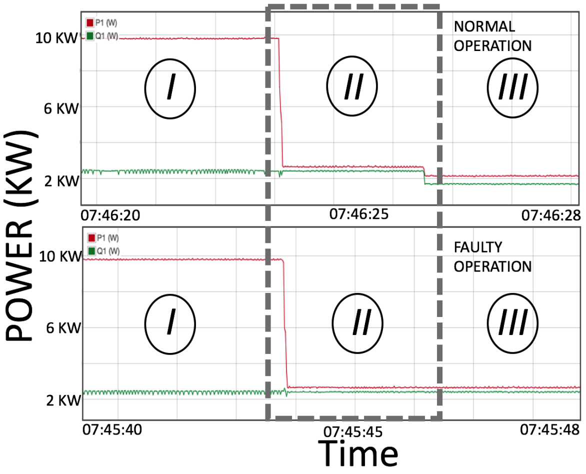


Figure 4: Example of the NILM detecting a missed procedural step (bottom plot, time segment *II*) in the lubrication system for the main propulsion engine.

A. EPLA Load Factor Verification

The Navy and Coast Guard use Electric Power Load Analysis (EPLA) [15] to size the ship's electrical generation and distribution components. Key parameters for EPLA are the ship's equipment's load factors, which are typically defined over a variety of operation conditions, e.g. anchor, shore, cruising, etc., and for a variety of ambient condition profiles, e.g. ambient temperature and relative humidity. Because these load factors determine component sizing, their accuracy is highly important. If sizing estimates are too high, components are over-engineered, resulting in excessive costs and low-operational efficiency. If estimates are too low, components are over-loaded, resulting in increased maintenance costs, component/system retrofits, and load shedding during times of high utilization [15].

The NILM system offers the ability to provide continuous comparisons of a load's effective load factor during operation with published and expected load factors. Such features are useful for improving future ship design and for updating electrical infrastructure on existing ships. The NILM is particularly adept at estimating load factors for cyclic loads whose operational status alternates between *ON* and *OFF*. For 24-hour average calculations as defined in [15], the load factor, LF, is defined as the ratio of the long-term average load, P_{avg}, and the connected load, P_{conn}, i.e. the nameplate power rating of the load [15]. For a cyclic load, the average power can be defined as,

$$P_{avg} = \frac{1}{T}\int_0^T D(t) P_{conn} dt \qquad (1)$$

where $D(t)$ indicates the time-dependent effective duty-cycle of the load. With P_{conn} a constant, the integral in (1) essentially averages the duty-cycle over the time-period of monitoring, T. Thus, the long-term average power can be rewritten as,

$$P_{avg} = D_{avg} P_{conn} \qquad (2)$$

Rearranging this equation reveals that the average duty-cycle, D_{avg}, is simply the ratio of the long-term average load, P_{avg}, and the connected load, P_{conn}. That is, for 24-hour average calculations of cyclic-loads,

$$LF = D_{avg} \qquad (3)$$

Fig. 5 shows an example of a monitored cyclic-load over a four-hour interval. This load is the main diesel engine lube oil heater, an automated heating element that maintains fluid temperature. The NILM detects this heater's *ON* and *OFF* events and determines the total time the heater is *ON* over the full observation time (4 hours in this example). This particular load is on for 105 minutes of the 240-minute observation period. Equivalently, this load has an average duty-cycle, $D_{avg} = \frac{105}{240} = 0.44$. It's important to note that this example is meant to illustrate the NILM's procedure in estimating average duty-cycles, but for (3) to hold, this monitoring should be performed over a much longer period.

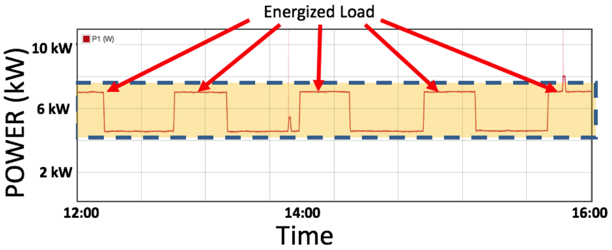


Figure 5: NILM power data showing the cyclic operation of the main diesel engine lube oil heater over a 4-hour period.

Table I compares published EPLA load factors for specified loads [15], [16] with average duty-cycles calculated by the NILM. These duty-cycles were calculated for two states: underway normal operation (Cruise) and inport normal operation (Shore). Similar to the example of Fig. 5, these average duty cycles were calculated over a relatively short example period and might vary if calculated over longer periods. It is also important to note that published material in [15], [16] assumes a constant load factor across ambient conditions for these loads; however, in general, load factors can differ across a variety of temperatures and relative humidities. For our purposes, ambient conditions were neglected. Thus, disparities between the published factors and the NILM-calculated duty-cycles might be exacerbated by this assumption. Still, the important point is that the NILM system provides the capabilities to check long-term load and ship operation against expected operation.

B. Generator Health

One of the main reasons that EPLA load factors are so important in vessel design is the strong correlation between generator loading and generator health. Diesel generator sets are designed to be operated in their upper range of loading (70-100% of rated load). Operating at low loads results in engine exhaust deposit build-up and lower temperatures, which leads to power loss, poor performance, and accelerated wear of components. This results in unplanned downtime and failure. Common best practice states that no more than two hours should be spent below 50% of rated load, and no more than 30 minutes should be spent below 30% [17]. The NILM system can present maintainers and operators a graphical visualization of loading characteristics for

		Shore		Cruise	
Load	Rated Power (kW)	Published Load Factor	NILM Average Duty-cycle	Published Load Factor	NILM Average Duty-cycle
Inport Salt-water Cooling Pump	7.5	0.80	1.00	0.00	0.00
Wastewater Discharge Pump	3.7	0.10	0.02	0.10	0.02
Main Engine Prelube Pump	2.2	0.00	1.00	0.00	0.62
Main Engine Jacket Water Heater	9.0	0.60	0.00	0.00	0.43
Main Engine Lube Oil Heater	12.0	0.60	1.00	0.00	0.58
Diesel Generator Jacket Water Heater	7.5	0.60	0.63	0.00	0.00
CPP Hydraulic Oil Pump	7.5	0.00	0.00	0.00	0.00
Diesel Oil Purifier	5.6	0.10	0.00	0.40	0.13

Table I: Table comparing published load factors of several cyclic loads with average duty cycles as determined through NILM data. The Shore and Cruise factors were calculated over selected 24-hour periods.

generator sets. Fig. 6 shows an example visualization of the SPENCER's SSDGs' loading profiles. At this particular time, Generator 1 was offline while Generator 2 provided the ship's power. An operator can easily see that the online generator is operating around 80% capacity and is thus within the recommended range of operation.

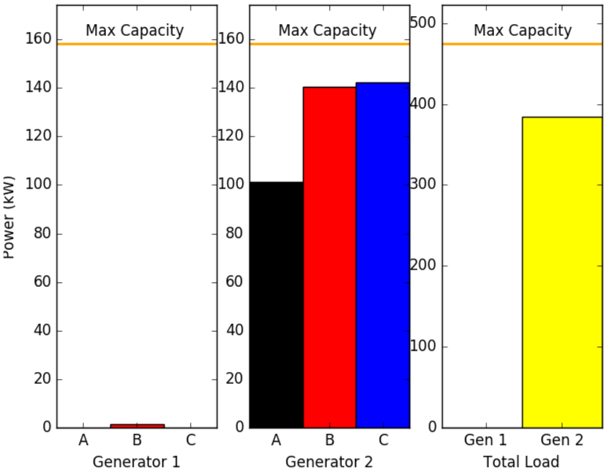


Figure 6: Example of the NILM's ability to automate measuring generator loading and report metrics via graphical visualizations.

C. *Energy Wastage, A Case Study*

Many shipboard systems are controlled via hysteresis control. In these systems, actuators or relays cycle operation based on setpoints from sensors, e.g. level switches in water tanks, pressure sensors in hydraulic or compressed air systems, or thermocouples in lube oil and jacket water heating systems. In such automated systems, faulty operation is difficult to detect unless full failure occurs. The automated control system often maintains operation in a degraded state, causing overuse of actuators, pumps, and heaters at the expense of excessive energy use and wear on the system.

An example of the NILM's ability to detect such faults is illustrated in the keep-warm system for one of the vessel's diesel generators. This system circulates water and lube oil through the generator set and cycles a pair of heaters *ON* or *OFF* based on the output of a temperature thermostat. Fig. 7 shows this arrangement and also a failed component as detected by the NILM. This system is designed to keep the heater *ON* when ambient temperatures are low, then turn the heater *OFF* once the specified temperature has been reached.

By comparing two identical generators on the same vessel, an anomaly in one of the systems was detected. The heater in one of the keep-warm systems was found energized with a load factor of ≈ 0.5 while in the other system (the faulty system) the load factor was closer to ≈ 0.03. This is unexpected as both generators and heaters have the same arrangement and machinery, and thus should operate similarly. This discrepancy between load factors spurred investigation of the system, which

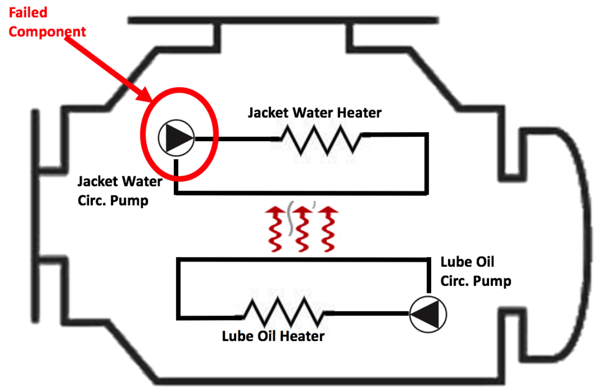


Figure 7: One-Line diagram of engine keep-warm system. The NILM was able to detect a faulty jacket water circulating pump.

revealed that the heater was functioning correctly; however, the circulating pump had failed. This resulted in the heater short cycling and only heating a small volume of water.

The NILM was able to detect another failure in the same system, this time in the lube oil heating system. Similar to the jacket water system, this arrangement maintains the lubricating fluid between two temperature setpoints, energizing at low temperatures and securing once the high temperature is reached. Again, one system had a load factor of ≈ 0.5 whereas the sister system maintained a load factor of 1. That is, the heater was always energized. Because the circulating pump in the jacket water system had failed and the jacket water system was not warm, the lube oil system was forced to overwork, leaving the heater in the constant *ON* state.

These two anomalies demonstrate the capabilities of shipboard NILM systems in machinery monitoring. These faults illustrate the NILM's ability to detect anomalies and direct troubleshooting, helping to narrow the scope of efforts. If machinery health is monitored over a longer timeline, it is easier to discern a failing component from a design anomaly.

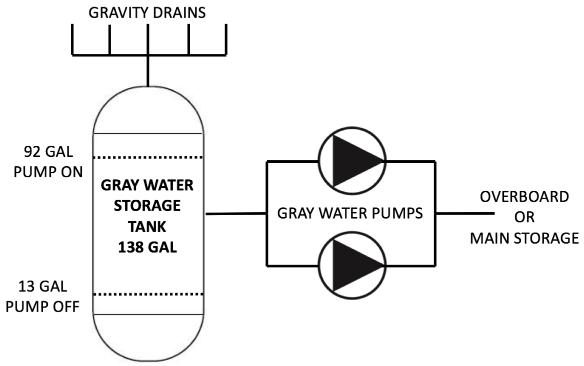
IV. Condition Based Maintenance Aid

With its ability to continuously measure, store, and analyze power data, the NILM system can be applied towards Fault Detection and Isolation (FDI) of closed-loop controlled systems. Closed-loop systems are widely used to control setpoints such as tank levels, temperatures, pressures, and other quantities. Despite the benefits, their automatic operation can mask underlying electromechanical failures without perceivable changes to operation. This leads to increased energy consumption and incurs excessive physical wear, since the closed-loop controller must operate the system more vigorously in order to compensate for system pathologies. Presented herein is a discussion of a single system in which two statistical metrics are monitored:

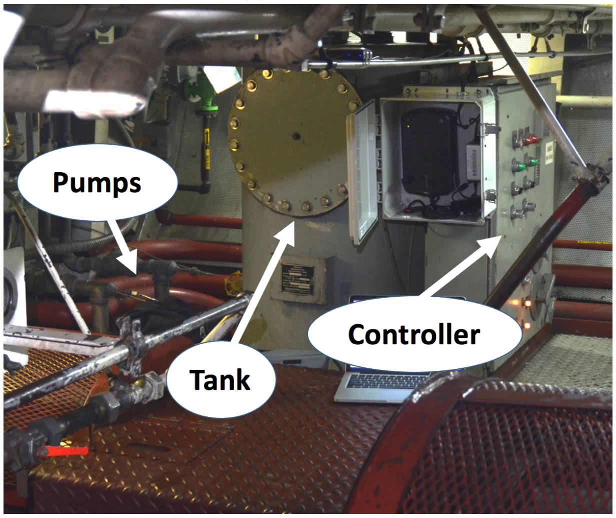
- Duration of a particular load event
- Time between consecutive load events

Using these two metrics in conjunction with an understanding of proper system operation provides a framework for diagnosing previously undetected system faults.

The Coast Guard relies on a gray water disposal system (Fig. 8) to process the several hundred gallons of wastewater the crew produces daily. This water originates from the use of showers, sinks, washing machines, deck drains, and other gray water sources. The system is comprised of a network of storage tanks, piping, and pumps to transfer, retain, process, and expel wastewater. This case study focuses on analyzing the portion of the system in Fig. 8a, with the actual machinery shown in Fig. 8b. In this network, two identical pumps (for redundancy) alternate each cycle to discharge the tank. Conductivity sensors detect water levels and provide



(a) Schematic



(b) Labeled Image

Figure 8: Coast Guard gray water system

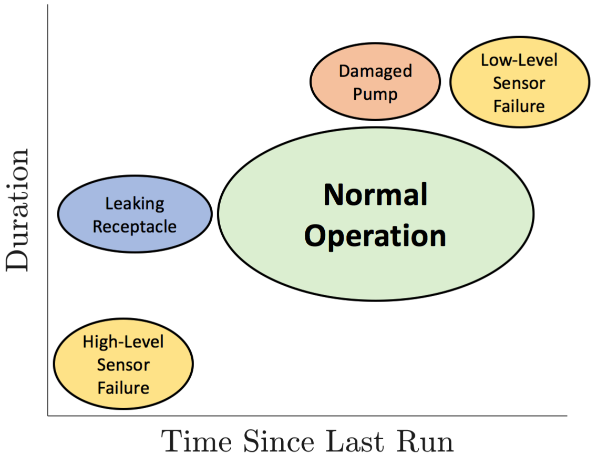


Figure 9: Various fault types in the gray water system manifest themselves in different regions of the NILM detected duration vs. time period space.

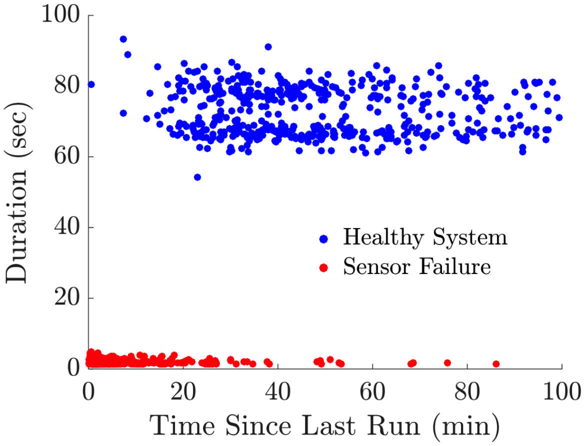


Figure 10: Duration vs. time period plot of healthy grey water system pump runs (blue points) and faulty runs (red points) caused by a failed high-level sensor.

inputs for pump control. The pumps run when the tank reaches a high level of 92 gallons (348 L) and halt at a low level of 13 gallons (49 L).

Equation (4) estimates the duration Δt of the pump run. This relies on the discharge volume V and the flow rate $\dot{Q}_{pump}$, which is provided in pump operating curves. Given the parameters of the gray water system, (4) predicts that a pump must run for $\approx$ 80 seconds to completely discharge 79 gallons of waste.

$$\Delta t = \frac{V}{\dot{Q}_{pump}} \tag{4}$$

The time between consecutive pump runs ΔT can be estimated by looking at the expected rate of liquid entering the tank relative to the total volume of the tank V. The rate depends on the number of gray water receptacles serviced by the tank N, the load factor of the receptacles ϵ, and the flow rate of the receptacles $\dot{q}$. Equation (5) predicts $\approx$ 40 minutes should elapse between pump runs.

$$\Delta T = \frac{V}{N\epsilon\dot{q}} \tag{5}$$

Normal operation of the gray water pump is identified by correlating the expected values for these two metrics. Fig. 9 shows this operating zone compared to those of various sensor and machinery faults. For example, a clogged low level sensor would cause the controller to miss its “turn off” signal and the pump would run continuously. In another instance, a mechanical failure in the pump may decrease its pumping volume, therefore increasing the pump duration well above the expected 80 seconds. By monitoring these parameters, even a faucet left running can be identified. This would result in more frequent pump runs, on the order of 10-15 minutes apart.

The NILM system monitored these pumps over two specific time periods: during normal healthy operation and during faulty operation. During one time period, the collected results were as expected. However, during the other, the high level sensor failed in the *ON* position and caused short cycling of the pumps. The controller continuously received the high-level alarm, energized the pump, but quickly received the low-level alarm. The NILM recorded these exceptionally frequent and short pump runs. The results over these two time periods are compared in Fig. 10, where healthy runs cluster distinguishably from faulty ones.

V. CONCLUSIONS

As presented in this paper, naval assets offer an ideal microgrid environment for NILM application. The platform provides insight into significantly complex shipboard systems and can fulfill the requirements for automation and monitoring. Compared to distributed networks of sensors, the NILM system is considerably less expensive, less cumbersome, and requires less maintenance. These aspects make the NILM system a desirable retrofit for existing vessels.

The usefulness of the NILM is due largely to its ability to detect the power signature of individual loads from aggregate electrical data. The disaggregated NILM data can be used for several tactical decision functions:

- As a “Shipboard Automated Watch Stander” (SAW)
- As an energy scorekeeper and EPLA Load Factors assessment tool
- As an automated condition based monitor

VI. FUTURE WORK

Building upon these accomplishments, there are several ongoing areas of research. These efforts include exploring alternate disaggregation techniques, expanding the platform to other vessels, improving sensor designs, and developing new user interfaces.

As discussed, the broad capabilities of the NILM system rely on its ability to discern individual loads. While current methods – which correlate transient peaks and steady-state power levels – are adequate, there are several additional pathways for improvement. Some include advanced signal filtering techniques and clustering algorithms. The NILM already derives and stores the real and reactive components of higher-power harmonics. Analyzing these additional streams of information can further refine equipment signatures to identify them more reliably.

The USCGC SPENCER has been fitted with both non-contact and contact NILM meters. Currently, non-contact meters monitor every load on the ship through an aggregate switchboard measurement, and contact meters show a closer, more granular view of several subsystems. A sister ship, the USCGC ESCANABA, is being instrumented with an identical NILM system. This vessel has a similar equipment arrangement and will act as a parallel testing environment. The expanded data set can provide additional opportunities to assess the efficacy of transient and fault detection methods.

The non-contact NILM meters used in this installation operate around bundled cables and keep the technician completely on the safe-side of the insulation, requiring no entry into the power panel. Since these sensors measure the electric and magnetic fields around cables, there may be instances where nearby current-carrying conductors cause interference in the readings. Therefore, research is underway for shielding these sensors in order to ensure uniform operation despite the surrounding environment.

Another area of improvement is the development of a standardized user interface for shipboard use. This interface would present a graphical summary of relevant metrics, system states, and possible faults. Currently, data is analyzed post-deployment; however, the ability exists to continuously process data in real-time and generate visual reports. This functionality can be extended to automatically track evolving metrics and changing states, as transients occur in the electrical network. This dashboard can also be customized by the operator to display particular systems of importance.

Contextualizing this ongoing research alongside existing NILM capabilities, the NILM system is poised to provide significant benefits in the maritime realm during the coming years.

VII. ACKNOWLEDGMENTS

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