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Improving Shipboard Maintenance Practices Using Non-Intrusive Load Monitoring

ABSTRACT

Field studies have demonstrated that it is possible to evaluate the state of many shipboard systems by analyzing the power drawn by electromechanical actuators (Cox et al. 2006; Cox et al. 2007; DeNucci et al. 2005; Mitchell et al. 2006; Ramsey et al. 2005). One device that can perform such an analysis is the non-intrusive load monitor (NILM). This paper focuses on specific field studies conducted aboard two US Coast Guard Medium Endurance Cutters and at the U.S. Navy's DDG-51 Land-Based Engineering Site (LBES). The field tests demonstrate that the NILM, which relies only on electrical measurements, can automatically detect many existing and impending failures. Many of these faults can be detected simply by examining the operating schedules of the appropriate electrical loads.

INTRODUCTION

Modern warships face a number of rapidly changing requirements. There is constant pressure to reduce manning, maximize readiness, and decrease maintenance costs. There is also an intense desire to increase operating tempos, forcing maintenance providers to make repairs faster and to ensure that equipment operates reliably for longer periods.

To meet the rapidly changing requirements of modern naval vessels, it is necessary to continuously monitor the state of critical machinery systems. Tools such as the Integrated Condition Assessment System (ICAS) have been developed to enable the necessary monitoring capabilities. ICAS uses sensor data to assess the status of critical systems and to provide operators and maintainers with the information needed to take action at the optimal time (DiUlio et al.

2003). One drawback of ICAS and other similar systems is that they require individual devices to be independently monitored by a number of different sensors (i.e. RTDs, tachometers, accelerometers, etc.). Some estimates indicate that ships in the DDG-1000 class may have as many as 200,000 sensors (Lopushansky 1999). Although such a large sensing network can be advantageous, it is also expensive and difficult to maintain. A simple, low-cost alternative with lower sensor density could increase reliability and enhance the capabilities of existing systems.

One device that can simplify the monitoring and assessment process is the non-intrusive load monitor (NILM). The NILM, which measures the current and voltage at one or more central locations in a power-distribution network, can determine both the operating schedule and the operational status of each of the major loads in an engineering plant (Leeb et al. 1995; Shaw 2000). In many cases the NILM can also use electrical data to assess the status of certain mechanical elements such as flexible couplings, valves, and filters (DeNucci et al. 2005; Cox et al. 2006; Cox et al. 2007; Mitchell et al. 2007). Because a NILM-based monitor greatly reduces the number of required sensors, it can decrease costs and increase the effectiveness of organizational-level maintenance.

To demonstrate the NILM's capabilities, the authors are conducting experiments aboard the *USCGC Escanaba*, the *USCGC Seneca*, and at the U.S. Navy's Land-Based Engineering Site (LBES). Following a brief description of the NILM itself, this paper presents some results obtained during our preliminary field studies. This paper focuses on results that demonstrate how the NILM can detect many common faults simply by examining the operating schedule of

the appropriate electrical loads. Emphasis is placed upon three sets of abnormal conditions, namely cycling-system leaks, pump faults, and controller and sensor failures. Each section includes relevant field examples.

NILM OVERVIEW

Figure 1 shows the block diagram of a standard NILM. Note that the NILM measures the aggregate current flowing to a bank of electrical loads. It then disaggregates the operating schedule of individual loads using signal-processing techniques. In an engineering plant, the candidate installation locations include generator output busses and distribution panels.

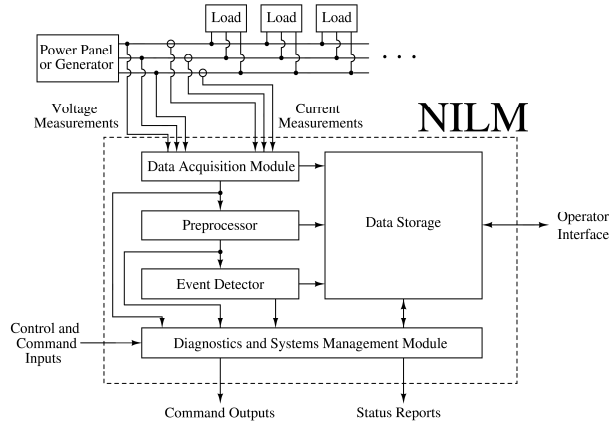


FIGURE 1. Diagram showing the fundamental signal flow path in a NILM.

Using measurements of the line voltage and aggregate current, a software-based preprocessor onboard the NILM computes time-varying estimates of the frequency content of the measured line current (Shaw 2000). Formally, these time-varying estimates, or spectral envelopes, are defined as the quantities (Shaw et al. 1998)

$$a_m(t) = \frac{2}{T} \int_{t-T}^t i(\tau) \sin(m\omega\tau) d\tau \quad (1)$$

and

$$b_m(t) = \frac{2}{T} \int_{t-T}^t i(\tau) \cos(m\omega\tau) d\tau. \quad (2)$$

These equations are Fourier-series analysis equations evaluated over a moving window of

length T (Oppenheim et al. 1988). The coefficients $a_m(t)$ and $b_m(t)$ contain time-local information about the frequency content of $i(t)$. Provided that the basis terms $\sin(m\omega t)$ and $\cos(m\omega t)$ are synchronized to the line voltage, the spectral envelope coefficients have a useful physical interpretation as real, reactive, and harmonic power (Leeb et al. 1995).

The spectral envelopes computed by the preprocessor are passed to an event detector that identifies the operation of each of the major loads on the monitored electrical service. In a modern NILM, identification is performed using both transient and steady-state information (Lee 2003). Field studies have demonstrated that transient details are particularly powerful because the transient electrical behavior of a particular load is strongly influenced by the physical task that is performed (Leeb 1995). As shown in Fig. 2, for example, the physical differences between an incandescent lamp and an induction machine result in vastly different transient patterns. Figure 3 demonstrates the positive identification of an induction motor driving a small vacuum pump. Further details of the detection and identification process can be found in Lee (2003) and Leeb (1993)

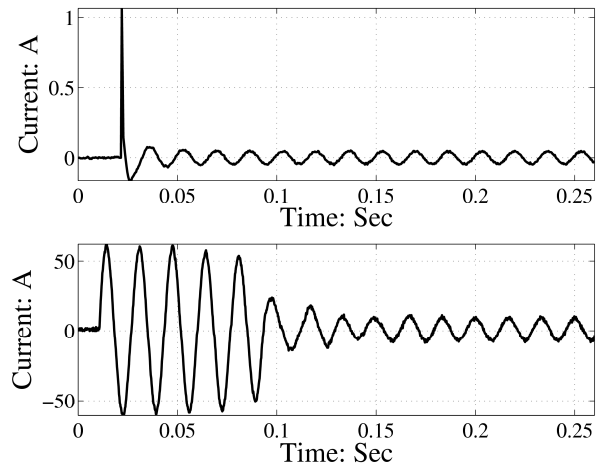


FIGURE 2. Top trace: Current drawn during the start of an incandescent lamp. Bottom trace: Stator current drawn during the start of an unloaded, fractional horsepower induction machine.

The final block in Fig. 1 is the NILM's diagnostics and systems management module. This software unit assesses load status using any required combination of current data, voltage data, spectral envelopes, and load operating schedules (Cox 2006). The successful application of this module has been demonstrated in numerous publications (Armstrong et al. 2006; Cox et al. 2006; Cox et al. 2007; DeNucci et al. 2005; Laughman et al. 2006; Lee 2003; Luo 2001; Mitchell et al. 2007; Shaw 2000). Shipboard applications are highlighted in DeNucci et al. (2005), Cox et al. (2006), Cox et al. (2007), and Mitchell et al. (2007).

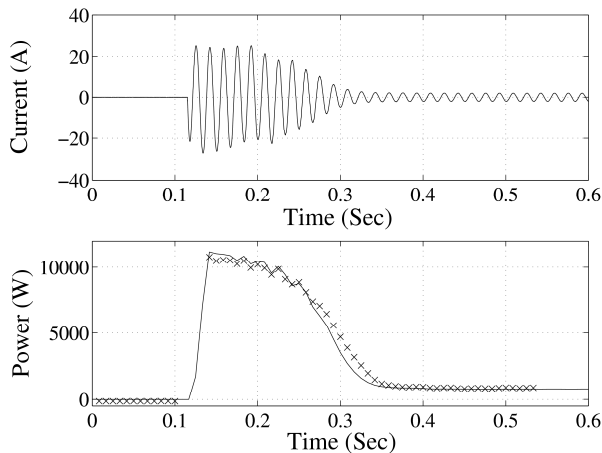


FIGURE 3. Measured current and computed power during the start of 1.7hp vacuum pump motor. Also shown in the power plot is a section of the template that has been successfully matched to the observed transient behavior by the NILM's event detector.

As shown in Fig. 1, the modern NILM is designed to interact with human or automated devices in a number of different ways. For instance, the NILM can use its diagnostic information to command certain loads to either commence or cease operations. Additionally, the NILM can provide regular status reports to human operators. To assist in future maintenance operations, the NILM stores all of the relevant data streams (i.e. currents, voltages, operating schedules, etc.) in either a local or remote database (Paris 2006). The NILM's vast storage capabilities make it possible for the operator to perform historical data trending. Note that this off-line analysis can be

conducted on a remote PC using convenient software packages such as Microsoft Excel (Paris 2006). The following sections describe how these capabilities can be used to prevent or detect certain critical shipboard faults.

LEAK DETECTION IN CYCLING SYSTEMS

Naval vessels commonly use compressed air or vacuum systems to perform a number of critical functions, including waste collection and pneumatic valve actuation. To ensure instant availability and to provide for short periods of high demand, these systems typically have a pressure tank that is periodically charged by an electrically actuated compressor or pump. A typical layout is shown in Fig. 4. As loads draw from the reservoir, system pressure decreases. Once a certain low-pressure set point has been reached, the controller transmits a start command to the pump or compressor, causing the device to begin charging the system. Once the pressure has reached the predetermined high set point, the pump motors are either de-energized or the pumps are directed to enter a re-circulation mode. From an electrical perspective, this behavior creates a *cycling system* in which electrical power usage follows a regular cycle of charging and discharging based on a pressure.

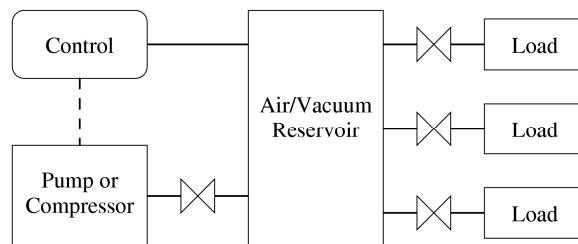


FIGURE 4. Diagram of a typical cycling system. Solid lines indicate air paths, and dotted lines indicate electrical connections.

Both compressed-air systems and vacuum-assisted waste-disposal systems have been examined during our initial field tests. Of particular interest has been the detection of leaks and valve failures. Clearly, large leaks will cause

the pumps or compressors to operate more frequently. The challenge, however, has been to determine if changes in the frequency of pump operation are caused by faults or simply by changes in system usage. This section presents results from those studies.

COLLECTION, HOLD, AND TRANSFER (CHT) SEWAGE SYSTEMS

In Cox et al. (2006) and Cox (2006), the authors proposed a generalized model that describes how pneumatic loads affect the operating schedule of the electromechanical actuator in a cycling system. Use of that model for diagnostic purposes requires one to consider how the system is operated. First, it is necessary to understand the dynamics of the pneumatic loads (i.e. leaks, valves, tools, etc.). Additionally, system usage must consistently follow some pre-determined stochastic process, although the specific statistics of that process do not have to be known a priori. Cox et al. (2006) showed that this model can be used to determine if leaks exist in CHT sewage systems. In those units, usage events (i.e. toilet flushes) have been found to arrive according to a Poisson process and individual flushes have been found to cause nearly instantaneous drops in vacuum. Under those conditions, it is possible to determine the form of an equation that approximates the shape of the distribution of the time between pump runs. In the field, the measured distribution can be created using NILM data and the curve-fit parameters can be determined via maximum-likelihood estimation. Complete details are presented in Cox et al. (2006) and Cox (2006).

The cycling system model has been tested extensively aboard the *USCGC Seneca*. Figures 5 and 6 illustrate the predictive power of the model. As shown, the predicted distribution matches closely to what is measured in the field. Use of this model aboard the *Seneca* has led to the successful detection of several leaks. On three separate occasions in the field, the NILM has immediately detected the failure of a check valve at the suction port of the vacuum pump. Experience has shown that such failures can go

undetected for several weeks, leading to hundreds or thousands of unnecessary pump runs.

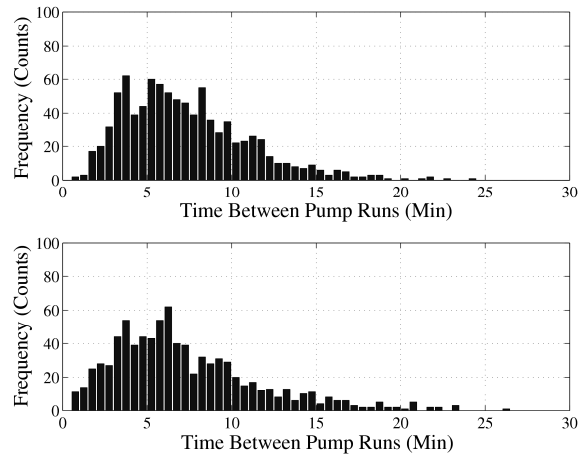


FIGURE 5. Simulated (top plot) and measured (bottom plot) frequency distributions for the time between pump runs under normal (i.e. no leak) operating conditions. Both plots reflect five days of usage. Data was collected aboard the *USCGC Seneca*.

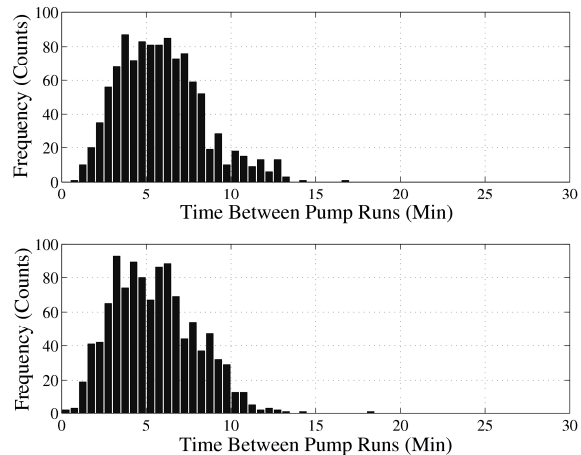


FIGURE 6. Simulated (top plot) and measured (bottom plot) frequency distributions for the time between pump runs in the presence of a small leak. Both plots reflect five days of usage. Data was collected aboard the *USCGC Seneca*.

COMPRESSED-AIR DISTRIBUTION SYSTEMS

The generalized cycling system model presented in Cox et al. (2006) and Cox (2006) is applicable in any system in which actuator cycling follows the behavior of a particular mechanical variable (i.e. pressure, temperature, etc.). In systems where pneumatic load activity is relatively

complex, the model indicates that other diagnostic tools are more appropriate than those used to study the CHT system. In compressed-air systems, for instance, loads such as tools and pneumatically actuated valves can operate for several seconds, several minutes, or even several hours. Furthermore, each load can reduce the pressure at a different rate. Because this behavior is so much different than that observed in the CHT system, it is more appropriate to analyze system behavior using a time-based approach.

A NILM is currently used to study the ship's service low-pressure (LP) air system aboard the *Seneca* and the low-pressure air system at the Navy's DDG-51 LBES. Figures 7 and 8 demonstrate how pneumatic load activity affects compressor cycling. The data shown in those figures was recorded before, during, and after the start of a gas-turbine generator (GTG) at the LBES. Valve actuation during and after the start clearly affects the lengths of the compressor's load and unload intervals. Trends in the lengths of those time periods can be used for diagnostic purposes.

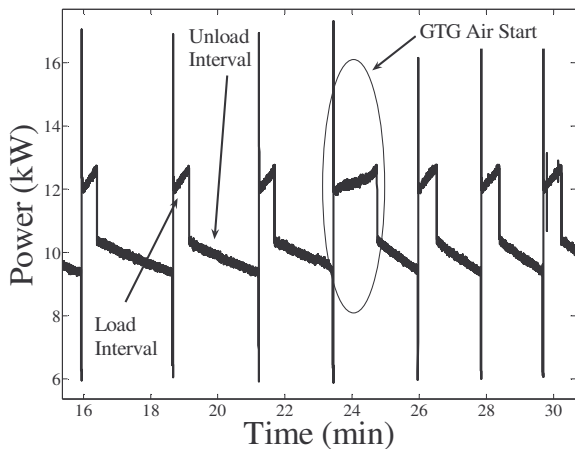


FIGURE 7. Power consumption by a low-pressure air compressor (LPAC) before, during, and after the air start of one of the GTGs at the Navy's DDG-51 LBES.

Time histories such as the ones shown in Fig. 8 have been used to detect leaks in the ship's service LP air system aboard the *Seneca*. Figure 9 shows diagnostic information created by the NILM for that system. Note that the compressor in this system is operated according to an ON/OFF scheme. Thus, when the receiver

pressure reaches a low set point, the compressor de-energizes completely. Figure 9 shows how the lengths of the on and off times varied over a typical day in port. For several hours a valve was accidentally left open, causing an increase in compressor run time and a decrease in the time between compressor runs. Using such plots, operators and NILM software routines can determine if leaks exist in the system.

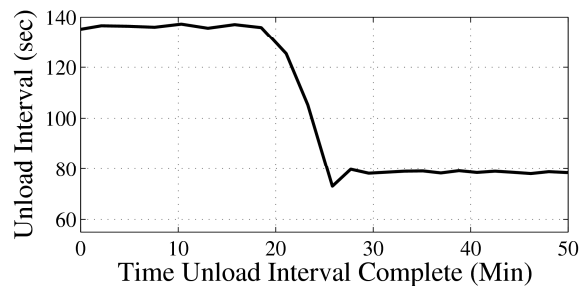
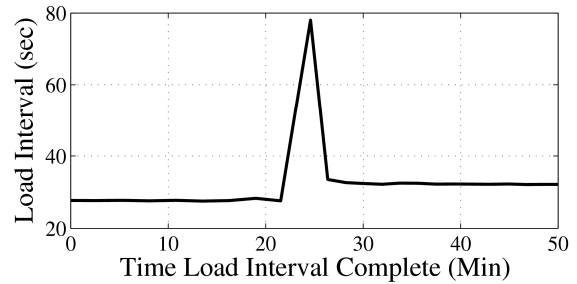


FIGURE 8. Time histories showing variations in the lengths of the LPAC's load and unload intervals. These time histories were created using the data shown in Fig. 7.

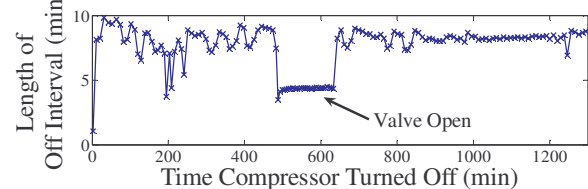
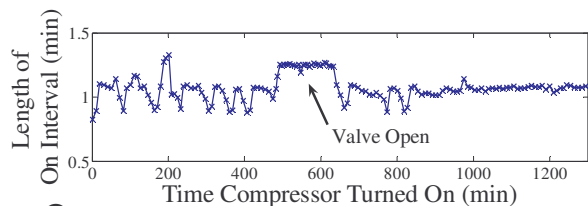


FIGURE 9. Time histories showing variations in the lengths of the on and off times of the compressor in the ship's service LP air system aboard the *Seneca*. During the indicated period, a valve was accidentally left open.

The operating-schedule analysis described above can be performed in a number of different ways. For instance, it is also possible to examine the number of times that a compressor has operated over a given time period. If a leak exists, this number should increase. As an example, consider Figure 10 which shows how the number of compressor runs varied over a 35-day period. To remove the effects of usage variations, the run-count value was calculated over a fixed four-hour window during the night when compressed air demand is normally quite low. As shown, a leak was in place until day 18. The crew detected the leak when they attempted to use the ship's whistle. A NILM could have alerted the crew much sooner.

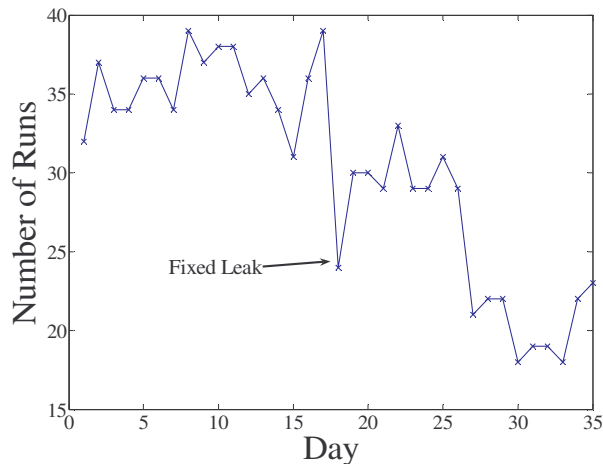


FIGURE 10. Variation in the number of compressor runs over a 35-day period. Each data point reflects the number of times that the compressor operated during a fixed four-hour window during the middle of the night. A leak was detected by the crew on day 18 and it was immediately fixed.

FAULTY PUMP OPERATION

Mechanical faults affect the electrical power drawn by pumps, compressors, and fans. Examples demonstrating the effects of leaks in compressed air and vacuum systems were shown previously. Many other examples have also been discovered during our studies. For instance, operator behavior, sea conditions, and fluid-system clogging have all been shown to affect the

electrical power drawn by pump motors. This section demonstrates failures that have been detected by the NILM while monitoring reverse-osmosis units and collection, hold, and transfer (CHT) sewage systems.

REVERSE-OSMOSIS UNITS

Many modern vessels produce desalinated water via reverse osmosis. In this process a large differential pressure is imposed across a semi-permeable membrane that has brackish water on one side and fresh water on the other. The high differential pressure, which is typically in the range of 750 to 1200 psi, forces water to pass from the diluted solution (Zarambo 1992).

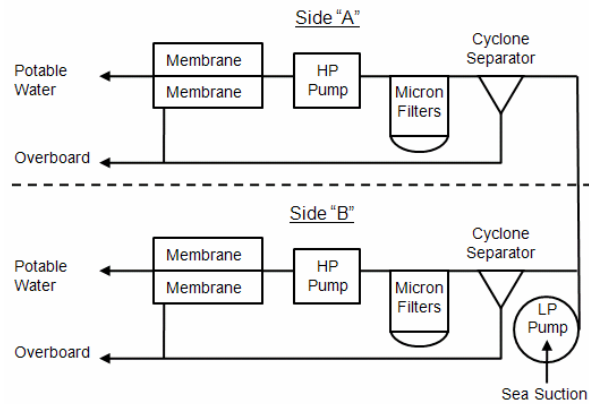


FIGURE 11. Simplified schematic of the reverse-osmosis system aboard a USCG Medium Endurance Cutter. Note that the cyclone separator can discharge water overboard. All three pumps are monitored by the same NILM.

Figure 11 shows a schematic of the reverse-osmosis units on the USCG's Medium Endurance Cutters. In those units, saltwater from the ASW system is vertically lifted by a small centrifugal pump known as the low-pressure (LP) pump. Once lifted, the incoming feedwater separates into two paths. After passing through a series of pretreatment filters, water in each path is raised to a high pressure by a positive-displacement pump. Each of these high-pressure (HP) pumps discharges into several membranes that separate the seawater into brine and potable water. On both the *Escanaba* and the *Seneca*, a NILM currently monitors the aggregate current flowing

to all three pumps. Figure 12 shows the power drawn during a typical system start.

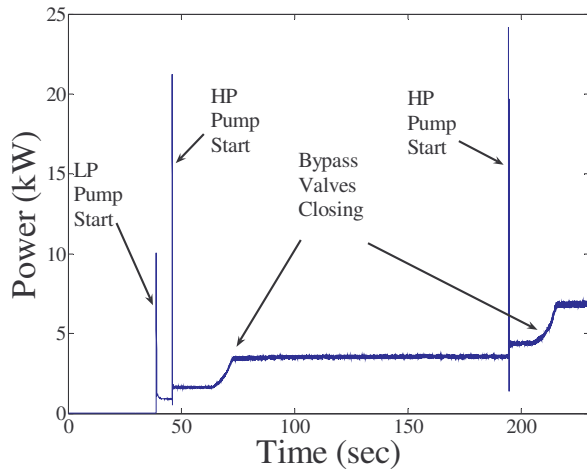


FIGURE 12. Power drawn by the pumps in the RO unit during a typical system start. Note that manual valve throttling causes a change in the steady-state power.

Field tests have demonstrated that the NILM can easily detect conditions that can lead to very serious pump failures. Examples include abnormal operation in highly contaminated waters and large variations in the steady-state input power.

Contamination can have a catastrophic effect on the positive-displacement pumps in the RO system. It is well known that RO units are to be secured before entering harbors or other regions that would overload the system's pretreatment capabilities (i.e. the micron filters) (Zarambo 1992). Occasionally, however, the crew may not be aware that the vessel has entered a region that may cause problems. If that happens, the pressure across the micron filters can increase, thus reducing the pressure at the inlets to the positive-displacement pumps. As a precaution, the controller is designed to secure the high-pressure pumps whenever their inlet pressures fall below a certain threshold. If the pump inlet pressure fluctuates, however, the pump may experience multiple restarts. Such activity usually goes unnoticed because manual inspections are performed only periodically.

Figure 13 shows the power drawn by all three pumps during a period when the *USCGC Escanaba* was passing through contaminated waters. Initially, the LP pump and one HP pump were operating. Shortly before minute 10, the HP pump secured, re-started, and then secured again for several minutes. During this time, the LP pump ran by itself. Around minute 14, the HP pump re-started, likely because its inlet pressure increased. Several minutes later, the HP pump secured and re-energized 4 times in less than 60 seconds. Engineering logs indicate that a nearby operator noticed this behavior and subsequently secured both pumps. After approximately 20 minutes, the system was brought back online, and it operated normally until about minute 96. At that time the HP pump again progressed through a series of starts and stops. In all, nine starts were recorded during an approximately two-minute interval. The HP pump remained secured until shortly after minute 100. A short while later, the system was secured by a watchstander who noticed a high differential pressure across the micron filters. The erratic behavior of the HP pump, which is difficult for human operators to notice, was easily detected by the NILM. In this case, the NILM could have acted to alert operators or to automatically secure the system.

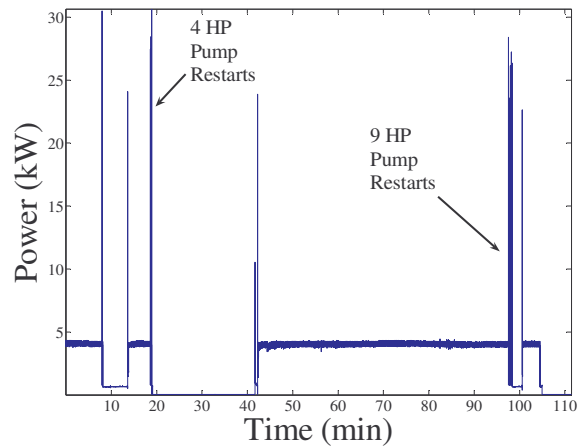


FIGURE 13. Power drawn by all three pumps in the RO unit as the *Escanaba* passed through contaminated waters. Note that only one HP pump was operating during this time.

Immediately following the behavior shown in Fig. 13, the NILM detected another abnormal phenomenon. Figure 14 shows the real power drawn by the pumps during the subsequent system start. When the HP pump came online, a large oscillation was observed. This oscillation, which was remarkably large in amplitude, continued for several days before it finally ended. After the authors discovered this behavior, they asked the crew if any abnormalities were observed. Uniformly, the answer was no.

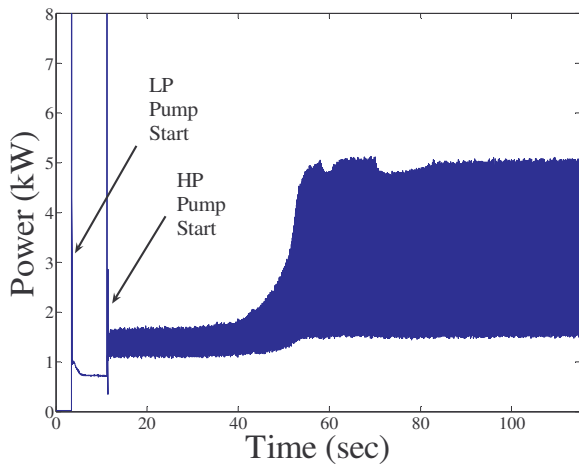


FIGURE 14. Power drawn by the LP pump and one of the HP pumps in the *Escanaba's* RO system. Note that there is significant variation in the power drawn by the HP pump. This data was recorded immediately following the detection of the behavior shown in Fig. 13.

Figure 15 shows the frequency spectrum of the real power waveform presented in Fig. 14. Note that there is significant spectral content at approximately 8.26Hz and its harmonics. Later analysis found that the frequency of this oscillation corresponds to the rotational frequency of the pump. Analysis has also shown that there is always some significant amount of spectral content at this frequency, although its amplitude is not always so large.

Approximately two months after the occurrence of the large oscillation, the HP pump in question failed. As a preliminary test, the authors trended the amplitude of the 8.26Hz spectral peak. Figure

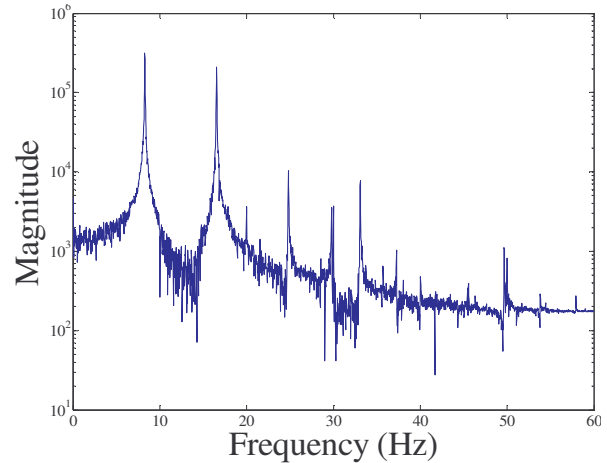


FIGURE 15. Frequency spectrum of the steady-state power waveform shown in Fig. 14. Note that there is significant spectral content at 8.26Hz and its low-order harmonics.

16 shows how the magnitude of this peak varied on several selected days between September 30, 2006 and February 1, 2007. The extremely high value recorded on October 30 corresponds to the behavior shown in Fig. 14. It is interesting to note that the pump was replaced on December 21 following the discovery of damage to both the piston and the cylinder housing. Potentially, a real-time analysis could have prevented this costly repair.

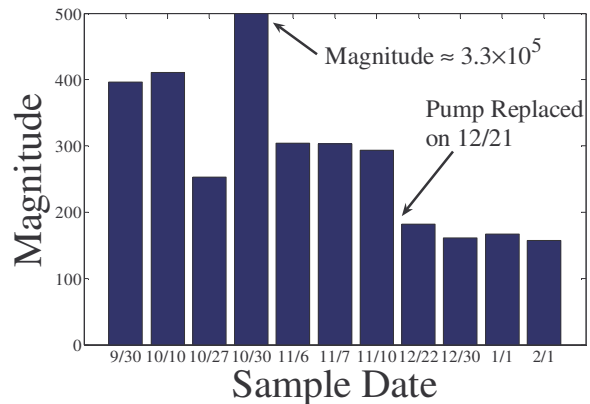


FIGURE 16. Trend in the magnitude of the 8.26Hz spectral peak. Note that on October 30, the oscillation was several orders of magnitude larger than normal. Additionally, the magnitude of the peak decreased significantly after the pump was replaced.

CHT SYSTEMS

On several occasions, the NILM monitoring the CHT system aboard the *Seneca* has detected clogs in the seal-water system that is used to prime the vacuum pumps. During normal operation, water from the seal-water tank fills the pump casing, keeping the pump cool and allowing it to prime. If the waste level in the vacuum collection tank becomes too high, some sewage can be pulled into the pump as it tries to evacuate the tank. As a result, waste can find its way into the seal water that flows through the pump casing. If a clog develops, the pump will no longer be able to evacuate the tank, and it will draw less real power than it would normally.

Figure 17 demonstrates the effect of a clog in the seal-water piping of one of the pumps aboard the *Seneca*. As shown, drops in vacuum pressure were forcing the fouled pump to come online. Because the pump was not able to evacuate the tank, the electrical power was much lower than normal. Eventually, the vacuum pressure fell to the lower set point, causing the second pump to assist the first. After noticing this behavior, the authors informed the crew. The ensuing investigation determined that one of the pumps had a clog in its seal-water inlet.

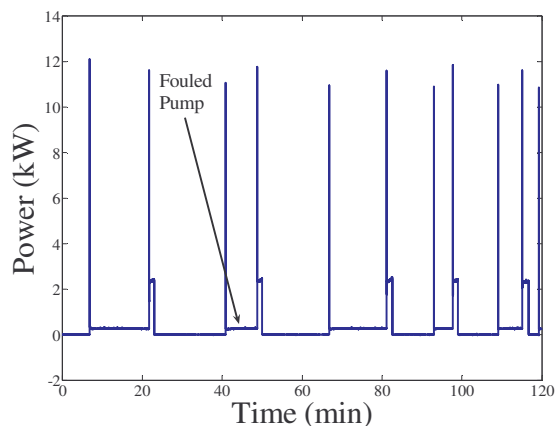


FIGURE 17. Power drawn by the vacuum pumps in the *Seneca*'s CHT system during a period when one of the pumps had a clog in its seal-water piping. The fouled pump draws significantly less power when running.

Seal-water clogs have been detected several times aboard both the *Seneca* and the *Escanaba*. It is

worth noting that such behavior, which can cause numerous pump overruns, has been found to persist for several days before it is noticed by the crew.

SENSOR AND CONTROLLER FAULTS

Sensor and controller faults affect the operating schedules of pumps, compressors, and fans. Both types of problems can cause actuators to energize either too frequently, too long, too short, or too intermittently. As a result, other very serious problems can develop. For instance, a failure in the CHT system can cause the collection tank to fill with sewage or the pump motors to overheat. Because such problems affect device operating schedules, the NILM is ideally suited to detect them. Several examples taken from CHT systems are discussed in this section.

The data presented in Fig. 18 was recorded aboard the *Seneca* during a period when various faults were in place. First, both the vacuum gauge lines and the pressure switch lines were clogged. Additionally, the pressure switches were improperly set. This combination of faults caused the vacuum pumps to run for nearly 20 minutes. Experience has shown that if the system is operating normally, a typical run should last only about 60 seconds. Discovery of the results shown in Fig. 18 prompted further investigation by the authors. Upon further study, it was determined that clogged gauge lines led the crew to believe that vacuum pressure was cycling between 12inHg and 14inHg. These limits, however, are not correct. Believing the problem to be the result of improperly set pressure switches, the crew reset the switches so that the vacuum remained within the proper limits (i.e. 14inHg and 18inHg). Once the switches were reset, the pumps ran as shown in Fig. 18. After about a week of troubleshooting, the crew corrected all of the system's problems and pump run times were once again on the order of 60 seconds.

Real-time use of the NILM could have prevented the behavior shown in Fig. 18. Figure 19 indicates one possible detection method. That figure shows how the average run time varied over the two months prior to the fault recorded in

Fig. 18. Visualization of this increasing trend would have indicated that the switch lines were clogged.

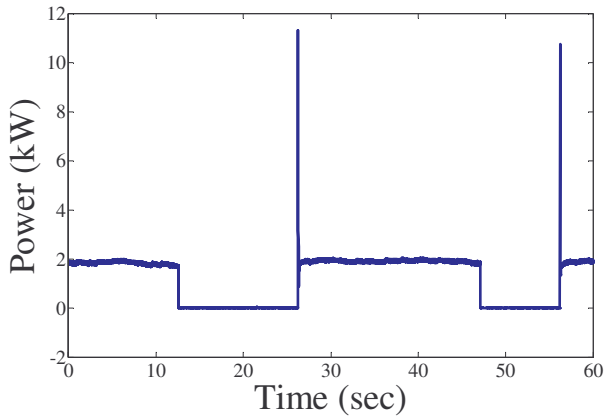


FIGURE 18. Vacuum pump behavior on the *Seneca* during a period when the pressure switches were improperly set and the switch and gauge lines were clogged. Under normal conditions, pump run times are approximately 60 seconds,

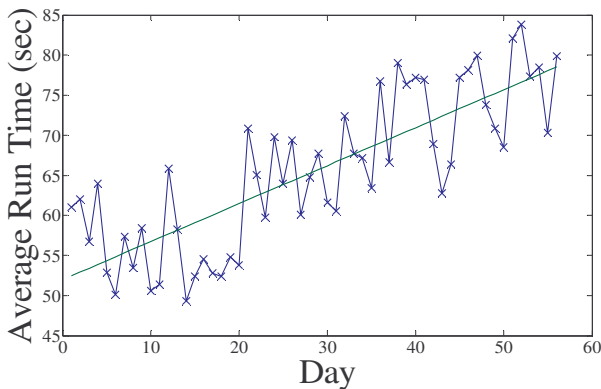


FIGURE 19. Trend in the average run-time of the vacuum pumps in the CHT system aboard the *Seneca*. The trend line is included to demonstrate that an upward trend was in place for nearly two months prior to the discovery of the clogged switch and gauge lines.

Controller faults can also affect pump behavior in many systems, and such problems tend to occur more frequently as systems age. Several such issues have been detected by the NILM in the CHT unit aboard the *Escanaba*. One particular problem appeared as shown in Fig. 20. In that figure there are numerous short pump runs, and each one was caused by a fault in the control logic. In particular, faulty wiring installed during some previous maintenance was causing the

discharge pumps to energize at the wrong times. Those pumps, which remove waste from the collection tank, are controlled by a set of probes inside the tank. When the waste occupies one-third of the total volume, the system becomes “armed”; when the waste occupies two-thirds of the volume, the pumps nearly empty the tank. During the period considered in Fig. 20, one of the pumps was being energized when the tank reached its one-third limit and it was being de-energized shortly after the waste passed below the one-third line. This fault resulted in numerous short runs. By comparison, the discharge pumps will normally operate once or twice a day for several minutes. Such needless cycling, which persisted for many weeks, could have been prevented through real-time use of the NILM.

Figure 20 also demonstrates several other fault-related behaviors. Note, for instance, that both vacuum pumps were energizing simultaneously. This was occurring because the crew had actually programmed the system to operate that way. Essentially, a combination of improper switch settings and clogged switch lines was causing pump overruns, and the proposed solution was to operate both pumps simultaneously. A real-time NILM could have sensed all of these problems and prevented any need to modify the control logic.

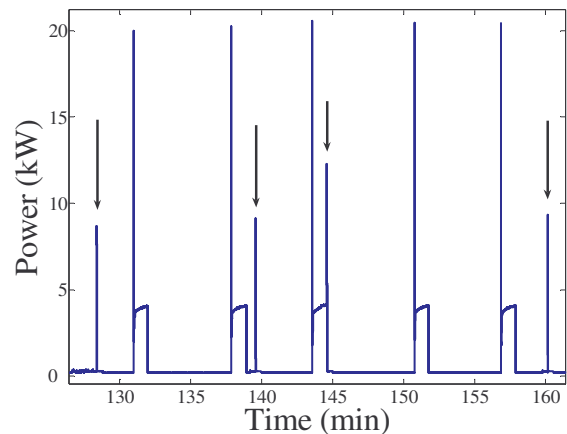


FIGURE 20. CHT pump behavior on the *Escanaba* during a period when the controller was found to be faulty. The pump runs indicated with small arrows correspond to the action of the discharge pumps. Additionally, several vacuum pump runs are shown. Note that both vacuum pumps were running simultaneously.

Failure of the level-sensing probes in the vacuum-collection tank can be quite serious, especially if the discharge pumps fail to run at all. Figure 21, for instance, shows sporadic discharge pump behavior that could have caused very serious problems. In that case, one of the sensing probes had actually fallen into the tank. As a result, the pumps would intermittently energize and de-energize. Such intermittency is shown in Fig. 21. This data, which was recorded aboard the *Seneca* while it was in port, led to the immediate detection and repair of the problem. Note that Figure 21 also displays evidence of the seal-water clog mentioned previously.

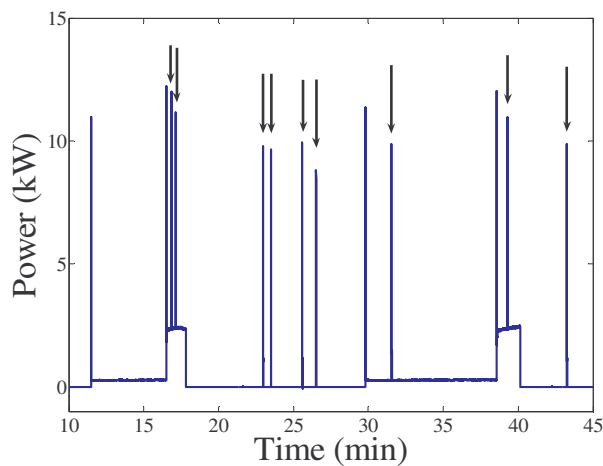


FIGURE 21. CHT pump behavior on the *Seneca* during a period when one of the level-sensing probes had fallen into the collection tank. The pump runs indicated with small arrows correspond to the action of the discharge pumps. Note that during this time period, one of the two vacuum pumps had a clog in its seal-water piping.

CONCLUSION

The non-intrusive load monitor clearly has the potential to simplify shipboard maintenance. This potential is strengthened by the fact that a single NILM can clearly provide useful diagnostic information about multiple loads. This capability means that it may be possible to enhance the performance of systems such as ICAS without having to add many new sensors.

Although the NILM has already been used to monitor several downstream loads, the authors continue to press for an even less intrusive

alternative. Ongoing efforts are aimed at developing instrumentation and software that can better detect the small power changes that are caused by the operation of small devices. Field tests are expected to begin in several months.

REFERENCES

- Armstrong, P., C. Laughman, S. Leeb, and L. Norford. 2006. Detection of rooftop cooling unit faults based on electrical measurements. *HVAC+R Research Journal* 12: 151–175.
- Cox, R., J. Mosman, T. McKay, S. Leeb, and T. McCoy. 2006. Diagnostic indicators for shipboard cycling systems using non-intrusive load monitoring. In *Proc. ASNE Day 2006*, June, Arlington, VA.
- Cox, R. 2006. Minimally intrusive strategies for fault detection and energy monitoring. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.
- Cox, R., P. Bennett, T. McKay, J. Paris, and S. Leeb. 2007. Using the non-intrusive load monitor for shipboard supervisory control. To appear in *Proc. 2nd IEEE Electric Ship Technologies Symposium*, May, Arlington, VA.
- DeNucci, T. et al. 2005. Diagnostic indicators for shipboard systems using non-intrusive load monitoring. In *Proc. 1st IEEE Electric Ship Technologies Symposium*, July, Philadelphia, PA.
- DiUlio, M., C. Savage, B. Finley, and E. Schneider. 2003. Taking the integrated condition assessment system into the year 2010. In *Proc. 13th Ship Control Symposium*, Orlando, FL.
- Laughman, C., P. Armstrong, L. Norford, and S. Leeb, 2006. The detection of liquid slugging phenomena in reciprocating compressors via power measurements. In *Proc. International Compressor Engineering Conference at Purdue*, July, West Lafayette, IN.
- Lee, K. 2003. Electric load information system based on non-intrusive power monitoring. Ph.D.

diss., Massachusetts Institute of Technology, Cambridge.

Leeb, S. 1993. A conjoint pattern recognition approach to nonintrusive load monitoring. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

Leeb, S., S. Shaw, and J. Kirtley. 1995. Transient event detection in spectral envelope estimates for nonintrusive load monitoring. *IEEE Trans. on Power Delivery* 10: 1200–1210.

Lopushansky, R. 1999. All optical shipboard sensing system. In *Proc. 45th International Instrumentation Symposium*, May, Albuquerque, NM.

Luo, D. 2001. Detection and diagnosis of faults and energy monitoring of HVAC systems with least-intrusive power analysis. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

Mitchell, G., R. Cox, J. Paris, and S. Leeb. 2007. Shipboard fluid system diagnostic indicators using non-intrusive load monitoring. To appear in *Proc. ASNE Day 2007*, June, Arlington, VA.

Oppenheim, A., A. Willsky, and I. Young. 1988. *Signals and Systems*. Englewood Cliffs, NJ: Addison Wellesley.

Paris, J. 2006. A framework for non-intrusive load monitoring and diagnostics. M.Eng. thesis, Massachusetts Institute of Technology, Cambridge.

Ramsey, J., et al. 2005. Shipboard applications of non-intrusive load monitoring. In *Proc. ASNE Reconfiguration and Survivability Symposium*, February, Atlantic Beach, FL.

Shaw, S., C. Abler, R. Lepard, D. Luo, S. Leeb, and L. Norford. 1998. Instrumentation for high performance nonintrusive electrical load monitoring. *ASME Journal of Solar Energy Engineering* 120: 224-229.

Shaw, S. 2000. System identification techniques and modeling for non-intrusive load diagnostics. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

Zarambo, F. 1992. Desalination plants. In *Marine Engineering*, ed. R. Harrington. Jersey City, NJ: Society of Naval Architects and Marine Engineers.

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