Detection of Rooftop Cooling Equipment Faults by Power Signature Analysis

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Background

The key to cost-effective on-line fault detection and diagnosis (FDD) is finding the right mix of sensors and automated analysis techniques to detect faults before they result in costly consequential damage. Much attention has been focused on temperature- and pressure-based fault detection of the vapor compression cycle of rooftop cooling equipment (Rossi and Braun 1997). However, temperature sensors must be installed in specific locations regardless of the resulting susceptibility to harsh environments or damage during inspection and service activities. Considering both long-term sensor reliability and suitability for detecting a broad spectrum of common faults in rooftop equipment, less intrusive power sensors coupled with power signature analysis (PSA) techniques may provide an attractive alternative or complement to the temperature- and pressure-based FDD methods currently in development.

PSA was developed at the Massachusetts Institute of Technology for load identification by the non-intrusive load monitor (NILM), a device installed at the building service entrance to track end-use loads (Hart 1992). Today's NILM technology identifies loads by rapidly sampling voltage and current and reducing observed step changes, start transients, and harmonic content to concise "signatures" (Leeb 1993, Shaw *et al.* 1998, Laughman *et al.* 2003, Lee 2004).

Description

This application of PSA detects faults in rooftop cooling equipment. Tests have shown that PSA techniques are able to detect all common fan and compressor electro-mechanical faults, as well as the difficult and economically important liquid ingestion faults (Armstrong *et al.*2004). The sensor hardware is minimally intrusive, using only one power measurement point at the control panel, and thus is easy to install, economical, and inherently reliable.

During the tests, voltage and current were sampled at the control panel of a rooftop unit (RTU) at 40kHz while faults were introduced in a repeatable manner. A Linux-based data acquisition and signal processing system was used to pre-process the data stream in real time and to analyze start transients and harmonic content of fan and compressor motor power signals. Fault-specific patterns were identified as indicated in Table 1. Selected fault signatures are shown in Figures 1 through 6. Figure 7 shows the non-intrusive nature of the NILM/PSA installation.

Payback

The value of FDD using the PSA approach is realized by *reduced down time*, better energy efficiency, *avoidance of consequential damage*, and the *efficient dispatch* of repair staff and replacement parts. *Catastrophic failure* of RTU motors and compressors can be *avoided by early fault detection*. Compressor failure, for instance, represents the largest repair cost item of all RTU repairs (see Figure 8). Root causes of failure include internal damage (e.g., from liquid ingestion), overheating from condenser or evaporator fouling, fan failure, bypass leakage, or any of the common electrical faults such as loss of phase, contactor faults, and short cycling. The PSA approach is capable of detecting faults in the early stages before serious compressor damage ensues. Savings over time from detecting just the faults that lead to compressor failures are estimated to be 10% of all RTU repair costs.

Table 1: Fault Detection Capabilities for a Rooftop Unit

Fault	**PSA Method**
Loss of phase	Current and voltage
Locked motor rotor	Start transient
Slow starting motor	Start transient
Unbalanced voltage	Voltage
Motor disconnect/failure to start	Event sequence
Incorrect control sequence	Event sequence
Short cycling	Event sequence
Contactor (improper contact closure)	Phase current transient
Air-side restriction	Change of mean, Figure 1
Refrigerant over-/under-charge	Mean, transient, Figure 2
Compressor valve, seal or other leakage	Start transient, Figure 3
Compressor flooded start	Start transient, Figure 4
Compressor liquid ingestion	Transient, Figure 5
Fan rotor faults that result in imbalance	Amplitude spectrum, Figure 6
Other compressor mechanical faults	Amplitude spectrum

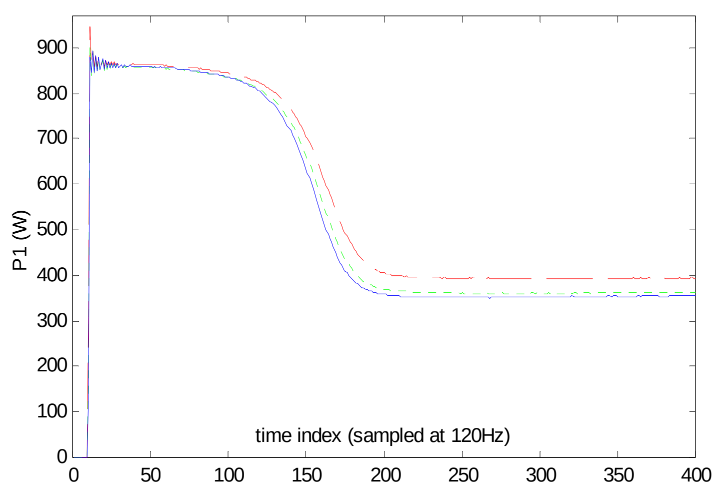

Figure 1a. Condenser flow blockage fault detected by change of mean power; shown are fan start transients with 0% (solid), 14% (dotted), and 39% (dashed) flow blockage.

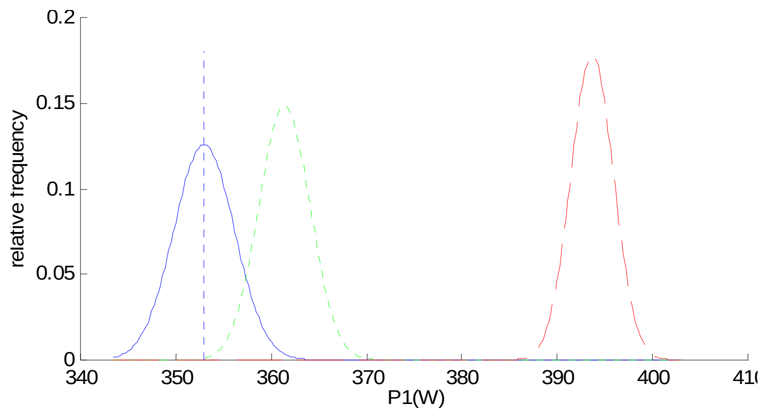

Figure 1b. Distributions of steady state power for condenser fan blockage of 0% (solid), 14% (dotted), and 39% (dashed).

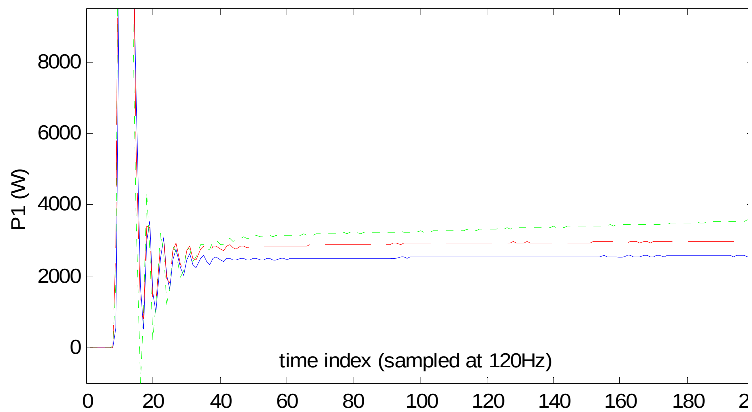

Figure 2. Improper refrigerant charge faults detected by change of mean (20% overcharge, dashed) and by change of start transient shape (20% undercharge, dotted)

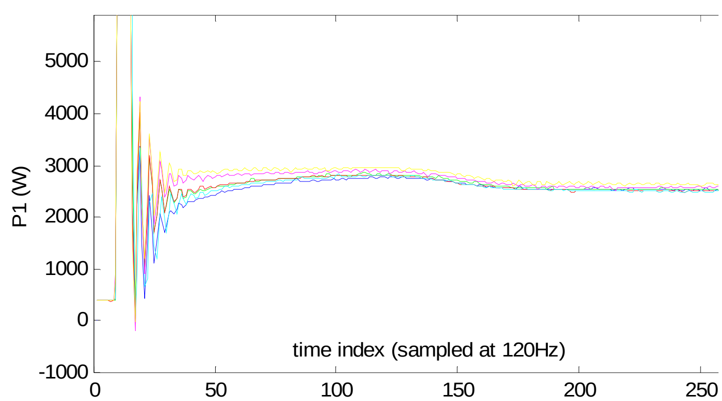

Figure 3. Compressor vapor bypass fault (top two traces) and no fault (bottom four traces) detected by start transient shape.

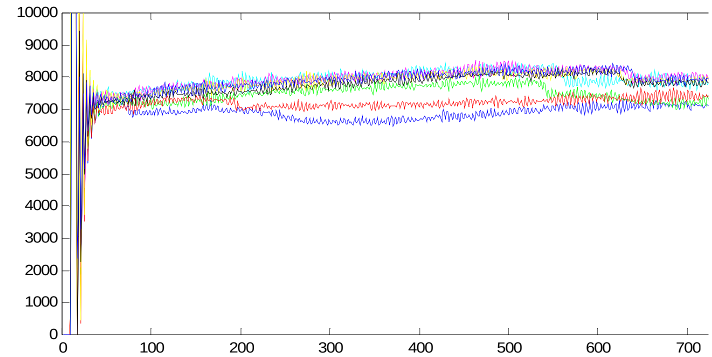

Figure 4a. Flooded start fault for typical hermetic compressors is detected by start transient shape change. Compressor power drops abruptly 1-5 seconds after start with cessation of boil-off.

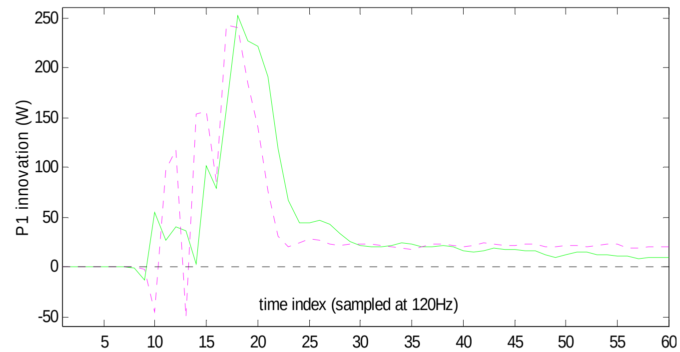

Figure 4b. Semi-hermetic reciprocating compressor flooded start fault is detected by changes in shape of the start transient. Shown are innovations with 1 cc liquid (solid) and 3 cc liquid (dotted) into suction port of half-ton reciprocating compressor.

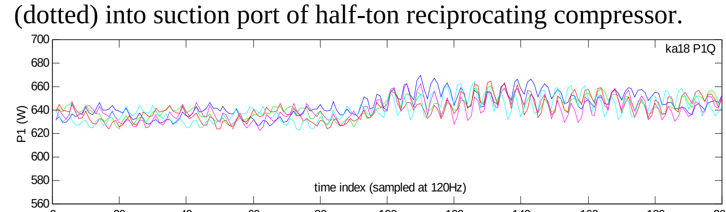

Figure5a. Liquid ingestion fault detected by the occurrences of transients during steady run of a half-ton reciprocating compressor (the transients from five repetitions are superimposed). Note the amplitude of compression cycle power variation as well as the mean power increase when liquid enters the compressor. Figure 5b shows the output of the detection algorithm.

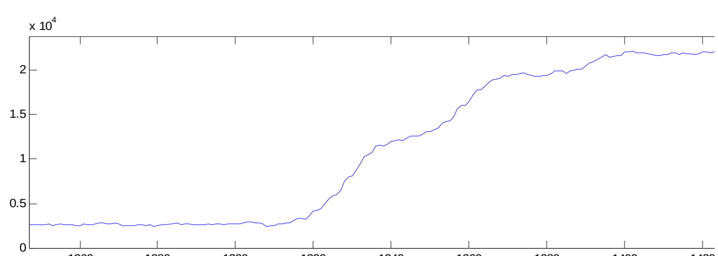

Figure 5b. A liquid ingestion transient is detected by tracking the weighted sum of deviations from up to 99 (k=1:99) k-step ahead ARX(5,1) forecasts. The ARX model is updated recursively, new weights are computed based on the model variances, and the weighted sum of the forecasts is evaluated at every time step. A fault is declared when the sum exceeds a threshold.

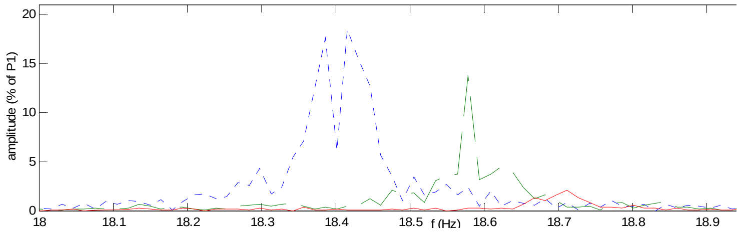

Figure 6. Imbalance faults are detected by frequency shifts and an increase in energy content of certain peaks in the amplitude spectrum. Shown are condenser fan power with no fault (solid) with 4 g (dashed) and with 8 g (dotted) attached to a blade tip.

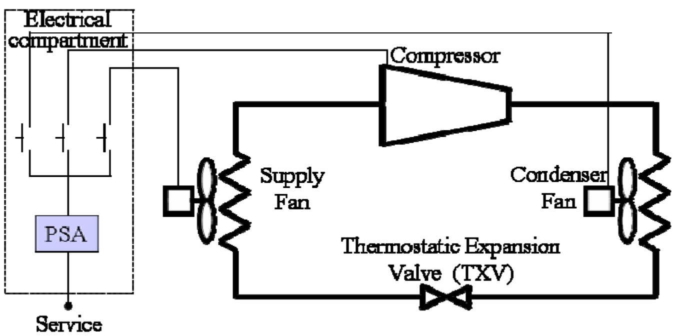

Figure 7. Single-point connection of PSA device.

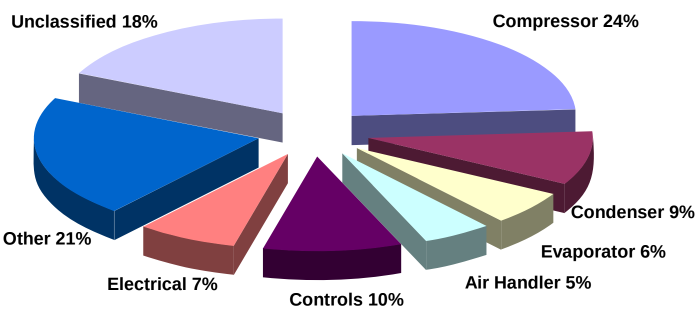

Figure 8. Percent of aggregate repair costs by main fault category (data from Breuker and Braun 1998).

References

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