

HVAC System Cloud Based Diagnostics Model

Fadi ALSALEEM^{1*}, Robert ABIPROJO², Jeff ARENSMEIER², Gregg HEMMELGARN¹,

¹Emerson Climate Technologies, Residential Solutions,
Sidney, OH, USA

Contact Information (937-493-2839, 937-498-3342, fadi.alsaleem@emerson.com)

²Emerson Climate Technologies, Residential Solutions,
Saint Louis, MO, USA

Contact Information (314-553-3460, jeff.arensmeier@emerson.com)

* Corresponding Author

ABSTRACT

We present a new monitoring and diagnostics model for residential Heating, Ventilation, and Air Conditioning (HVAC) systems. This model will provide a new diagnostics technology system that leverages the latest technology advancements. The model benefits from the cloud computing advantages and offers continuous diagnostic capabilities. Using embedded sensors and monitoring modules for the indoor and outdoor HVAC units, various measurements are transmitted to a cloud sever utilizing the homeowner pre-existing Wi-Fi network. On the cloud side, algorithms process the data and generate triggers that a problem may exist. Relevant information is then shared with home owners and contractors via e-mail & portals. In this paper we explain the system in more detail by providing actual case studies which demonstrate the value in a proactive maintenance and repair model as supported by time-series data. This contrasts the reactive model that exists today.

1. INTRODUCTION

Market trends are shifting toward big data and cloud computing but the HVAC industry has not fully utilized these advancements, especially in the residential market space. Recent advances in HVAC systems have been focused on exploring better refrigerants, introducing energy saving variable speed components, deploying advanced control algorithms, and improving local fault diagnostic capabilities.

HVAC systems Fault Diagnostics and Detection (FDD) received great deal of attention from research. For example Braun (2003) highlighted the importance of the FDD for HVAC systems and reviewed some of his previous work in developing rules used for classifying faults. Also he pointed out the need for using low cost sensors to make the FDD solution more appealing for HVAC systems compared to other industries such as nuclear and aircraft. Refer to the work of Katipamula, S., and Brambley (2005a) and (2005b) and Halm-Owoo and Suen (2002) for a good summary in some of the HVAC fault diagnostics trends.

In this work we highlight the use of cloud computing in providing continuous diagnostic capabilities for residential vapor compression and furnace systems to leverage a complete HVAC System Cloud Based Diagnostics Model (HSCDM). This model has the advantages of being able to alert homeowners on system shutdowns, proactively inform them on the states of their heating and cooling systems for degradation, and on system operating efficiency.

2. HARDWARE DESCRIPTION AND DATA FLOW

In this section we briefly discuss the evolutions of the hardware and cloud computing infrastructure of HSCDM.

2.1 Initial Prototyping and Proof of Concept

Data acquisition hardware and custom interface boards were utilized during early concept testing. Initial data gathering and processing architecture used 10 sets of laptops running compiled code. These were deployed upon several residential HVAC systems. This concept provided a rapidly deployable and flexible development platform that could be monitored and modified remotely. The system transmitted data to an FTP site. A suite of programs then analyzed that data for potential HVAC equipment faults. The deployment of these systems enabled the refinement of data gathering protocols and demonstrated a proof of principle. During this prototyping phase, a matrix of temperature and current sensors provided feedback from many different locations across the HVAC systems. This experimentation allowed us to determine the minimum number of sensors along with their optimal locations to provide the necessary fault detection coverage.

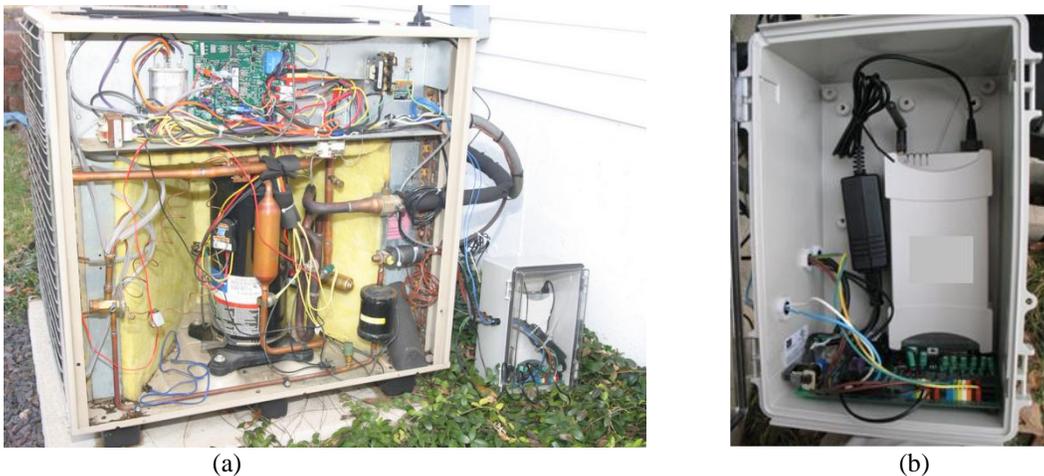


Figure 1: Data acquisition hardware used in the HSCDM prototyping and proof of concept; (a) the hardware installs on an outdoor unit, (b) the hardware

2.2 Production environment

The final HSCDM field hardware (Figure 2a) consists of two embedded kits as shown in Figure 2. The indoor kit is equipped with voltage and current sensors as well as temperature sensors to track air supply, air return, indoor liquid line, and suction line temperatures. The outdoor kits measure the aggregate outdoor current and voltage. Power Line Communication (PLC) protocol is utilized for outdoor-indoor communications. Sensor data is transmitted through the homeowner Wi-Fi router to the cloud infrastructure. The complete cloud structure (Figure 2b) employs a sophisticated array of cloud hosted software including listeners, analysis engine, databases, Customer Relationship Management (CRM) and billing solutions. The first level of the cloud structure, known as the listener, receives the sensor data and adds system specific information entered through the commissioning processes such as unit tonnage and Seasonal Energy Efficiency Ratio (SEER). The listener then directs the data to the cloud analysis engines. The analysis engines function as a multi-queue structure that support parallel processing. The analysis engines also interface with databases for continuous system-learning, analysis, and decision processes along with a CRM to communicate faults and performance evaluations.

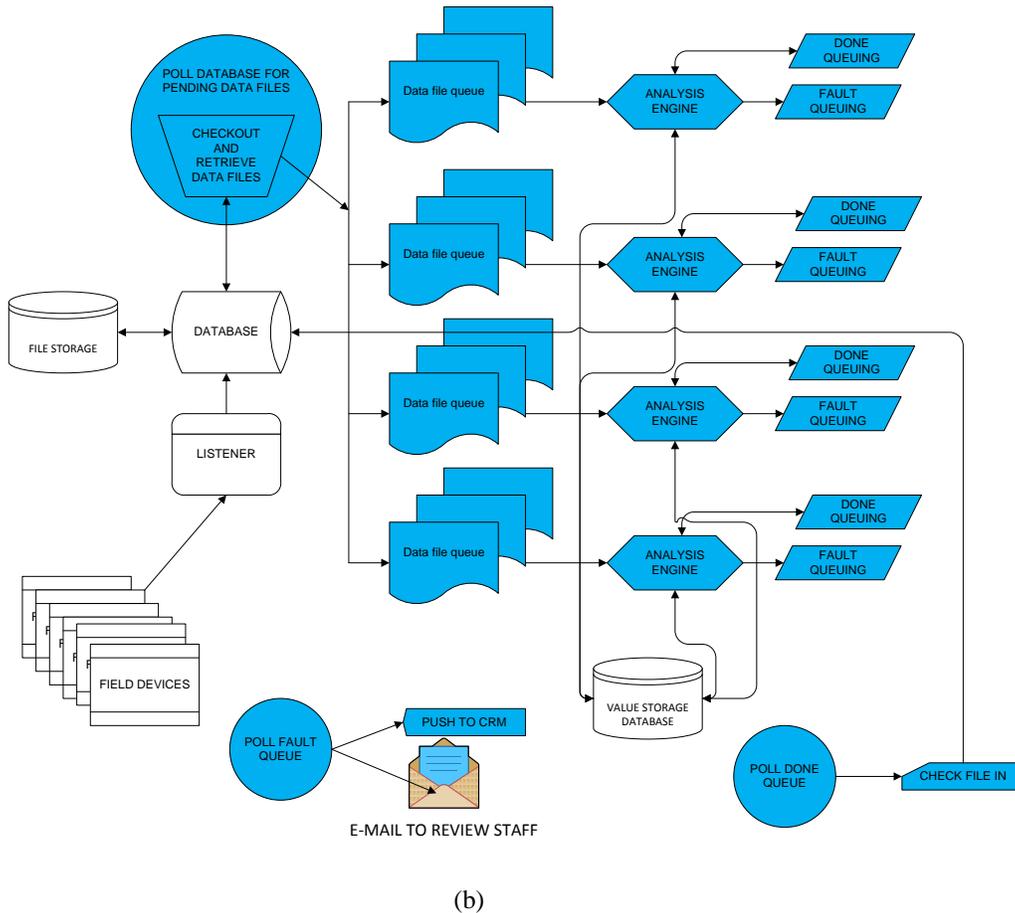
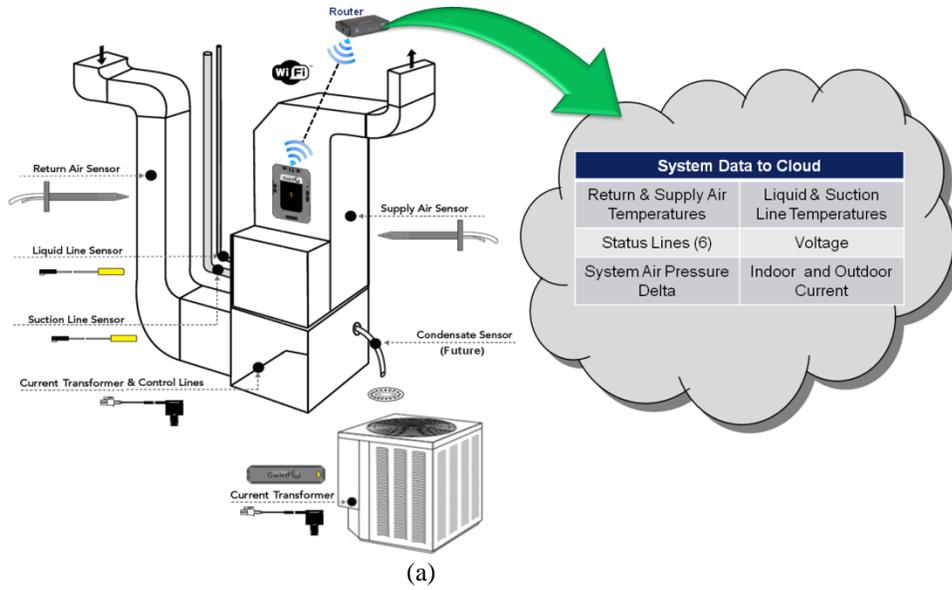


Figure 2: Schematic of the final HSCDM, (a) Hardware, (b) Cloud structure

3. DIAGNOSTIC CLASSIFICATION

Different types of diagnostic classifications are adapted in the new HSCDM. Classifications include general versus components and sub-system faults (Figure 3), long term versus sudden faults, urgent versus non urgent faults, and proactive versus reactive faults. A specific fault may belong to one or more of these classifications. The different types of classifications helped to design fault detection algorithms and understand their complexity level. In this paper the focus will be on the proactive classification.

For example, faults belonging to the proactive class tend to be very difficult for a homeowner to observe, as the HVAC system provides only a reduced level of cooling or heating, but for longer run times. Accurately detecting and communicating impending failures to homeowners appears to deliver high value. The alert provides homeowners the opportunity to proactively respond to these faults and also protects their HVAC system against additional, more catastrophic damage. Secondly, the proactive diagnostic allows them to conveniently schedule service instead of reacting to a hard failure at a problematic time.

Reactive fault terminology refers to catastrophic malfunctions where the system fails to provide cooling or heating as expected. When a homeowner notices a loss of cooling or heating, they must troubleshoot the problem, find a contractor, and then call for a service appointment. Unfortunately many HVAC systems progress through more severe fault stages which result in a more costly repair.

Even with this type of fault, HSCDM offers a more valuable solution compared to other diagnostics models. Multiple field case tests showed that under 'easy to fix' fault conditions such as compressor run capacitor failure, the compressor can trip hundreds of times before the homeowner realize there is a problem, resulting in risking serious compressor damage. Using the HSCDM model and quickly detecting, alerting, and giving the homeowner direction to turn off the thermostat to protect the compressor and just as important, providing the repair technician more failure detail before service so they can prepare with the right parts. This preparation reduces the overall service maintenance cost and time.

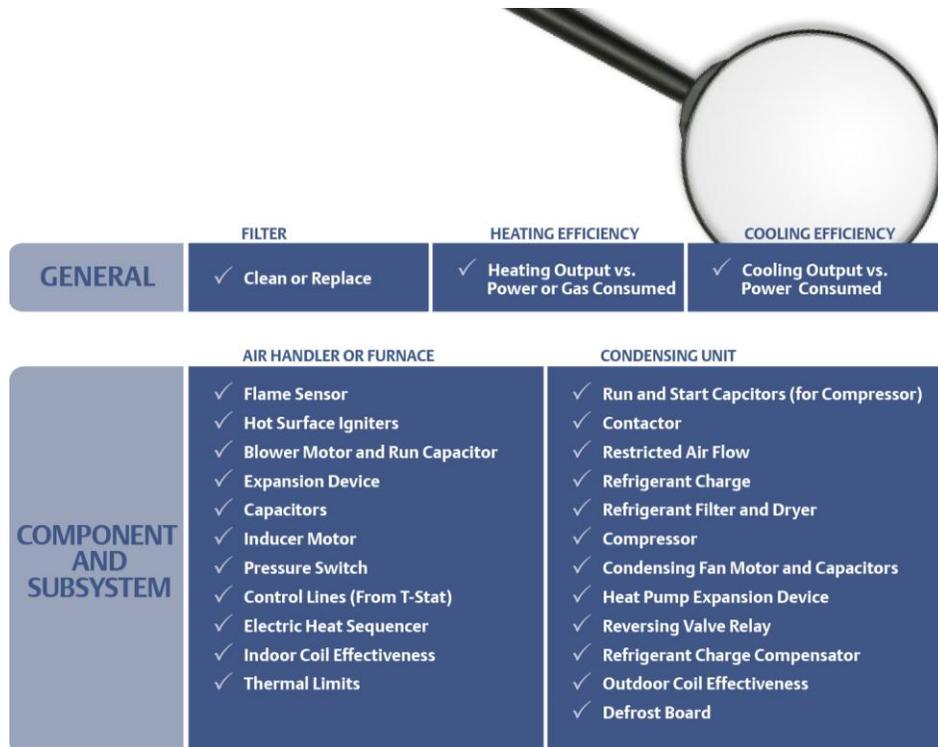


Figure 3: General versus components and sub-system faults classification adapted in the HSCDM

3.1 Proactive Diagnostics

In this section we provide detailed examples of leveraging the new HSCDM in detecting proactive faults. Some of these faults are not severe enough to affect homeowner comfort, but if ignored they lead to complete system shutdown. Secondly, the faults may have a significant adverse impact upon the cooling and heating energy bill. Three proactive fault examples for a vapor compression system are given first, and then the proactive concept is demonstrated for a gas furnace system.

3.1.1 Run Capacitor Degradation

HVAC run capacitor degradation detection offers an example of a proactive fault. Data analysis found a strong relationship between the outdoor power factor and run capacitor condition. Hence, a new algorithm implemented within the HSCDM provided the ability to track the outdoor unit run capacitor degradation and warn that failure may be more imminent. The algorithm detects a sudden change in the outdoor power factor accompanied with sharp increase in current. As a run capacitor failure prevents the startup of the compressor, cooling (or heat pump heating) fails until the capacitor replacement occurs. This algorithm has the advantage of alerting the homeowner prior to total failure to start.

Figure 4 shows an actual case of an online monitored HVAC system through HSCDM. In the figure shown below, red is the total outdoor current in amps, the split temperature is black, and the calculated power factor is blue. The figure shows that at approximately 7:00 pm there was a sudden decrease in the calculated power factor. This change was accompanied with a sudden increase in the outdoor current which implies a sudden degradation in the run cap capacitance. In response, the HSCDM automatically triggered the run capacitor advisory.

Even with this capacitance degradation the system was able to provide enough cooling capacity to satisfy the thermostat call while the compressor ran. However, the system failed to start during the next call around 4 am, and the compressor tripped until homeowner was notified to turn the thermostat off to prevent further risk to the compressor. This later reactive and more severe alert could have been avoided with early warning and action.

Advantages of this new predictive run capacitor advisory include the ability to predict HVAC systems shutdown which gives both the homeowner time to schedule the maintenance visit and provides the repair technician with information. In this case, a run capacitor can be procured in advance of system diagnosis to avoid the time and travel costs to obtain the part.

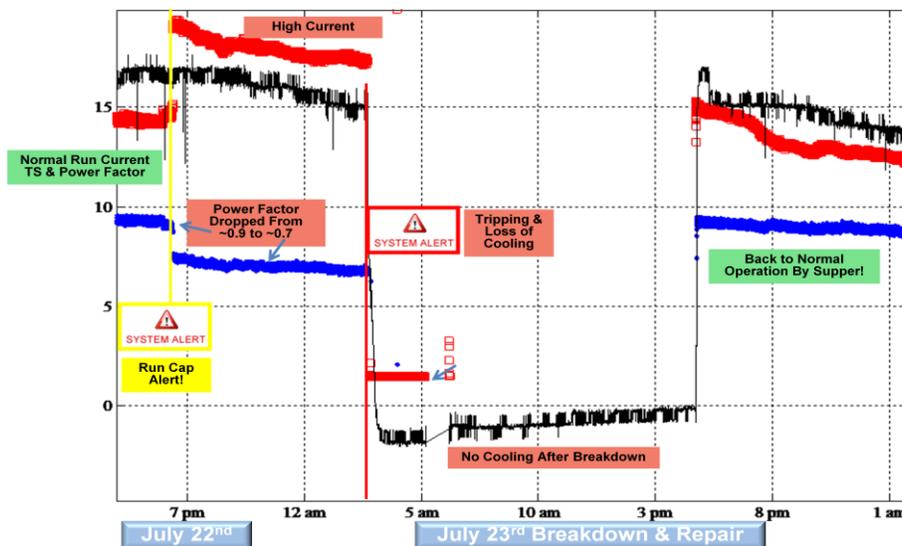


Figure 4: Real case of a proactive run capacitor fault detection. Red = total outdoor current in amps Black = split temperature Blue = calculated power factor

3.1.2 Filter Alert

Another advantage the HSCDM offers is the ability to implement more sophisticated algorithms to track complex system behavior, such as in detecting filter blockage. A commonly known phenomenon exists regarding loading of a typical indoor motor blower that results in a power consumption increase. The HSCDM filter algorithm benefits from this simple fact and was created to capture filter blockage over time by monitoring indoor motor current. (The full description is out of scope of this paper.) Difficulty in isolating other motor loading characteristics aside of the filter complicates this algorithm. Figure 5a illustrates the outcome of the filter algorithm for an install, highlighting the filter degradation over time. The chart also confirms when the homeowner changed the filter. Figure 5b visually confirms the predicted poor filter performance.

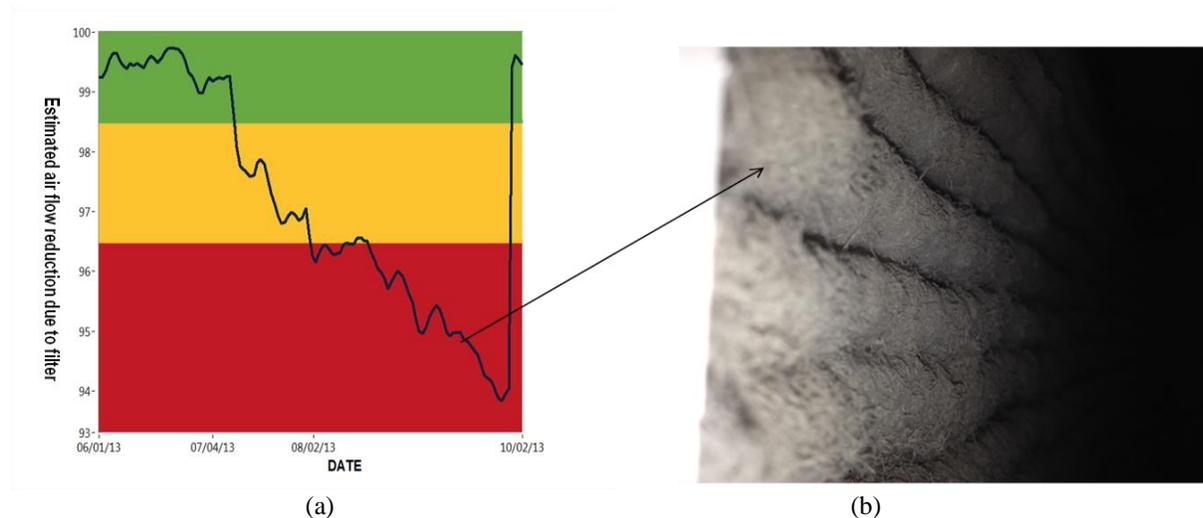


Figure 5: Real case scenario for proactive filter fault detection, (a) cloud data, (b) filter.

3.1.3 AC System Grade

By storing averages of temperatures and power over time, the HSCDM offers a unique way to provide system reporting and health grades. Shown in Figure 6 are the automated reports for a given HVAC system. In this reporting mechanism, power was primarily used to gauge system performance. Other parameters used separately or in combination generate similar performance grade alerts. These include indoor split temperature and run time.

Given only basic system information of this install, the HSCDM estimates the normal power that this system should consume at a given ambient temperature. Consuming more power than normal suggests high side fault problems such as; high charge, non-condensable gas or low outdoor air flow. Lower power suggests low side faults such as low charge or low indoor air flow.

For this specific HVAC system, the automated reporting generated an advisory immediately after installing the monitoring kit. This reporting highlights a poor system score due to high power consumption as compared to normal levels for that tonnage. The first reaction from the homeowner was to wash and clean his outdoor coil with water. As this did improve the system grade, the HSCDM reporting mechanism generated another performance based advisory. This time more comprehensive service revealed an over charge problem. Removing the extra charge improved the system's power performance, Figure 6.

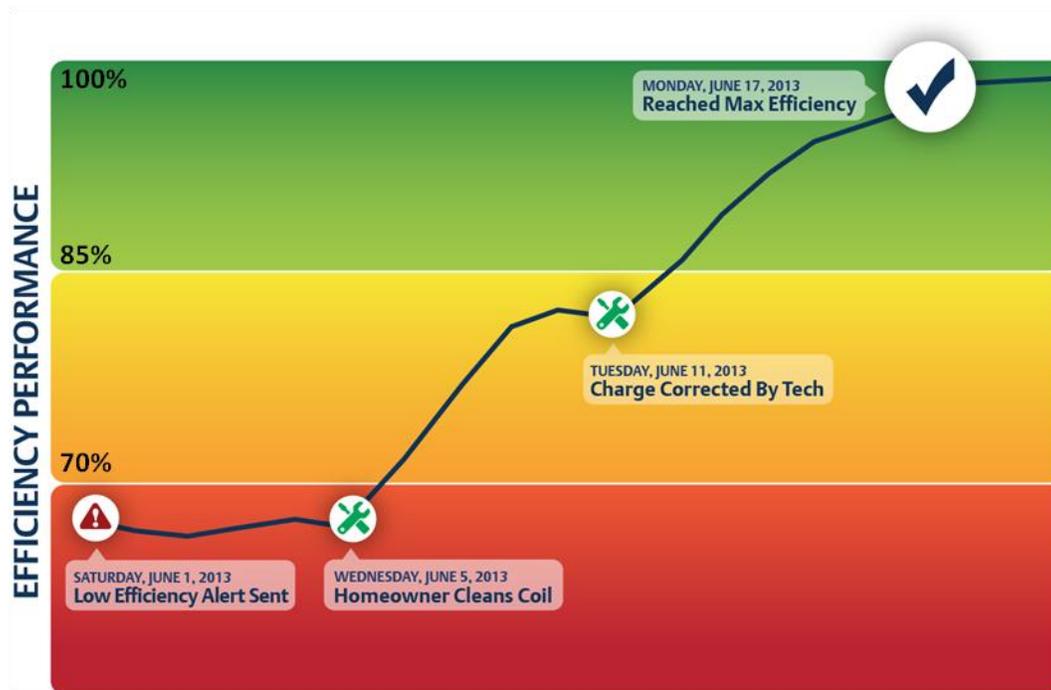


Figure 6: Real case scenario for a proactive fault detection with system grade.

3.1.4 Furnace Performance Diagnostic

HSCDM also provides the ability to continuously monitor furnace operation. Furnace availability during the heating season is critical for homeowner comfort, health, and damage protection. The heating system supplies more than just comfort to homeowners. It is a necessity as it also protects water throughout the home from freezing which can cause substantial property damage.

On occasion, spurious conditions or an intermittent failure may cause a heating system to slip into a lockout condition. Some furnaces reset after a lockout period, like 1 hour, but others older models could lockout indefinitely. This condition could leave a home with a dangerously low temperature condition, especially if they are not home at the time to notice. Such an indefinite lockout condition requires a power-cycle of the furnace which can be performed simply from the thermostat or breaker box. Informing homeowners of such condition helps to avoid detrimental consequences.

HSCDM processes and analyzes the various sensor data at the cloud engine both in time and frequency domains. It determines whether proper furnace operation occurs. Furnace sequence analysis over a range of potential failure conditions generates advisories based on exceptions from learned system signatures. The system performs component level anomaly and degradation analyses that combine with the analysis of the furnace sequence of operation to provide more thorough diagnostics. These include systems such as the inducer fan, fan pressure switch, igniters, flame probes, and gas valve.

An example of a normal sequence of furnace operation is depicted in Fig 7. A typical furnace operation starts with the fan pressure switch checking for flue pressure followed by the activation of inducer fan. Upon successful initiation phase, the ignition cycle commences followed by the post-purge period to allow the heat exchanger to heat up. The sequence continues with the circulator blower operation. The inducer fan would usually stop immediately after the heat run call ceases, but the blower would typically continue to run for a little bit longer to remove excess heat out of the system.

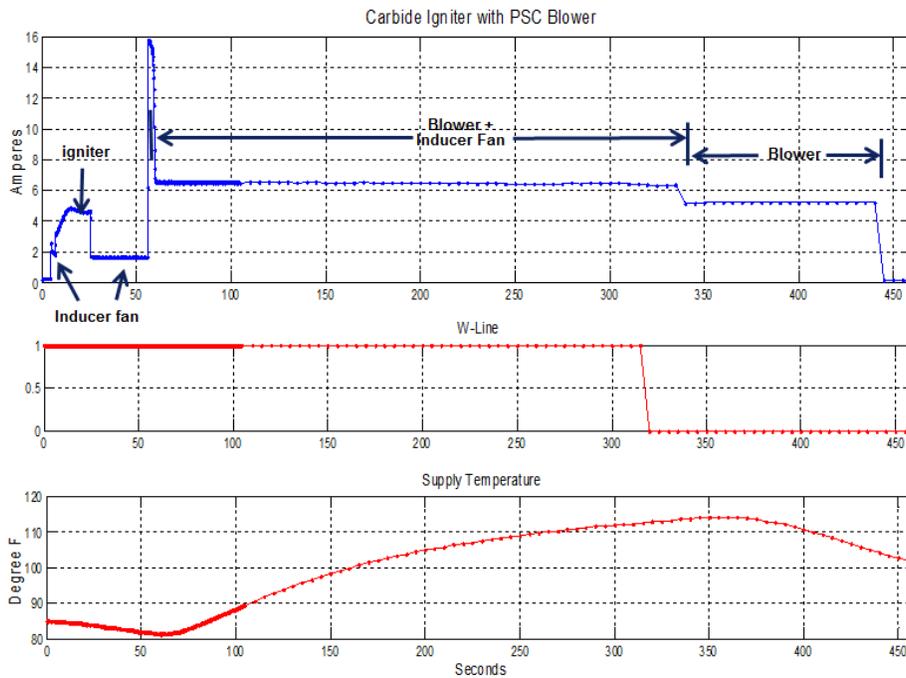


Figure 7: Furnace normal sequence of operation

Figure 8 shows an example of visibility that HSCDM supplies in detecting a degrading flame probe. In this actual case, the degrading flame probe started to cause occasional failures to light and subsequent lockouts. These symptoms can be difficult for homeowners to notice or feel. The condition will only worsen. Early detection, notification to homeowners, and correction of such conditions ensure furnace availability when needed most.

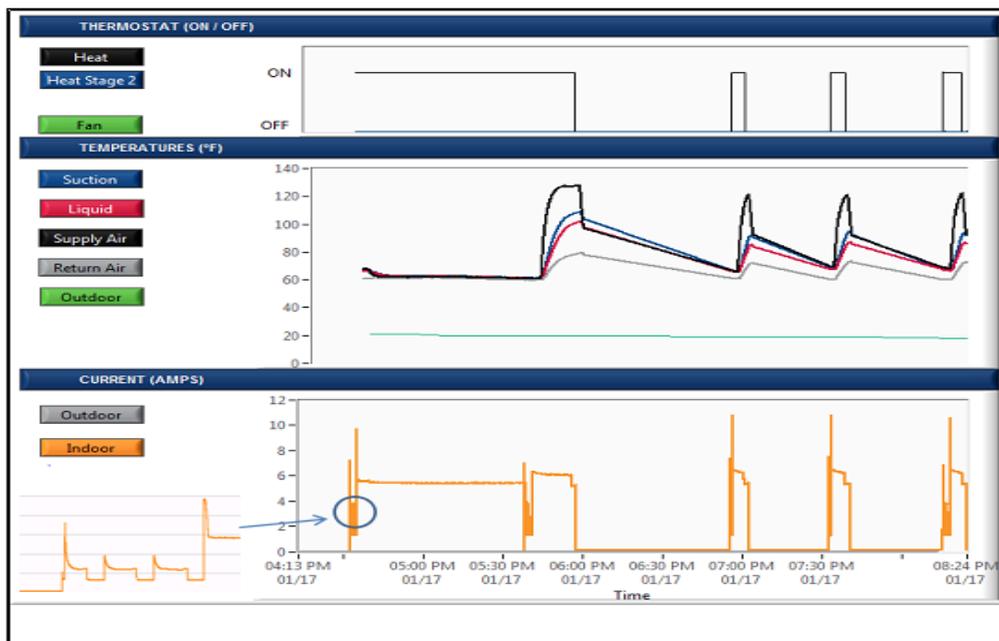


Figure 8: Case of detecting a degrading flame probe

3.2 Reactive Faults

Reactive faults include those which the cooling or heating system failed to provide sufficient comfort to homeowner. Systems lock out or complete shutdowns are good examples for these severe faults. Small but sudden failures, such as a compressor run capacitor, compressor start capacitor, or outdoor fan capacitor can cause these faults as well. Unfortunately, some of these faults can exist for a significant period of time before the homeowner notices. Late notice may significantly impact compressor reliability, the most expensive part to repair.

Even with these types of faults, the HSCDM offers more value compared to other diagnostics models. For example, Figure 9 is a real case of an install where the system was tripping excessively (one trip each two minutes). Using the HSCDM, the homeowner was notified by email about this fault and the potential causes and instructed to turn the thermostat off to prevent damage to the compressor. To our surprise, even with severe tripping and the absence of any cooling effect, the homeowner had not noticed a problem yet because his home includes two HVAC systems. It took an alert to convince him to examine vent air temperature, turn the system off, and schedule a service visit.

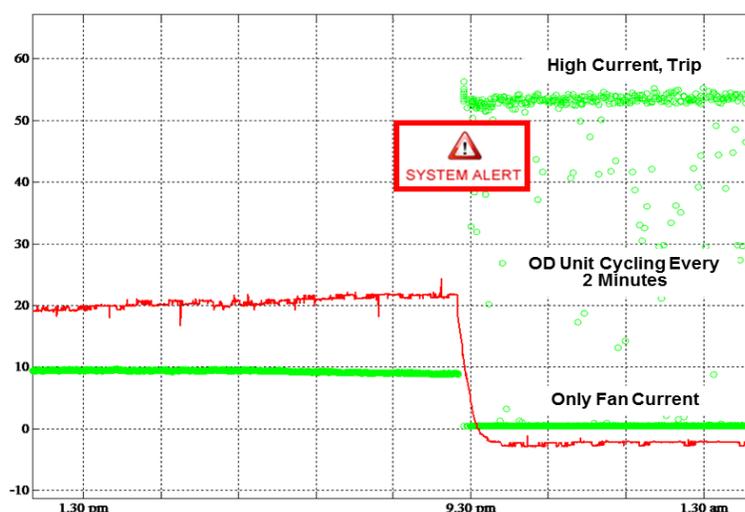


Figure 9: Real case of reactive fault; compressor severe tripping due to compressor start capacitor failure.

4. CONCLUSIONS

The HSCDM cloud-based software model, along with the Wi-Fi connected data acquisition system offers flexible and configurable architecture for the remote monitoring of HVAC systems. The model provides continuous and near real-time monitoring of HVAC systems and demonstrates the capability to alert homeowners and contractors in regards to urgent system shutdowns. The system keeps homeowners informed on their system health and efficiency and delivers information regarding self-maintenance items such as air filters. The system also serves contractors by supplying them with finer visibilities for component level diagnostics, which increases overall service efficiencies.

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