Quantifying Potential System Level Energy Savings: An Applied Research Oriented Approach Using a Residential Air-conditioner

by

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Abstract

Public awareness of saving energy varies with the oil prices and utility costs. As practitioners, engineering technologists should continue to work on saving energy or improving energy efficiency. To save energy one must know how energy is used and wasted. Applied research projects can be designed around an existing energy consuming system to investigate the potential of efficiency improvement at the system level and at the component level. By quantifying the potential savings, the potentials for incorporating newer technologies can be investigated. Existing systems such as residential air-conditioners are useful to demonstrate the process of energy quantification. Certain electrical and physical measurements must be required to quantify the energy consumption. Excel is an excellent tool for data analysis. A good understanding of the system operation may help identifying potential alternatives that would improve the system efficiency. An applied research project built around a residential air-conditioner indicated that about twenty-one percent of cooling energy on a hot summer day can be saved by using an attic fan. This experiment can be replicated by changing other process variable such as attic insulation, flow rate of the fan, etc. This paper discusses system level savings derived when an applied research oriented approach is used to assess residential air conditioners.

Introduction

More and more engineering technology programs are starting undergraduate research and graduate programs. So, the word "applied research" becomes a buzz word amongst engineering technology faculty. Applied research could be done with different objectives. One may be interested in cause and effect relationship of a system; another may be interested in behavioral characteristics of a system; another one may be interested in incorporating a new technology into and exiting system. In many applications, electrical energy powers a mechanical system. Students need to be aware of both electrical and mechanical characteristics. The goal of this paper is to demonstrate how to find a need, gather data, and analyze. It is author's hope that the reader would find similar applications, conduct an experiment, and convert it into a scholarly work.

Need

The summer of 2006 in the United States was unique to many people because of unusually high ambient temperatures. Electrical power lines were overloaded, causing disrupted electrical power to some parts of the country. Energy engineers had their share of headaches in the midst of all that.

Many home owners wonder what is going on with their air conditioners and how they can contribute to the long-term solution of the energy crisis. Some technical information related to saving energy may help in their efforts. Energy engineers have wondered about improving the energy efficiency of electrically driven machines. Most energy engineers have learned mechanical engineering principles in their academic past. When it comes to the electrical engineering side of energy engineering, they tend to rely on external sources to learn about electrical energy details. They may be interested in how to measure and use electrical properties without taking several electrical engineering courses.

Guidelines for Investigating Energy Systems

Before investing in new energy-efficient retrofits, a good understanding of the existing problem is a must. Knowing the details, one may seek devices that address specific types of past problems. To improve energy efficiency continuously, energy engineers have to rely on innovative methods and devices with newer technologies. A recent article [1] explains how the energy consumption of a pumping system in a new carpet manufacturing facility has been reduced by 90 percent, compared to a traditional design approach, by using larger diameter and shorter length pipes. Undoubtedly, the advancements in power electronics in the last two decades have contributed to energy efficiency improvement more than any other technology. Imagine an industrial facility without variable speed drives, fluorescent light fixtures with electronic ballasts, electrical power distribution networks full of harmonics problems, etc. The field of power electronics advances at a rapid rate, and potentials for further energy savings in appliances, electric vehicles, computers, etc. are very high [2]. But power electronics is not a part of mechanical or industrial engineering curriculums. And, it is not necessarily included in all electrical engineering curriculums either. The future of energy efficiency improvements will require a good understanding of the energy conversion which typically belongs to mechanical engineering or mechanical engineering technology, and power electronics which is typically taught in electrical engineering or electrical engineering technology. Power electronics may help manage energy problems if we know exactly where and how energy is used and wasted.

Several steps may be followed during the analysis to acquire a better understanding of the energy usage. They include:

1. Have a good understanding of the operation of the energy consuming system,
2. Be aware of the disturbances to the process being performed,
3. Use appropriate electrical and other measuring instruments to collect relevant data,
4. Verify data and examine unexpected variations, and
5. Analyze the data as they relate to the ongoing process to identify the energy saving opportunities.

Methodology

The remainder of this paper explains how to gather the needed electrical characteristics of a residential air-conditioner unit and what conclusions useful for energy conservation could be derived. A simple, do-it-yourself type, attic fan was used to explore its effects on the cooling load. The findings may be useful to energy engineers and home owners. First, necessary electrical and temperature measurement were taken in hot-summer day without an attic fan. After that, same type of data was obtained during a day similar (temperature profile and wind) to the previous one with an attic fan.

Measuring electrical power requires proper safety precautions, and the author or the publisher is not responsible for any physical harm to person or property that may be caused by replicating the following procedures.

Operation of a Residential Air-conditioner

In order to understand the electrical measurements discussed below, a brief explanation of the refrigeration cycle as it relates to a typical residential air-conditioner is given. A thorough explanation can be obtained from the resources available from American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE).

The air-conditioning loop consists of four major components – a compressor driven by an electric motor, a radiator, an evaporator, and hermetically sealed tubes to connect the previously mentioned three devices. Several other devices--receiver, fan, blower, and expansion valve--are added to increase the controllability and efficiency of the system. See Figure 1.

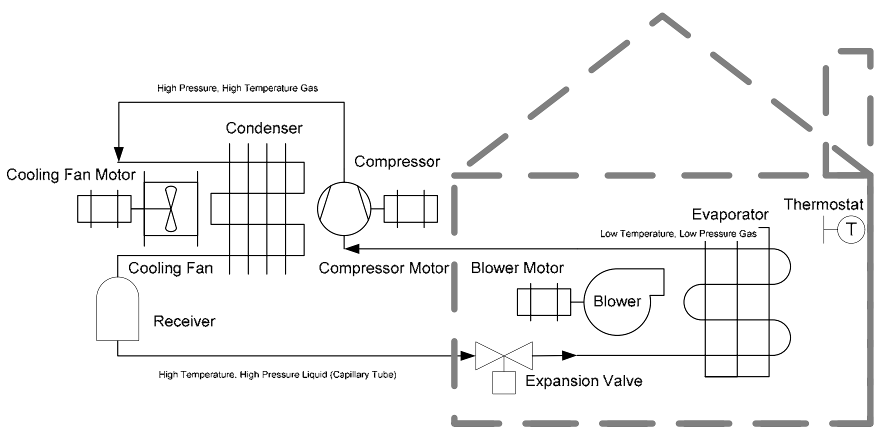

Figure 1 Devices in a typical residential air-conditioner

The compressor, using the power from an electric motor, compresses the refrigerant gas present at its input to make high pressure and hot gas at its output. The pressurized gas flows into the condenser located outdoors. A fan removes the heat from the gas, forming pressurized liquid at the output of the condenser. The receiver accumulates and keeps the liquid until it is released to the evaporator by the expansion valve in a controlled fashion. In a residential air-conditioner, the compressor, the condenser, and the fan are housed in a single unit located outdoors. This liquid is forced to flow through a capillary tube with a very small diameter to the evaporator, which consists of pipes with a much larger diameter than the capillary. As the pressurized liquid is released to a larger space in the evaporator, the liquid vaporizes, absorbing the heat from its surroundings. A blower fan next to the evaporator coil removes the cold air formed around the pipes. The pressure of the refrigerant gas is dropped. The refrigerant gas then flows to the compressor for compression, which initiates the cycle again.

With this brief overview, it is evident that several items need to be evaluated to improve energy efficiency. The total efficiency of the system depends on the efficiency of the motor, the compressor, the evaporator, and the condenser. The motor is the initial energy converter and the device seen by the utility grid. The energy efficiency analysis of the sub-components, other than the electrical side, is beyond the scope of this paper. But how the inefficiencies of other components may influence the electrical side is given throughout the paper, as necessary.

Disturbances

The term “disturbances” is used to explain what actions or events may alter an on-going process. The process carried out by a residential air-conditioner is cooling a living space. The word “cooling” means maintaining the temperature (the physical parameter) of the space lower than its surroundings. The desired temperature is set at the thermostat located in the living space. Heat penetrates to the living space through walls, attic, doors, and windows when the outdoor temperature is greater than the indoor temperature. The insulation of walls, attic, floors, and glass determines how fast (the heat transfer rate) the outdoor temperature affects the indoor temperature. Also heat is added by the people and animals living in the space and by opening and closing windows and doors. The temperature inside the attic space is much higher than the ambient temperature in the summer due to the trapped air. All these are disturbances to the process of cooling. So the air-conditioner’s job is to remove all this added heat.

Obtaining Electrical Measurements

The accuracy of energy saving prediction requires accurate field data. Appropriate instruments must be used to collect relevant data. Users of new equipment need to spend time familiarizing themselves with different types of measurements [3].

A variety of meters is available for electrical measurements. For energy-related data collection, a meter should be able to measure the power of the fundamental frequency and the harmonics. To put it in simpler terms, the meter should be capable of measuring “true rms” current, capable of recording inrush current, and fast enough to detect harmonics of 50Hz or 60Hz fundamental frequency. For this experiment, a Fluke 43B power analyzer was used. Fluke 43B measures many useful electrical properties via two connections--line voltage via a direct connection and current via a clip-on current probe. There is no need to disconnect any wires. Remember that energy engineers should not disrupt on-going processes while taking required measurements. The photo in Figure 2 shows that the current probe and voltage leads are directly connected at the electrical distribution panel.

Figure 2 Power analyzer connections

Attic Fan

Home owners frequently ask whether they should add an attic fan. During industrial energy audits, energy managers may have wondered about the same question. To observe the effect of an attic fan, a regular 24”, off-the-shelves ventilation fan was mounted in the standard attic entrance located in a garage. As shown in Figure 3, the fan fits right into the space. Screws are necessary to hold it in place. The remaining space needs to be covered. A remote temperature transmitter with an extended temperature sensor is mounted on the right edge of the frame to measure the temperature in the attic. The garage door was left open about 1ft to help air circulation. Some attics have built-in louvers, exposed to the outside, where a fan can be installed. In that case there is no need to leave the garage door open.

Figure 3 A low cost attic fan and the attic temperature transmitter

Useful Measurements and Significance

All pieces of electrical equipment are designed to perform within a certain input voltage range and a frequency. Especially the performance of an electric induction motor is significantly affected by a slight variation of the frequency. Supply voltage must be within specified tolerances. The supply voltage and frequency are tightly controlled in the United States, but this is not so true in many other countries.

<u>Voltage & Current</u>
First, one needs to evaluate the supply voltage and current. Smooth, symmetrical sinusoidal waveforms are desired. Distorted waveforms indicate the presence of harmonics.

The voltage waveform in Figure 4 has a smooth, symmetrical shape. The current wave form is not that smooth, but it still has a symmetrical shape. See Figure 4.

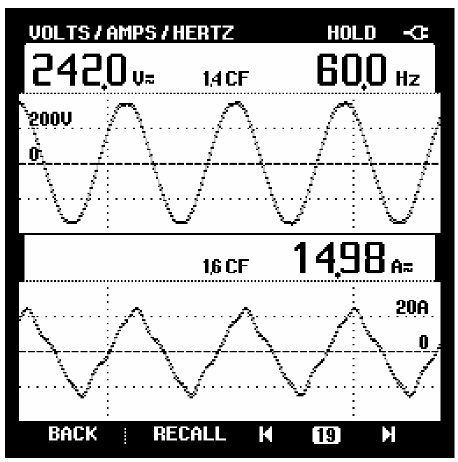

Figure 4 Voltage and current waveform of a residential power supply

<u>Harmonics</u>
Harmonics are an integer multiple of a fundamental frequency, which is 60Hz in the United States. Table 1 summarizes the relationships among harmonics. In addition to the order number and the multiplier, each harmonic has a sequence number. Positive (+) sequence harmonics create magnetic fields in such a way that they try turn the rotor faster than the speed caused by the magnetic field of the fundamental frequency. Negative (-) sequence harmonics try turn the rotor slower than the than the speed caused by the fundamental. If any of these sequences are present, the motor loses its torque and heats up. If the waveform is symmetrical, then the negative sequence disappears [4]. If the zero sequence components, especially in the current, contain significant amplitudes, they appear in the neutral wire causing overheating of the neutral conductor.

Table 1 Harmonics and their sequences

Order	F	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	7th		50th	Etc.
Frequency	60	120	180	240	300	360	420	…	3000	...
Sequence	+	-	0	+	-	0	+	…		…

To verify the presence of harmonics, one must then examine the harmonic distribution. Fluke 43B measures the amplitudes of harmonics up to the 51^{st}. Figure 5 indicates that the 14.7A out of 14.82A was caused by the fundamental frequency, 60 Hz. Three odd harmonics of the fundamental frequency, 180Hz, 300Hz, and 420Hz claims 1.3A, 0.89A, and 0.29A respectively. The most important reading is the total harmonic distortion (THD%). THD indicates to what degree the waveform deviates from a pure sine wave. A 0% indicates no deviation [4]. For power lines, voltage THD must be less than 5% and current must be less than 20%.

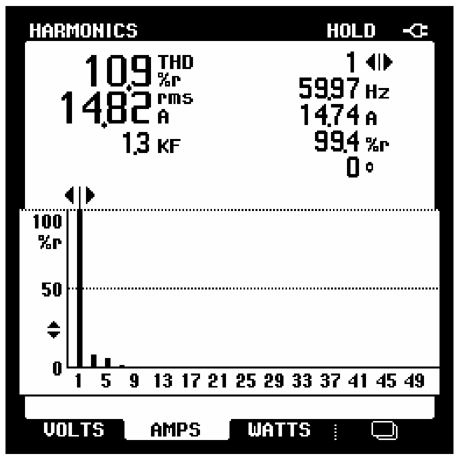

Figure 5 Harmonic components of the current

Power factor

Power factor (PF) is the ratio of real power to apparent power. The utility companies would like consumers to use all the generated power. When PF is one (PF=1), the device consumes all the supplied power, with no reactive power presence. When PF is zero (PF=0), no useful power is delivered, only reactive power. The device has a reactive power component when PF falls between 0 and 1. The problem of reactive power is that it does not contribute to usable energy generation. The utility sees the reactive power as a waste of energy and bills the consumer additional charges. Residential customers may not see this cost directly but pay a higher rate for energy, which is in kWh. For industrial customers, the bill contains a separate line item. Energy managers should pay close attention to a plant's PF. There are PF correction device available for entire plants. But the best solution is to correct the PF at its sources. Modern power electronics is capable of correcting PF at its source. Integrated circuits (IC) are available and integrated into electronic ballasts, motor drives, power supplies, etc.

In the presence of harmonics, two power factor components are given – Power Factor (PF) and Displacement Power Factor [DPF]. PF refers to the fundamental frequency only. DPF includes all harmonics when calculated. No harmonics means DPF equals to PF.

In our example, we saw some presence of current harmonics, and we should expect different numbers for PF and DPF. As shown in Figure 5, PF and DPF are 0.85 and 0.86 respectively. The usable power was 3.08kW, and the utility grid saw the device as a 3.62kVA load. Reactive power was 1.9kVAR. One may also calculate the reactive power by using the power triangle method: $kVAR = \sqrt{(kVA^2 - kW^2)}$.

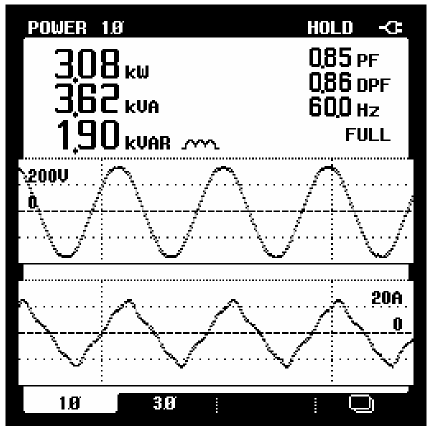

Figure 6 PF and DPF of a residential air-conditioner

<u>Operational patterns and characteristics</u>
To understand the energy consumption of a process, voltage and current need to be monitored over time. Two scenarios were set up to investigate the effect of a simple attic fan. The disturbances to the process were controlled for both cases. The most important item is to explore the operational characteristics of the air conditioner and to determine energy saving opportunities.

By using the Sag & Swell feature of the Fluke meter, on and off patterns, including current and voltage, were recorded for an extended time period. Figure 7 depicts operational characteristics

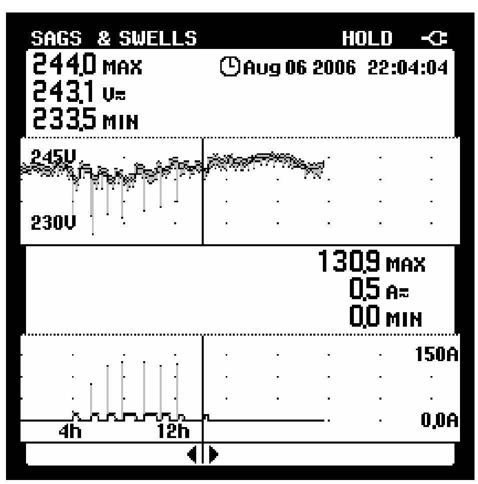

Figure 7 Operational characteristics of air conditioner without the attic fan

At first glance, it appears that voltage has some variations but drops significantly when the air conditioner is turned on. Spikes appearing in the bottom graph indicate an inrush current during the motor start up. The initial inrush current has lower value than the later ones. To get a clear picture, actual values related to each event are tabulated in Table 2. The table also includes other useful information such as time of day, temperature values, and the operational periods. The house thermostat was set at 77^0F, and indoor temperature was measured about 20ft away from the thermostat. The table only shows the temperatures at the start up of the air conditioner.

Table 2 Specific values related to Figure 7 display

Figure 7	Attic fan off								
	Date 8/6/06	Start 8:15 a.m.			End	7:27 a.m. (8/7/06)			
Period	1	2	3	4	5	6	7	8	
On time	11:58	13:23	14:40	15:48	17:31	18:47	20:04	22:04	
Off time	12:23	14:06	15:23	16:56	18:39	19:39	20:38	22:38	
Duration	0:25	0:43	0:43	1:08	1:08	0:52	0:34	0:34	6:07
Peak current (A)	24.6	85.8	126.9	135.1	136.4	128.0	130.1	130.9	
Run current (A)	16.4	16.7	16.4	16.6	16.5	16.3	15.7	15.2	
Voltage max (V)	242.5	242.7	242.3	242.2	143.3	244.0	245.4	244.0	
Voltage average (V)	240.8	240.5	239.9	242.1	241.8	243.1	244.4	243.1	
Voltage min (V)	231.2	232.0	232.4	231.6	233.1	233.8	235.4	233.5	
Temp. Outdoor (F)	88.2	88.7	88.6	88.7	87.0	85.6	82.6	78.2	
Temp. Indoor (F)	77.8	78.6	77.9	78.6	78.4	77.9	77.3	76.6	
Temp. Attic (F)	100.8	105.1	108.2	116.0	111.2	103.0	97.4	88.3	

The air conditioner operated a total of 6.07 hours during a hot summer day when the indoor temperature was set at 77F, an upper end of the human comfort zone. Of course, most homes are maintained around 72F, resulting in much longer operational time.

A second set of data was collected while the attic fan was operational. Operational patterns were obtained via Sag & Swell feature of Fluke 43 as shown in Figure 8. Table 3 represents actual data values. Some variation of outdoor temperature was expected.

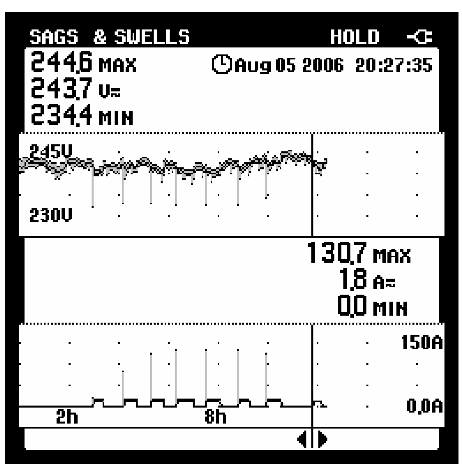

Figure 8 Operational characteristics of air conditioner with the attic fan

The graph in Figure 8 follows the same features observed in the graph in Figure 7: lower peaks initially, higher peaks as the day progresses, voltage drops and current spikes during start ups, and longer operational periods between 2:00 p.m. until 7:00 p.m. Table 3 tabulates the actual value at each event. Again, the table only shows the temperatures at the start up of the air conditioner.

Table 3 Specific values related to Figure 8 display

Figure 8	Attic fan on								
	Date 8/5/06		Start 8:52 a.m.			End	21:01 a.m.		
Period	1	2	3	4	5	6	7	8	
On time	11:38	12:51	13:59	14:59	16:11	17:28	18:36	20:27	
Off time	12:08	13:29	14:33	15:46	16:50	18:02	19:15	20:53	
Duration	0:30	0:38	0:34	0:47	0:39	0:34	0:39	0:26	4:47
Peak current (A)	24.4	86.0	127.3	136.2	134.6	136.7	127.0	130.1	
Run current (A)	16.5	16.8	16.6	16.8	16.3	16.0	16.1	15.5	
Voltage max (V)	243.1	244.0	242.9	242.9	242.1	243.1	244.4	244.6	
Voltage average (V)	241.8	242.4	241.1	241.6	240.6	241.8	242.8	243.7	
Voltage min (V)	232.8	233.1	233.2	232.5	232.5	232.8	234.3	234.4	
Temp. Outdoor (F)	89.2	89.2	87.1	87.4	86.5	86.2	83.7	80.4	
Temp. Indoor (F)	78.1	78.5	78.6	78.8	78.1	77.9	77.6	77.0	
Temp. Attic (F)	95.0	106.0	108.0	111.0	108.4	105.0	98.1	86.0	

A graphical representation of a dataset helps the investigator better detect variations between datasets than numbers. Figure 9 is a graph showing how temperatures were changed during the day for both scenarios.

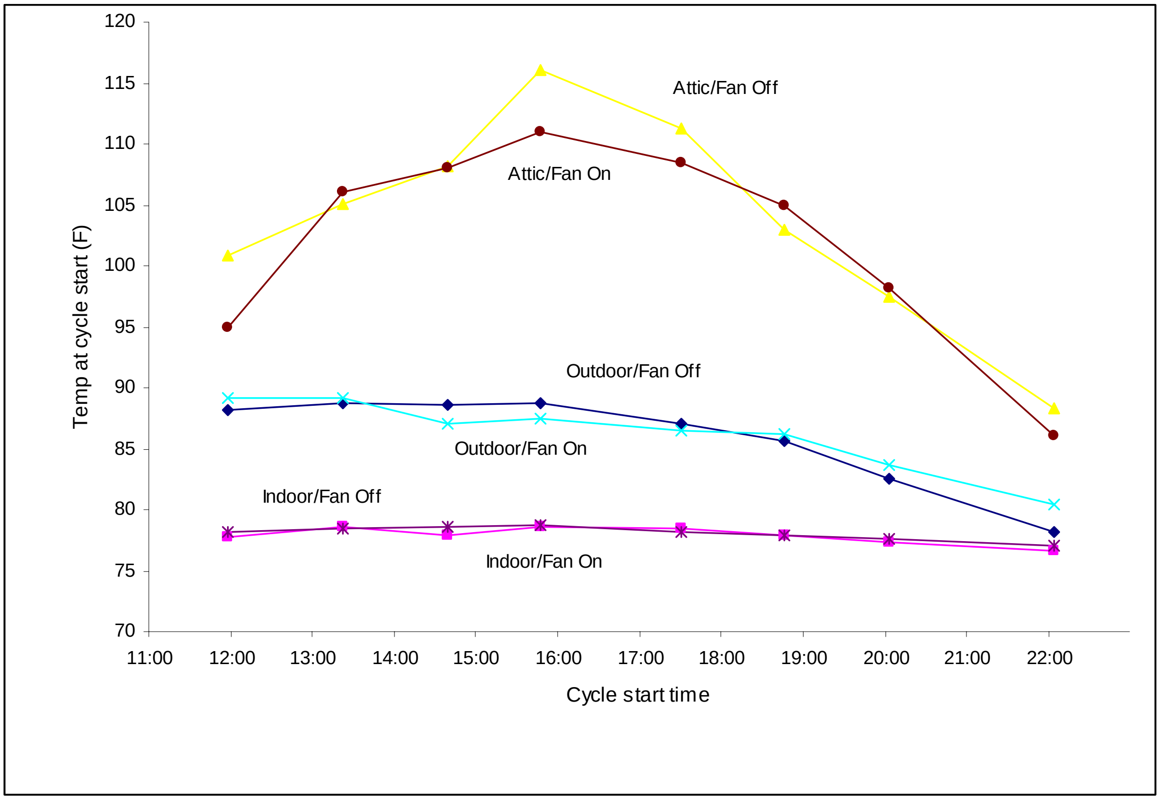

Figure 9 Temperatures with and without the attic fan

Ambient temperatures on both days reached to a maximum at around noon and started decreasing after 3:00 p.m. The attic temperature follows a similar pattern but at a higher temperature. The small attic fan was able to curb the peak. This assumption is supported by the difference between total operating time – 6 hours and 7 minutes with fan off and 4 hours and 47 minutes with the fan on. This was about a 21.7% energy reduction [= 100%*(367min-287min)/367min].

Energy saving opportunities

Attention should be given to system level energy saving opportunities and device specific energy efficiency improvement opportunities. At the system level, one may control disturbance by adding new devices, adding or removing material, and changing the operational patterns. Energy managers may collect system level data and work with vendors to improve overall efficiency. At the same time, device specific data can be collected, and one can work with the device manufacturers to further increase the energy efficiency of the device itself.

Our data shows 21.7% energy savings when the attic fan was on. Based on this finding, one system level opportunity is to consider adding a permanent attic fan. The result may depend on the amount of air an attic fan can circulate though the attic space, the outdoor to indoor temperature differences, etc. For home applications, single-phase attics fans are available from $40 and up. Some attic fans come with a built-in temperature sensor to turn the fan on and off automatically. Another low cost system level opportunity is to use shades on door and windows to prevent direct infiltration of sun rays. Also, one could consider adding insulation to the attic, which will save energy in the winter as well.

Summary and Conclusions

An experiment was set up to highlight the importance of exploring energy saving opportunities at the systems level. While using features of modern meters, the electrical characteristic of a residential air-conditioner were investigated. Several steps for collecting meaningful data are outlined and explained using the experiment.

At the system level, 21.75% less energy was used in a day when an 18” off-the-shelf fan was used as an attic fan. It is recommended to repeat the experiment several times before making a decision to install a permanent attic fan. A different set of process disturbances may yield a different amount of savings. By addressing system level saving opportunities, one may get a quick return.

The approach to identify device level energy efficiency improvement will be discussed in another paper by the same author.

References

[1] Wawkin, P. A., Lovins, A. B., & Lovins, A. H. (1999), *Natural Capitalism: Creating the Next Industrial Revolution*, Little Brown. (also view via www.rmi.org/sitepage/pid298.php)
[2] Lidow, A, *The Power Conversion Process as an Instrument for Change*, International Rectifier Corporation, www.irf.com/aboutir-info/psworld97.html
[3] Kulatunga, A. (2005), *Preparing Energy Managers and Technicians for Energy Data Collection: New Instrument Familiarization Activities*, Energy Engineering, May 2005.
[4] Fluke43B Power Quality Analyzer User Manual, (2001), Fluke Corporation