Motor Current Signature Analysis— A Potential Diagnostic for Air Conditioners

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ABSTRACT

Recent advancements in modern electronics have made it possible to collect the various "transient noise" signals that are present on electric power lines of motor-driven equipment while using a simple non-intrusive, clamp-on inductive pickup. Electronic filters are used to analyze the noise signal with an on-the-spot, real-time analysis. An exploratory study, conducted at a national laboratory, examined the potential for using the motor current signature on heat pumps and air conditioners as a diagnostic tool. Preliminary results show that there is some correlation between the motor current signature and the performance of a heat pump. However, tests and associated analysis were limited, and additional research is needed to determine the full potential of motor current signature analysis (MCSA).

INTRODUCTION

The use of MCSA appears to have promise as an on-site diagnostic and monitoring tool for determining the performance of air conditioners and heat pumps. A large percentage of heat pumps and air conditioners currently operate at low performance due to some equipment problems. One of the most common equipment problems is improper refrigerant charge, caused either by leaks in the system or improper initial charging. Measurements made by the lab's Efficiency and Renewables Research Section have shown the performance penalty that is paid for operating a heat pump or air conditioner at a reduced refrigerant charge level (Domingorena 1980; Miller 1982). Equipment damage, as well as performance degradation, can result. A simple non-intrusive air conditioner and heat pump diagnostic tool would prove very useful to auditors and servicemen to determine improper refrigerant charge and other component failures or degradation.

Researchers in the lab's Engineering Technology Division have been studying methods for improving the operational readiness of motor-operated valves (MOV), a type of valve found in large numbers in nuclear plant safety systems. They discovered that the electric power leads supplying the motor, in addition to providing the electric current necessary to drive the MOV, were carrying useful diagnostic information related to the condition of both the valve and its actuator. An MCSA method was thus developed that provides a means to non-intrusively extract valuable diagnostic information from the motor power leads (Eissenberg 1987; Haynes 1987).

Although the motor current signature was found to contain many types of information useful for condition monitoring, the most striking and unique was the frequency spectrum—obtained by processing the motor current signal and passing it through a frequency analyzer. The motor current frequency spectrum contained peaks associated with all of the periodic load variations encountered by the motor in driving the mechanical equipment (in this case, the valve operator and valve). In that regard, the motor itself was acting as a transducer, sensing mechanical load variations and converting them to electrical impulses, which were transmitted down the electric power cable. When quantified and trended with time, this measurement has proven to be a valuable diagnostic tool in determining the operational readiness of motor-operated valves.

The spectra obtained from MCSA are similar in many respects to those obtained from conventional machinery vibration analysis, where accelerometers directly mounted on the housing of the mechanical equipment are used to obtain the spectra. Advantages of MCSA include the use of non-intrusive, clamp-on probes as sensors. These sensors, which can be located anywhere along the power line, detect all mechanical loads, whereas accelerometers generally sense vibration in only one plane.

Using a novel signal processing technique, the researchers discovered that gear meshing signatures could be obtained on a tooth-by-tooth basis. By using this technique, individual bad gear teeth could be detected from motor current signals.

Although developed initially as a method applicable to motor-operated valves, MCSA has been demonstrated to apply to fans, pumps, and compressors. Figure 1 is a schematic of its application to condition monitoring of a centrifugal pump. Actual MCSA data acquisition and

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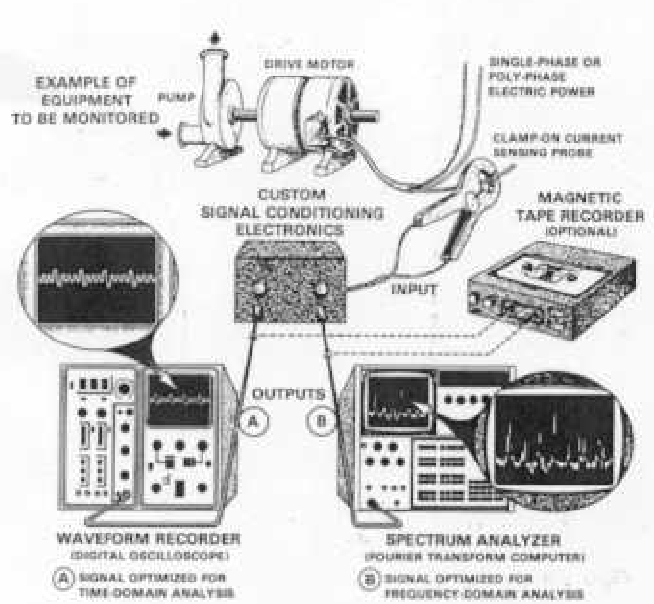

Figure 1

analysis instrumentation are presented in Figure 2. The laboratory is developing a data base of MCSA diagnostics vs. MOV degradations from in-situ tests at a nuclear power station. A patent application covering aspects of this development has been filed by the Department of Energy (DOE).

TEST OF MCSA ON AIR CONDITIONERS AND HEAT PUMPS

Following Engineering Technology Division work on motor-operated valves, work was initiated to determine if MCSA could be used as a diagnostic tool on air conditioners and heat pumps. Two independent series of tests were made. The first tests were conducted to determine the effect of refrigerant charge level on the performance of a heat pump in the Energy Division's environmental chamber. The test unit was a split system, air-to-air heat pump with a reciprocating compressor. The second series of tests were on several through-the-wall air conditioners in a building located on the lab site. Both tests showed that MCSA has the potential to be used as a diagnostic tool for air conditioners and heat pumps.

Environmental Chamber Testing

The heat pump test in the environmental chamber was split into three parts. During the first portion of testing, the refrigerant charge was lowered from 10.5 lb to 6.5 lb in one-pound increments. Steady-state conditions were established at each charge level, and heat pump performance data and motor current spectrum data were acquired. The second portion of the testing was carried out after each steady-state test. The compressor was de-energized for 12 minutes. Then it was restarted, and the motor current was measured as a function of time during the transient startup period. In the third part of the environmental chamber testing, the refrigerant charge was increased from 6.0 lb to 10 lb in one-pound increments, with the 10.5 lb condition repeated at the end of the test.

Figure 3 shows that the cooling capacity and COP both reach a maximum value at the 9.5 lb charge. Reducing the charge from 9.5 lb to 6 lb resulted in a 51% drop in capacity and a 38% drop in COP. The figure also shows that data repeatability was quite good. Figure 4 shows a typical motor current spectrum for the 9.5 lb refrigerant charge. The frequency range in Figure 4 is from 0 to 200 Hz. The 59.7 Hz and the 179.1 Hz are the primary and third harmonics of the frequency of the power source. The 53.8 Hz and the 173.2 Hz peak are side bands around the 59.7 Hz and the 179.1 Hz peak and are related to motor slip.

Figure 2

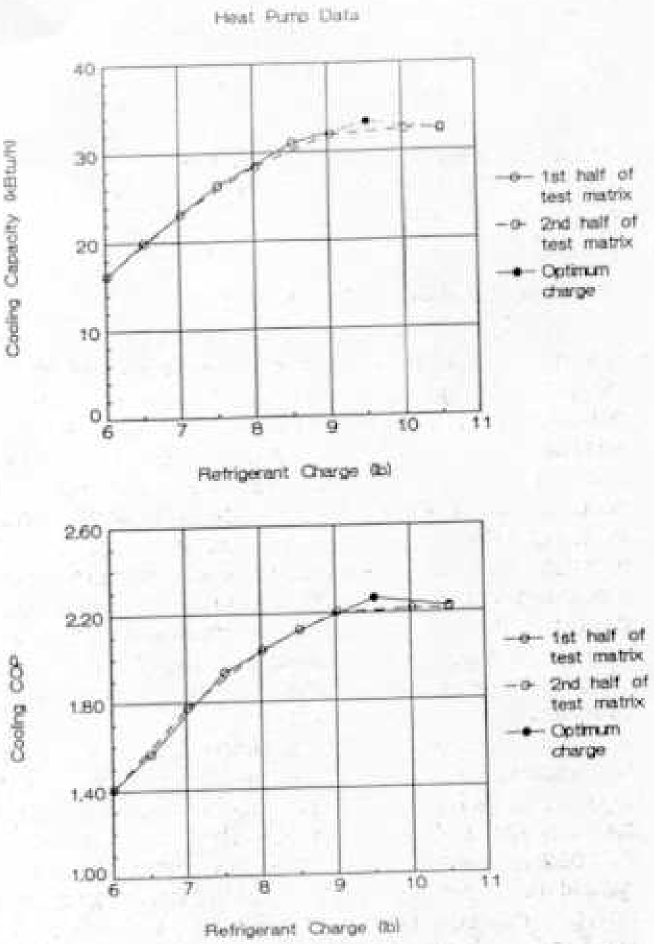

Figure 3

To further explain, the frequency span between the 53.8 Hz peak and the 59.7 Hz peak (59.7 − 53.8 = 5.9 Hz) reflects the difference between the actual motor speed and the synchronous motor speed times the number of motor poles. This has been referred to as the slip frequency. Therefore,

SLIP FREQUENCY =
(SYNCHRONOUS SPEED − ACTUAL SPEED)
x (MOTOR POLES).

Since the motor was a 2-pole design, its synchronous speed would be

SYNCHRONOUS SPEED
= [2 × POWER LINE FREQUENCY]/# POLES
= [2 × 59.7]/2
= 59.7 Hz.

Therefore, the actual motor speed may be calculated as follows:

ACTUAL SPEED
= SYNCHRONOUS SPEED −
[SLIP FREQUENCY/# POLES]
= 59.7 Hz − [5.9 Hz/2]
= 56.75 Hz
= 3405 rpm.

Figure 5 shows how the refrigerant charge affects the current spectrum. The peak amplitude at 53.8 Hz is normalized with respect to the value at 9.5 lb charge and is plotted to show the general trends. Figure 5 shows that the amplitude drops about 30% when the charge was reduced from 9.5 lb to 6 lb, while Figure 5b shows the corresponding amplitude of the 59.7 Hz peak.

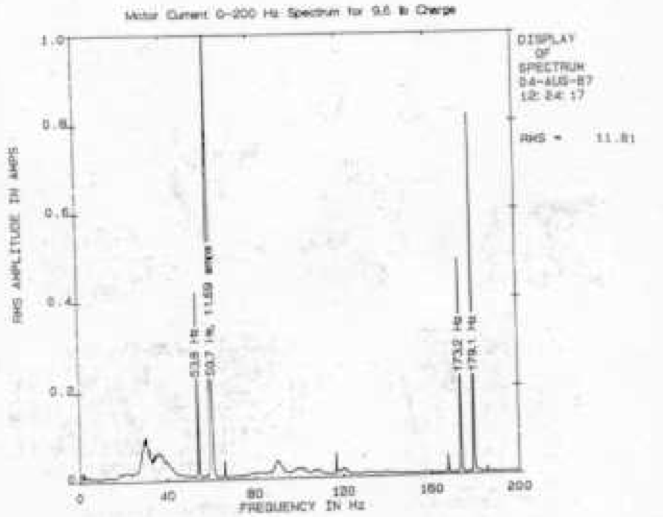

Figure 4

Current analysis during startup transients also indicated trends in motor current waveforms that were

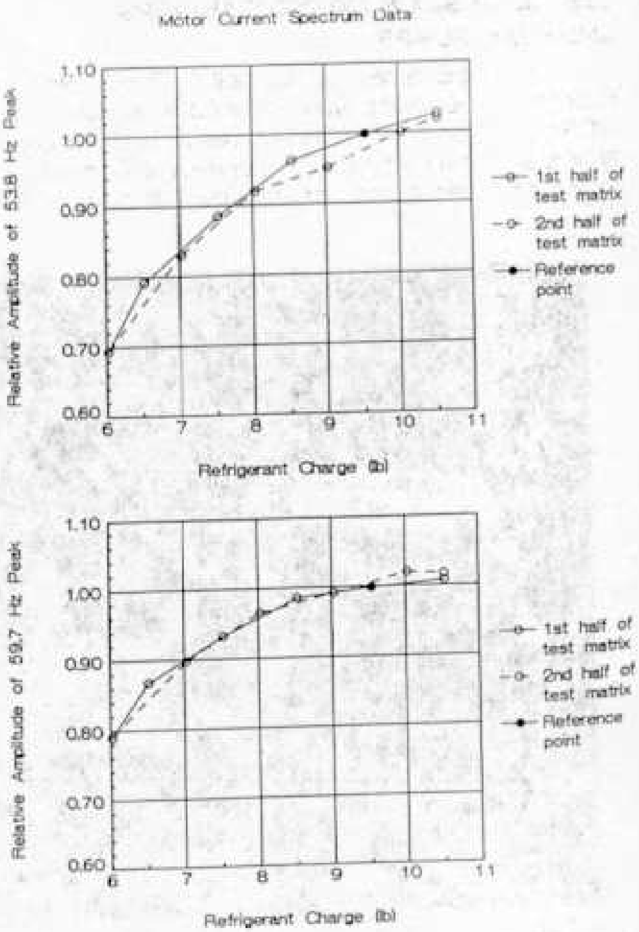

Figure 5

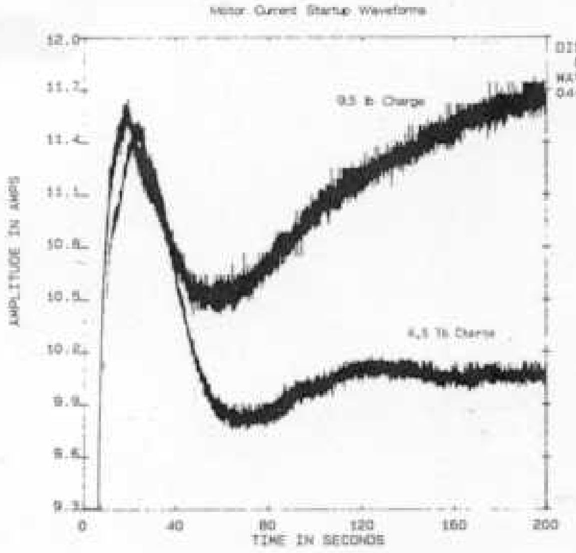

Figure 6

related to refrigerant charge. Figure 6 shows compressor motor current waveforms for the 9.5 lb and 6.5 lb refrigerant charges that were measured during 200 sec startup transients. Additional signal conditioning was used during the startup testing. The motor current signal was passed through an rms-to-DC converter that performed two functions: (1) converting the AC signal into an equivalent DC signal that was proportional to the rms value of the AC motor current, and (2) filtering out frequencies that were above about 5 Hz. The filtering completely damped out the current surges that occurred when the motor was turned on.

A peak in the compressor current occurred at roughly 30 seconds because at startup, saturated refrigerant vapor was pumped by the compressor. As time progressed, the evaporator pressure decreased as the compressor continued to pump refrigerant. The evaporator coil became starved for refrigerant and therefore compressor current dropped, as seen in Figure 6. However, with the system undercharged at 6.5 lb, the compressor was unable to establish proper charge distribution, resulting in the variation of current trends from 60 to 200 sec for testing at 6.5 lb vs. 9.5 lb charge.

The effect of refrigerant charge on motor current startup waveforms is quantified more clearly in Figure 7. The top plot shows: (1) the maximum current of the peak at about 20 sec, (2) the minimum current in the valley at about 60 sec, and (3) the current at 200 sec. The bottom plot shows a dimensionless parameter equal to the current at 200 sec divided by the peak current at about 20 sec. The motor current ratio is presented because it may be a parameter that is rather insensitive to the effects of extraneous variables such as voltage or air temperatures. If a low voltage, for example, changes the current at 200 sec and the peak current at about 20 sec by proportional amounts, then a ratio of these currents will not be affected by voltage.

All spectrum data displayed good repeatability during testing. However, some repeatability may have been related to the close control of other variables in the environmental chamber. Repeatability may be much worse in field applications where voltage and air temperatures cannot be controlled. The results of this test show that the reduction in refrigerant charge reduced the cooling capacity by about 50%, and a maximum variation of about 30% was observed in the MCSA.

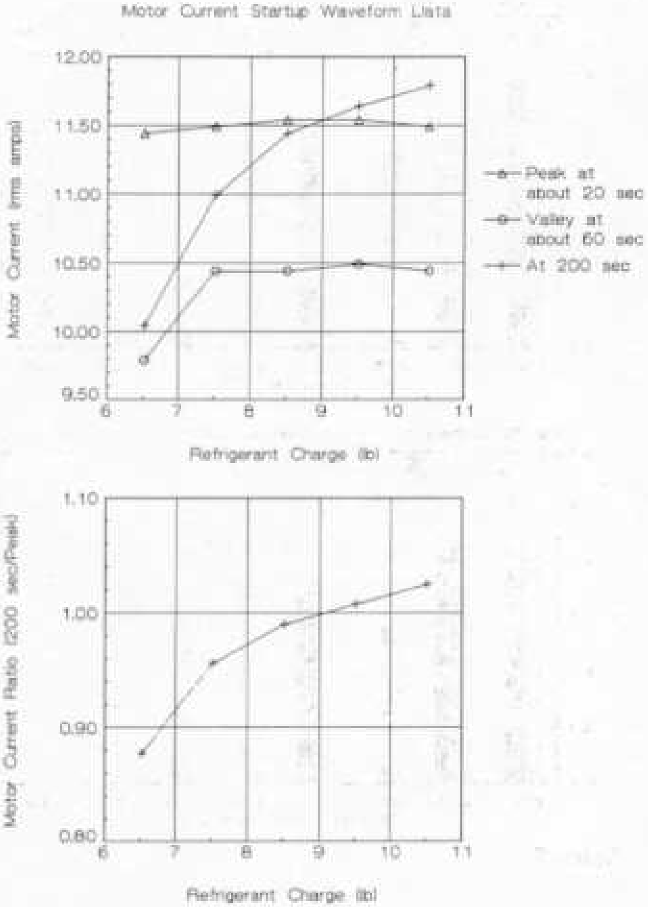

Figure 7

In-Site Testing

Tests were conducted on several window air-conditioning units located in a lab building. A major objective of these tests was to acquire and analyze electric current signatures in order to explore the feasibility of using an electric current-based method for evaluating the efficiency of air-conditioning systems. In addition to motor current signatures, a range of performance data were acquired for each unit. These measurements consisted of manually measuring air flow rates with a calibrated vane anemometer, dry-bulb discharge temperatures with a portable platinum RTD, power input with a kilowatt-hr meter and stopwatch, and wet-bulb temperatures with a sling psychrometer. The measurements were repeated four times—two in the cooler morning outside temperatures and two in the warmer afternoon temperatures—although not all units were measured for each period. Capacities and COPs were calculated from these data. It is estimated that the results are accurate to ±10% at best because of the relative "crudeness" of the measurements. Figure 8

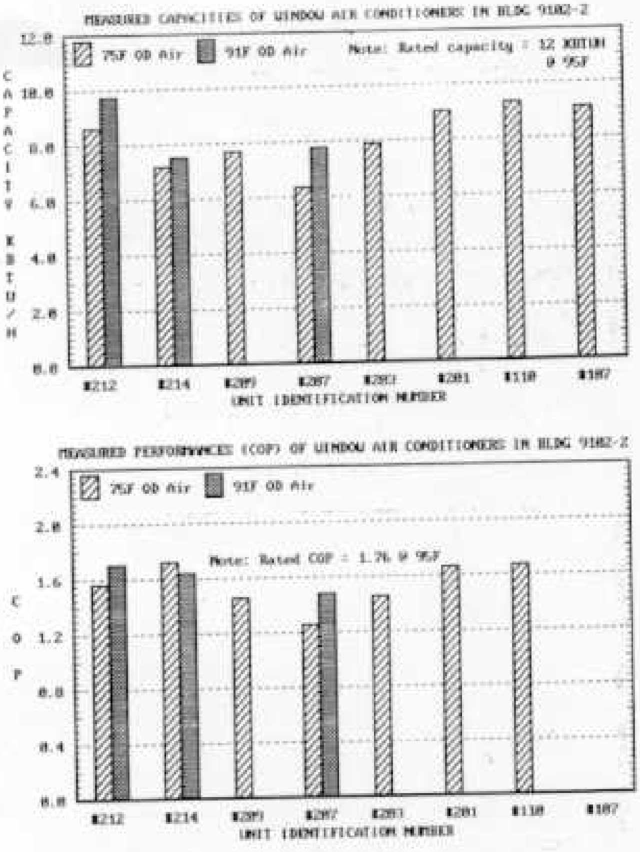

Figure 8

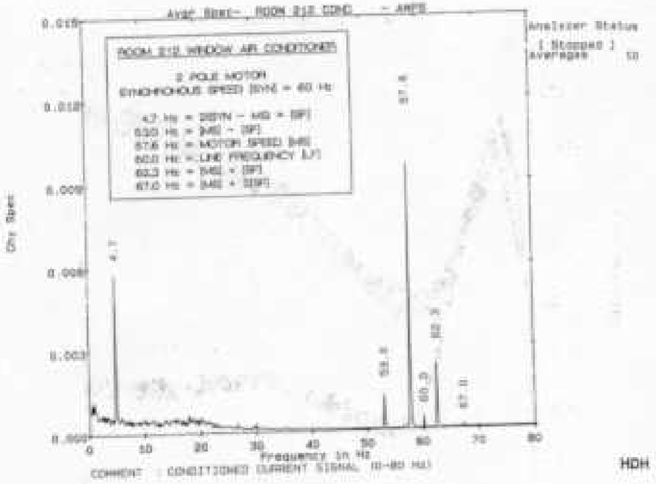

Figure 9

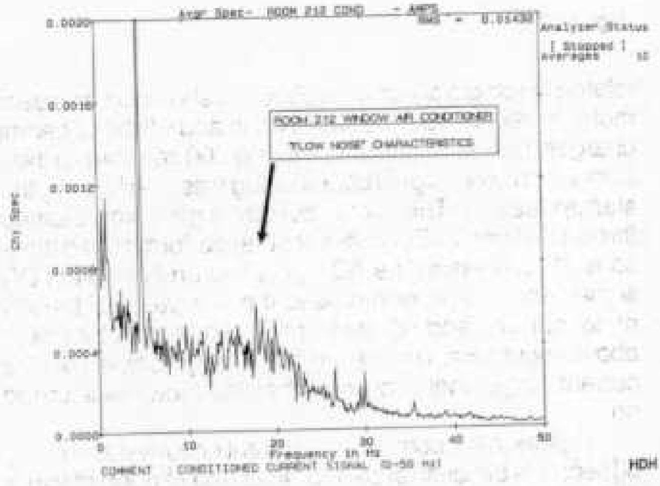

Figure 10

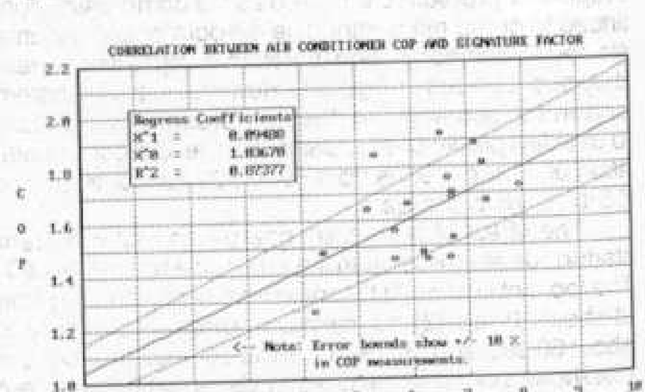

Figure 11

illustrates the results of some of the in-site measurements taken on the units.

Utilizing custom signal conditioning electronics, the motor current signals were processed and analyzed by a spectrum analyzer. A typical electric current spectrum is presented in Figure 9 and illustrates that compressor motor speed measurement is possible using MCSA. Figure 9 illustrates that, in addition to compressor speed, low-frequency components are also present. Preliminary research has identified low-frequency signature characteristics in water pumps that appear to reflect water pressure perturbations. Acting on an initial assumption that this "flow noise" may possibly cause or result in system inefficiencies, a motor current signature factor was derived by ratioing the 0-30 Hz "flow noise" (see Figure 10) magnitude to the total signal magnitude as follows:

$$\text{Signature Factor} = \frac{\text{(Total current signal RMS)}}{\text{0-30 Hz signal RMS} - \text{(motor slip peak RMS)}}$$

All signal magnitudes are expressed in amps (RMS). The motor slip frequency peak (identified as SF in Figure 9) is subtracted from the 0-30 Hz signal since its existence is determined directly by the motor speed rather than flow. Therefore, the denominator of the above equation represents the "flow noise" magnitude more accurately. If this "flow noise" reflects system inefficiency, it is conceivable that a lower "flow noise" magnitude would correspond to more efficient operation. Thus, the greater the signature factor, the higher performance the unit exhibits.

The relevance of this initial theory was tested by plotting the signature factor vs. the calculated COP for seven window air-conditioning units from data that were collected during the morning and afternoon of two days. Figure 11 illustrates that a correlation probably exists between COP and this signature factor. Additional MCSAs may provide further insight into the relationships between air-conditioning unit performance factors and corresponding motor current signature characteristics. This could lead to the refinement of motor current signature factors that provide high sensitivity and selectivity to a variety of electrical and mechanical disorders affecting the performance of air-conditioning systems.

SUMMARY

An exploratory study, conducted at a national laboratory, examined the potential for using the motor current signature on heat pumps and air conditioners as a diagnostic tool. Preliminary results show that there is some correlation between the motor current signature and the performance of a heat pump. In summary, the MCSA of heat pumps and air conditioners under close control laboratory conditions has shown some repeatable trends that could possibly be used as a non-intrusive diagnostic tool. However, there is a need to better understand interpretation of the noise analysis in field applications. Several parameters of the noise analysis have to be better understood before this concept can be developed into a more universal heat pump/air conditioner diagnostic tool.

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