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LABORATORY EFFICIENCY COMPARISONS OF MODULATING HEAT PUMP COMPONENTS USING ADJUSTABLE SPEED DRIVES

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ABSTRACT

The operating efficiencies of an indoor centrifugal blower and a hermetic reciprocating compressor, both having induction motors, were measured in a breadboard heat pump test facility. The indoor blower was tested using a six-step voltage source inverter (VSI) produced in the early 1980s and also using a motor-generator (M-G) (ideal induction motor drive) for blower motor drive frequencies ranging from 20 to 60 Hz. The reciprocating compressor was driven in separate tests by a VSI, a pulse-width modulated inverter (PWMI), and an M-G to observe the effect of each adjustable-speed drive on the efficiency of the compressor for drive frequencies ranging from 15 to 90 Hz.

Laboratory data indicated that the coefficient of performance (COP) of the heat pump and component efficiencies became increasingly sensitive to the magnitude of three-phase voltage input to the induction motors as drive frequency decreased from 60 to 15 Hz. A linear relation of volts per hertz yielded best compressor efficiency and thus best COP; however, for the indoor blower, the volts per hertz relationship was varied with speed for the best combination blower-and-blower-motor efficiency.

A VSI efficiency of only 85%, measured at 60-Hz drive frequency, caused the overall blower and drive system (blower motor and inverter) efficiency to drop 16.5% of efficiency measured with the blower driven by the M-G set. The isentropic efficiency of the compressor was observed at 15-Hz speed to be roughly 30% less than that measured with the ideal induction motor drive, due to the indirect effect of current harmonics on the compressor and compressor motor.

INTRODUCTION

Several methods of capacity modulation, such as cylinder unloading, hot-gas bypass, or multiple compressors, are employed in industrial applications to match the system capacity to the load. In residential use, these capacity modulation schemes are not as cost efficient as compressor speed control through use of inverters. Also, the efficiency of inverter drives is much better than other available speed control schemes (i.e., eddie current drives and cylinder unloading) especially for operation at reduced speed.

The combined efficiency of a standard production induction motor and inverter drive operating at base speed, full load was stated by Mohan (1981) to range from 80-90%. For constant torque applications, the combined motor-inverter efficiency was observed by Mohan to drop at 20% base speed to 70-80% for VSI drives and to roughly 60-70% efficiency for PWMI drives. Lloyd (1982) reported similar drops in efficiency with a PWMI drive; however, the motor-inverter efficiency with a VSI drive was roughly 50-60%. The drop in efficiency with the VSI reported by Lloyd was stated to be due to a less advanced VSI design.

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Both studies addressed only the bench test induction motor/inverter efficiency. For in situ heat pump applications with reciprocating compressors, it can be anticipated that the drop in efficiency reported in Mohan's and Lloyd's work may be larger due partly to the effect of inverter current harmonics in increasing the motor operating temperature and also to the resultant effect of increasing suction gas superheating prior to compression. The following results reveal the effect of adjustable speed drive on overall compressor isentropic efficiency and indicate the full magnitude of compressor efficiency losses resulting from an inverter drive.

For best COP and capacity control in a continuously variable speed heat pump (CVSHP), the indoor airflow would be modulated in some manner proportional to compressor modulation. Testing was also done to demonstrate proper control of the variable-speed induction motor of an indoor blower and also to quantify the effect of variable-speed drives on combined blower and blower motor efficiency as speed decreases.

LABORATORY FACILITY

A split-system air-to-air CVSHP that was commercially available in the early 1980s was breadboarded with various adjustable speed drives. The adjustable speed drives used in the study were

1. a six-step VSI,[a]
2. a PWMI[b] and
3. an M-G set.

In general, inverters have two sections: (1) a converter section that rectifies single-phase input AC voltage to DC voltage, and (2) an inverter section that inverts DC potential to variable voltage, variable frequency three-phase output potential. The six-step VSI rectifies and filters single-phase input voltage to adjustable DC voltage through the use of silicon-controlled rectifiers (SCRs). A six-thyristor inverter section is connected to a DC bus and sequentially switches the DC voltage at 120° intervals on three-phase output lines to create a six-step line to neutral voltage that approximates three-phase sine waves. The switching rate of the thyristors controls the output frequency and motor speed; however, the magnitude of output voltage is controlled by the SCRs in the converter section.

The PWMI differs from the VSI in that the inverter section controls both frequency and magnitude of output voltage. The PWMI rectifies single-phase input to constant potential DC. The DC voltage is then applied to the motor in a series of pulses to simulate three-phase current sine waves. Frequency and average voltage are controlled and harmonic content is minimized through proper control of the width and spacing of the voltage pulses.

The M-G set outputs a clean three-phase sine wave voltage; it was used as a basis of comparison for the inverter drives. The M-G set was designed for automatic control of both voltage and frequency output (i.e., voltage drop proportional to frequency drop, termed constant volts per hertz); it also has an external potentiometer circuit for the variation of output voltage independent of output frequency.

Compressor and Compressor Motor

The reciprocating compressor is hermetically sealed and has a rated capacity of 36.5 KBtu/h (10.7 kW)[c]. The compressor has dual pistons, and the total piston displacement is 3.64 in^3 (59.6 cm^3). The 2.75-hp (2-kW) compressor motor is a two-pole, three-phase, three-wire induction motor with y-connected stator windings. The compressor contains leaf spring valves

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[a]Commercially available in the early 1980s and supplied with the test unit.

[b]International product commercially available in 1983 and designed to have diminished harmonics and torque pulsation effects as compared with earlier design PWMI drives.

[c]Compressor rated at 45 F (7.2°C) evaporator; 120 F (48.8°C) condenser; 70 F (21.1°C) suction; 15 F (8.3 C°) subcooling.

and has a positive-feed oil pump for low-speed operation. The compressor was designed to operate in the heating mode from 15- through 90-Hz line frequency (i.e., 855 to 5130 rpm, assuming a slip difference of 150 rpm). However, in the cooling mode, the maximum speed was limited to 60 Hz (3420 rpm) due to possible damage to the compressor valves at high refrigerant flow rates as speed increases.

Indoor Blower and Motor

The indoor fan is a centrifugal blower that is 10 in (0.25 m) in diameter by 8 in (0.2 m) in width. The direct-drive blower is coupled to a 1/3-hp (0.25-kW) motor. The indoor blower motor is a six-pole, three-phase, three-wire induction motor with y-connected stator windings. The manufacturer of the blower specifies the indoor blower to have air-moving capacity of 1200 scfm (0.57 m^3/s) at 0.72 in (0.18 kPa) of external static pressure drop.

Test Stand

Testing of the indoor blower and compressor of the CVSHP was conducted in environmental chambers that are capable of controlling indoor and outdoor ambient dry-bulb and dew-point temperatures. A host computer and data acquisition system (DAS) were used to monitor all temperatures, pressures, powers, and flows. Single-phase refrigerant flow rate was measured in the liquid line using a turbine volume flow meter. Single-phase power input to the inverter drives was measured using thermal-watt converters.[d] Three-phase power input via a three-wire connection to the compressor was measured using a digital AC meter that was externally configured for a standard two-watt-meter measuring technique. Accuracy of measurement is stated as $\pm$0.5% of reading +0.1% of range for sinusoidal and nonsinusoidal (distorted) curves having frequencies ranging from 40 Hz through 1.2 kHz. Measurement accuracy of an identical instrument from 15-40 Hz was observed in a separate study by Cathey (1988)[e] to be within roughly 3% of a calculated calorimetric reference base.

EXPERIMENTAL PROCEDURE

Compressor tests

Initial testing was conducted with the compressor driven by the M-G set. Three-phase voltage, input to the compressor, was varied for line frequencies of 15, 30, 45, and 60 Hz to determine the effect of line voltage on compressor isentropic efficiency.[f] At each discrete compressor speed, the voltage applied to the motor was varied until a minimum load current was observed. An optimal volts per hertz relationship was developed and held constant for all testing with the M-G set.

Compressor testing was conducted with the CVSHP operating at previously determined optimal levels of refrigerant subcooling at condenser exit, indoor airflow, superheat at the inlet to the compressor, and refrigerant charge per compressor speed, which resulted in optimal COP (Miller 1987). Once optimal COP performance was observed with the compressor driven by the M-G set, the DAS, on command, monitored refrigerant-side and air-side steady-state data at 10-s intervals for a period of 0.5 hr. The test was then immediately repeated with the compressor operating under nearly identical refrigerant condensing and evaporating conditions (see Table 1) and driven by the PWMI drive.

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[d]Thermal converters contain an electrical circuit in which the difference of power dissipated in two heaters is proportional to the power measured.

[e]Personal communication: Dr. J. J. Cathey, University of Kentucky Research Foundaton.

[f]Compressor isentropic efficiency is defined here as the ratio of isentropic compressor work (based on shell inlet to exit conditions) to measured power input and includes the effects of motor performance.

Testing was also conducted for comparison of compressor performance when driven by a VSI and the M-G set. During these tests, the CVSHP operated with capillary tube restrictors (supplied with the heat pump by the manufacturer); as a result, optimal refrigerant subcooling at the condenser exit and superheat at the inlet to the compressor were not maintained for some test points.

The previously determined optimal volts per hertz relationship observed with the M-G set was maintained during testing with the PWMI and VSI drives. This was accomplished by setting the three-phase RMS voltage input to the compressor motor by the inverters to optimal RMS voltage tested with the M-G set operating at 60-Hz drive frequency. Each inverter then automatically controlled the volts per hertz as speed was reduced, similar to control with M-G drive.

Indoor blower tests

As was done in testing with the compressor, three-phase voltage input to the blower motor by the M-G set was varied for drive frequencies ranging from 20-60 Hz. An optimal volts per hertz relationship was developed. The resultant blower and blower motor performance was then compared with performance when the blower motor was driven by the M-G set adjusted for a constant volts per hertz relationship.

Indoor blower tests were repeated with the blower motor driven with a VSI. Comparison of combined blower and blower motor efficiency resulting from the two drives gave indication of the effect of inverter waveform on blower motor efficiency.

Inverter drives

The operation of the PWMI and VSI drives was characterized by measuring the time and frequency domains of the current output. Data were collected while the PWMI and VSI supplied power to the compressor operating under similar loads as in previous tests. Similarly, data were collected for the indoor blower motor driven by a VSI. A clamp-on current probe (1000:1 ratio) was connected to an output lead of the respective inverter, and a personal computer (PC) monitored the voltage drop across a precision resistor (i.e., voltage drop directly proportional to output current). The current pulsations and harmonic currents were analyzed as functions of line frequency for a quantitative indication of the characteristics of the waveforms provided by the inverter drives. Also, the motor slip[g] was measured through analysis of the harmonic spectrum from 0 to 200 Hz.

COMPRESSOR AND ADJUSTABLE SPEED DRIVE RESULTS

Motor control with constant torque

Studtmann (1970) analyzed the equivalent circuit for one phase of a three-phase induction motor operating at near rated load. He indicated that by applying a sinusoidal voltage (Vac) of frequency (F), the equivalent circuit could be reduced to a magnetizing inductance (X_m) and a load resistor.[h] The current into the magnetizing branch could be represented by the following equation:

$$i_m = \frac{Vac}{jXm} = \frac{1}{j2\pi L_m} \left(\frac{Vac}{F}\right), \qquad (1)$$

[g]Slip is the difference in rotating speed between the rotor and the magnetic flux field, which is at synchronous speed.

[h]Resistance in an equivalent circuit that represents mechanical shaft load.

where

i_m - magnetizing current producing stator flux,

Vac - AC voltage applied to load,

F - frequency of Vac,

L_m - energy in magnetic flux field (inductance),

X_m - magnetizing inductive reactance branch of magnetizing impedance,

j - mathematical operator indicating Vac leading i_m by 90°.

The magnetizing current (i_m) produces the magnetic flux in the motor air gap, which in turn produces the internal rotor torque. By the above equation, the magnetic flux is directly proportional to the voltage (Vac) and inversely proportional to the frequency (F). If the ratio of Vac/F is held constant as the frequency (F) (and motor speed) is reduced, then the magnitude of the magnetizing current (i_m) and magnetic flux and, therefore, the rotor torque will be constant. Therefore, operating with a constant Vac/F ratio would prevent magnetic saturation and excessive motor losses for induction motors operating over a range of constant torque loads.

Best Volts-per-Hertz Control

Due to the above sine-wave-driven characteristics for a three-phase induction motor with constant-torque load, cooling mode tests were conducted as a function of input voltage to the compressor to observe (1) the sensitivity of COP to applied voltage and (2) the Vac/F ratio that would yield best compressor efficiency (i.e., usable as an operating base for comparison of efficiency with inverter drives).

The COP of the CVSHP and compressor current draw are plotted in Figure 1 as a function of the compressor line voltage for compressor drive frequencies of 15-60 Hz. The COP at 60 Hz varied only 1% for a ± 10% variation of voltage about the optimal of 220 Vac. Similarly, a ± 10% variation about the optimal voltage, observed at minimum current draw, caused roughly a 1% drop in COP at 30-Hz speed and roughly a 4% drop in COP at 15-Hz speed. Results indicate variation of voltage input to the compressor has the largest effect on COP at 15-Hz compressor speed. At 60-Hz drive frequency, the stator winding resistance drop is only a small percentage of the applied voltage. However, as frequency is reduced with constant Vac/F, the stator resistance drop remains constant and becomes a large percentage of the applied voltage (i.e., the magnetizing current i_m becomes a larger portion of the total current draw). Therefore, a slight variation of input voltage will have a more pronounced effect on compressor efficiency and system COP. The results imply an inverter must compensate for any voltage variation from the power grid (i.e., control output voltage to motor) for optimal CVSHP efficiency at reduced speed.

The optimal voltages occurring at the minimal current draws produced a constant Vac/F ratio that was indicated by Studtmann (1970). It should be noted, however, that for field applications, Rice (1988) predicts that the load torque for a modulating reciprocating compressor in a CVSHP varies from 50-65% of nominal torque in the heating mode and from 60-100% of nominal torque in the cooling mode. Although minimizing current draw at each compressor speed would still produce optimum efficiency, the optimum Vac/F ratio would not be constant because of the variation of load torque. In recent work by Kirschen, et al. (1987), a prototype variable-speed induction motor controller was developed that yields optimum motor efficiency at any load torque and speed. The controller is based upon an adaptive adjustment of the rotor magnetic flux until input power is minimized while regulating the torque or the speed. Future work on optimal motor control systems responsive to motor load changes appears promising if rising energy costs make such controllers economically viable.

PWMI and M-G Drives and Compressor Efficiency

M-G Drives. Compressor overall isentropic efficiency for both heating and cooling mode optimal COP tests is plotted as a function of compressor speed in Figure 2. Compressor operating conditions are listed in Table 1 for the points depicted in Figure 2. The compressor isentropic efficiency remained fairly constant from 60 to roughly 20 Hz (i.e., 30% speed) with the compressor driven by the variable-frequency sinusoidal drive (i.e., M-G set). At 15-Hz speed, the efficiency decreased 20% of efficiency measured at 60 Hz.

These efficiency trends observed with the M-G drive are similar to results observed by Skogsholm (1978) in which the efficiency of induction motors in the 40- to 400-hp (30- to 300-kW) range, operating at constant torque, remained fairly constant down to about 20% speed and dropped rapidly to zero below 20% speed. The rapid drop in efficiency for constant torque application below 20% speed is partly due to the increase in the percentage of slip[i] assuming the motor core, stator winding, and friction losses remain constant. The total power delivered to the rotor can be expressed as follows:

$$P = \left(1 - \frac{S}{100} \right) W_{syn}\, T \tag{2}$$

where

- P = total power delivered to rotor,
- W_{syn} = synchronous speed,
- T = torque developed at rotor,
- S = unit slip, percentage difference between rotor rotating speed and W_{syn} using W_{syn} as a base.

From the expression and for measured slip in Table 2, a 3.9% unit slip at 60 Hz results in roughly a 3.9% loss in efficiency. However, at quarter speed (i.e., 15 Hz), the measured 15.5% unit slip would result in a 15% drop in efficiency. The fractional unit slip (S) is dissipated as rotor loss. These results show that operating at high unit slip results in inefficient induction motor operation.

PWMI Drive. Efficiency trends with the PWMI drive are similar to those observed with the M-G drive; however, the losses in compressor isentropic efficiency due to the PWMI drive increase as speed decreases. In Figure 2, results of testing at 60-Hz drive frequency and 40 F (21°C) outdoor temperature indicate that compressor efficiency, with the PWMI drive included, dropped 12% from that with the M-G drive. Roughly half of the efficiency degradation is due to efficiency losses in the PWMI (i.e., 5% loss), and the remainder is due to the effect of inverter harmonics on the compressor and motor as depicted by the efficiency loss curves in Figure 2. At 10 F (-12°C) outdoor temperature, the compressor isentropic efficiency at 60 Hz dropped 16% of efficiency with M-G drive. Similar results were also observed in the cooling mode for tests conducted at 82 F (28°C) outdoor temperature and 60-Hz drive frequency. These drops in efficiency at near full load agree with data presented by Mohan (1981).

At 15-Hz drive frequency, the compressor efficiency losses[j] due to the PWMI drive increase to 25% in the heating mode and to 35% in the cooling mode, as seen in Figure 2. The efficiency losses from only the inverter range in Figure 2 from 5% at 60 Hz, near full rated load, to 7.5% at 15 Hz, and therefore do not fully account for the total losses as speed is reduced. The observed increase in efficiency losses is a result of the effect of current harmonics on the induction motor of the compressor. The effect of these harmonics produced by the PWMI will vary with frequency and also with motor design (i.e., design of stator and rotor as well as air gap). The increase in induction motor losses due to inverter harmonics was attributed by Mohan (1981) to be principally the result of increased stator and rotor winding losses and stray load losses.

PWMI Current Waveform. Although a detailed analysis of these losses is outside the scope of this paper, the current waveform and current harmonics are plotted in Figures 3 and 4, respectively, for an indication of the in situ characteristics of the PWMI. Current waveforms at 15- through 90-Hz modulation frequency in Figure 3 depict the basic operation of a PWMI. As speed is reduced, the PWMI varied the width of the voltage pulse, reflected in current pulse (Figure 3) and spacing of the pulses for control of the inverter output frequency, voltage, and harmonic content. The difference in pulse width and rate for the test PWMI is easily seen in Figure 3 for 15-Hz vs 60-Hz frequency.

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[j] Compressor efficiency losses were calculated using resultant hermetic compressor isentropic efficiency with M-G drive as base.

[i] Slip is the difference in rotating speed between the rotor and the magnetic flux field.

PWMI Harmonics. This particular PWMI incorporated a microprocessor that varies the spacing of pulses as a function of frequency. The manufacturer states that this will minimize the harmonic content at each frequency as compared with earlier-design PWMIs. A Fourier analysis of the current waveform was conducted for review of the harmonic content at each frequency (Figure 4). At 15-Hz frequency, Figure 4 reveals the lower-order harmonics (i.e., fifth, seventh, and eleventh that are multiples of 15-Hz modulation frequency) to be minimal as compared with the higher-order harmonics (41st and 43rd). Similar results are also apparent at 30 Hz with the high-order harmonic components at the 29th and 31st fundamental easily seen in Figure 4. At 60- and 90-Hz frequency, these higher-order harmonic components were not present even with the harmonic frequency scale expanded to 2000 Hz. Results at 60- and 90-Hz frequency in Figure 4 indicate that the total harmonic content is composed of the low-order harmonics (i.e., third, fifth, seventh, and eleventh multiples of modulation frequency).

At speeds below 60 Hz, the low-order harmonics are reduced while significant high-frequency harmonics are introduced by the PWMI. It should be noted that these high-frequency harmonics can lead to excessive harmonic losses by imposing a series of high-voltage impulses on the motor windings (Andreas 1982). These harmonic currents tend to be concentrated in areas of high flux density and result in heat generation that increases motor winding temperature. This in turn would cause additional suction gas superheating prior to compression. Jacobs (1976) determined experimentally that as the amount of superheating increases, the effective compressor efficiency decreases [i.e., observed a 2% loss in compressor performance for every 10 F (5.5°C) rise in suction temperature]. Therefore, the harmonic content of the PWMI drive (a direct loss in motor efficiency) and the resultant additional suction gas superheating combine to give the drop in compressor isentropic efficiency shown in Figure 2.

VSI and M-G Drives and Compressor Efficiency

M-G Drive. The isentropic efficiency of the compressor was again measured with the compressor first driven by the M-G set and then by a VSI. The compressor operating conditions for these particular tests are listed in Table 3.

The isentropic efficiency and efficiency trends in Figure 5 for the compressor driven by the M-G set are nearly identical to those observed in Figure 2 despite the difference in optimal operating conditions for some test points. At 15-Hz frequency in the heating and cooling mode and at 30-Hz frequency in the heating mode, saturated refrigerant was observed entering the compressor and the refrigerant subcooling at condenser exit was not optimal (i.e., depicted in Figure 5 by open symbols of particular test points). Yet as seen in Figure 5, the efficiency at 15-Hz speed dropped roughly 20% of the 60-Hz efficiency, similar to results in Figure 2.

VSI Drive. Testing with the VSI drive caused a noticeable drop in compressor isentropic efficiency similar to the PWMI drive as compressor speed was reduced. At 60 Hz for both heating and cooling mode tests, the isentropic efficiency dropped 10% of efficiency measured with the M-G drive. A 50% speed reduction (i.e., 30-Hz speed) caused the compressor efficiency losses due to the VSI to increase to 30% for heating mode testing and to 20% for cooling mode testing. Further lowering of the compressor speed to 15 Hz resulted in even larger efficiency losses of roughly 35%. The increase in compressor efficiency losses as speed is reduced, shown in Figure 5, is again due to the effect of harmonics produced by the VSI drive.

VSI Harmonics and Current Waveform. The current waveform and current harmonics are plotted in Figures 6 and 7, respectively, for an indication of the performance of the VSI when driving the compressor motor. As seen in Figure 6, the switching sequence of the VSI is set at six times per cycle (i.e., six-step characteristic of VSI) for all modulating frequencies. Unlike the PWMI, the output voltage of the VSI is controlled by a DC bus. It should also be noted that the current waveforms at 60 and 90 Hz are similar for both VSI and PWMI drives, indicating that the PWMI is simply a variation of the VSI. At full load, the VSI has an efficiency of 95% as stated by the manufacturer. Mohan (1981) estimated that a VSI would cause an additional 1 to 2 percentage points reduction in motor efficiency when operated at full load. However, as speed and load decrease, the harmonic currents apparently cause increased compressor efficiency losses as seen in Figure 5. The VSI produced fairly high third, fifth, seventh, eleventh, and thirteenth harmonic currents for all modulation frequencies displayed in Figure 7. These harmonics do not contribute to the output torque and result in increased motor losses and motor temperature, both of which decrease the compressor isentropic efficiency. At 15- and 30-Hz modulation frequencies, the harmonic content is seen in Figure 7 to be higher than the content at 60 or 90 Hz. These trends, therefore, indicate the cause of compressor efficiency losses as speed is reduced from 60 to 15 Hz.

Comparison of Compressor Losses Due to the Inverters

The compressor efficiency loss curves in Figures 2 and 5 are plotted in Figure 8 for review of trends for specific models of both style inverters operating at nearly identical conditions. It must be noted that this comparison should not be generalized to all VSI vs PWMI due to the continuing advancement of both designs and the specific technologies of the components utilized. Also, the harmonic currents depicted in Figures 4 and 7 can be affected by the motor design. Mohan (1981) indicated induction motors with high values of leakage reactance (i.e., leakage flux through airgap that leads magnetizing current by 90°) will have less harmonic currents and lower harmonic losses. With due regard for the above caveats, results in Figure 8 show that in the cooling mode the compressor efficiency losses due to the PWMI were similar to losses due to the VSI. In the heating mode, the PWMI caused roughly 30% less compressor efficiency losses for drive frequencies of 20 and 30 Hz. Compared with the results shown by Skogsholm (1978) and Lloyd (1982), both of which compared PWMI with VSI, the microprocessor control of the PWMI voltage pulse rate reduced current harmonics and improved PWMI efficiency to levels comparable to, if not better than, VSI design of the early 1980s.

VSI AND M-G DRIVES AND BLOWER EFFICIENCY

Optimal Voltage Control

The indoor blower of the CVSHP was designed by the manufacturer to be driven by a separate VSI. The VSI was programmed at the factory to operate with a Vac/F ratio different from the constant relation observed for the compressor. This more optimal Vac/F relation for the blower motor was independently determined in the Energy Systems laboratory by varying the Vac output per blower speed and searching for minimal current draw (i.e., Vac was reduced at each speed until an inflection of current was observed). Combined blower and blower motor efficiencies were then compared with the blower driven by the VSI (with the manufacturer's built-in voltage control) and with the M-G set operating (1) with a constant Vac/F ratio and (2) with the Vac/F ratio found optimal in the laboratory.

Blower Efficiency with M-G Drive

The results of indoor blower tests conducted with the M-G set are displayed in Figure 9.

The optimal voltage observed at different blower motor speeds is reduced from the linear voltage relationship (i.e., Vac/F = constant) previously observed for the compressor. This occurs because the torque for a fan application varies approximately with the square of the fan speed (Rice 1988). As speed is reduced, the fan torque is much reduced compared with a constant torque application. These trends for a fan, therefore, require the input voltage Vac to be reduced at low speeds (i.e., light loads) in order to prevent magnetic saturation and excessive motor losses.

The optimal voltage control yielded noticeably better combined blower and blower motor efficiency than that measured with the M-G drive adjusted for constant Vac/F control. In Figure 9, the measured efficiencies are similar at 60 Hz for the two control schemes; however, the optimal voltage at 60 Hz was only 145 Vac as compared with 220 Vac for constant Vac/F control. The reduced optimal voltage may indicate that (1) the 1/3-hp (0.25-kW) motor was oversized and/or (2) the blower was not fully loaded (by lab measurements, it was not). Reducing the blower speed from 60 to 20 Hz caused the overall blower and blower motor efficiency to drop from 21% to 17% for optimal voltage control while efficiency dropped from 21% to 7% for control with constant Vac/F.

Blower Efficiency with VSI

The combined blower and blower motor efficiency measured with the voltage from the M-G drive optimally controlled was also compared with efficiencies measured with the blower driven by the VSI.

The blower and drive system (motor and inverter) efficiency trends for the VSI drive and for an assumed 100% efficient VSI drive, depicted in Figure 10, were calculated using measured single-phase input and three-phase output powers, respectively. The combined blower and blower

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TABLE 1
Compressor operating conditions for the optimal flow control test series

Compressor Operating Conditions	Heating mode 40 F (4°C) Outdoor temperature M-G	PWMI	Heating mode 10 F (-12°C) Outdoor temperature M-G	PWMI	Cooling mode 82 F (28°C) Outdoor temperature M-G	PWMI
	F / (°C)		F / (°C)		F / (°C)	
Drive frequency: 90 Hz						
Condensing temperature				95.2 (35.1)		
Evaporating temperature				-4.3 (-20.2)		
Drive frequency: 60 Hz						
Condensing temperature	103.5 (39.7)	103.0 (39.4)	87.4 (30.8)	86.6 (30.3)	116.3 (46.8)	117.1 (47.3)
Evaporating temperature	23.9 (-4.5)	23.4 (-4.8)	-1.1 (-18.4)	-2.4 (-19.1)	42.9 (6.1)	42.9 (6.1)
Drive frequency: 30 Hz						
Condensing temperature	96.0 (35.6)	96.3 (35.7)			102.9 (39.4)	102.1 (38.9)
Evaporating temperature	30.7 (-0.7)	30.7 (-0.7)			53.0 (11.7)	53.7 (12.1)
Drive frequency: 20 Hz						
Condensing temperature	89.0 (31.7)	88.3 (31.3)				
Evaporating temperature	32.5 (0.3)	33.0 (0.6)				

TABLE 2
Unit Slip Measured for the Induction Motor of the Compressor Driven by Various Adjustable-Speed Drives

Modulation Frequency (Hz)	Unit Slip[a] (%) for Adjustable-Speed Drives M-G[b] Set	PWMI[c]	VSI[d]
60	3.97	3.98	4.10
30	7.18	7.75	7.48
15	15.50	17.63	

[a]Unit slip is the percentage difference between rotor rotating speed and synchronous speed using synchronous speed as the base.
[b]Motor-generator drive.
[c]Pulse-width modulating inverter.
[d]Voltage source, six-step inverter.

TABLE 3
Compressor Operating Conditions
for the Capillary Flow Control Test Series

Compressor Operating Conditions	Heating Mode 40 F (4°C) Outdoor Air Temperature		Cooling Mode 82 F (28°C) Outdoor Air Temperature	
	M-G	VSI	M-G	VSI
	F / (°C)		F / (°C)	
Drive frequency: 60 Hz				
Condensing temperature	100.9 (38.3)	101.3 (38.5)	120.6 (49.2)	121.0 (49.4)
Evaporating temperature	24.8 (-4.0)	24.5 (-4.2)	42.6 (5.9)	39.0 (3.9)
Drive frequency: 45 Hz				
Condensing temperature	94.8 (34.9)	96.3 (35.7)	112.2 (44.6)	116.1 (46.7)
Evaporating temperature	27.9 (-2.3)	29.2 (-1.6)	47.5 (8.6)	48.0 (8.9)
Drive frequency: 30 Hz				
Condensing temperature	89.6 (32.0)	90.3 (32.4)	102.8 (39.3)	108.4 (42.4)
Evaporating temperature	32.5 (0.3)	34.7 (1.5)	54.4 (12.4)	55.2 (12.9)
Drive frequency: 15 Hz				
Condensing temperature	79.9 (26.6)	80.1 (26.7)	90.4 (32.4)	88.1 (31.2)
Evaporating temperature	37.6 (3.1)	39.4 (4.1)	61.7 (16.5)	58.3 (14.6)

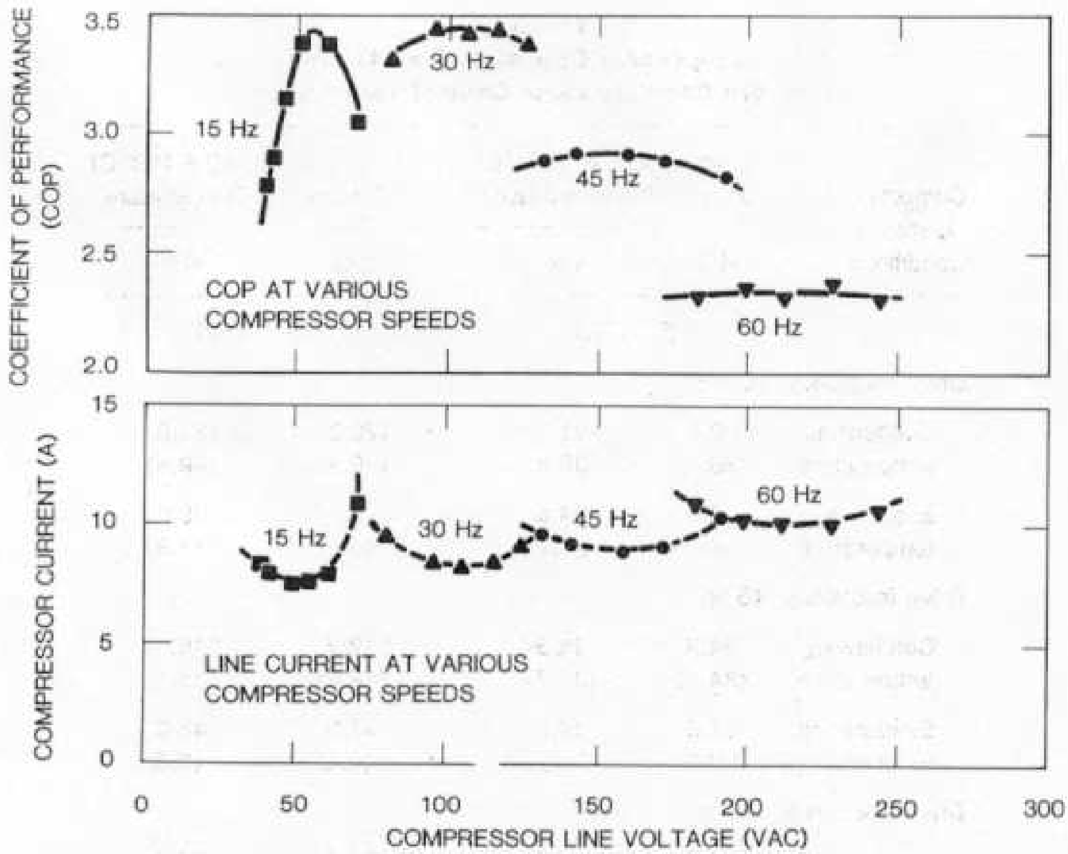

Figure 1 COP and compressor current as affected by three-phase voltage for cooling mode test conducted at 82 F (28°C) outdoor temperature

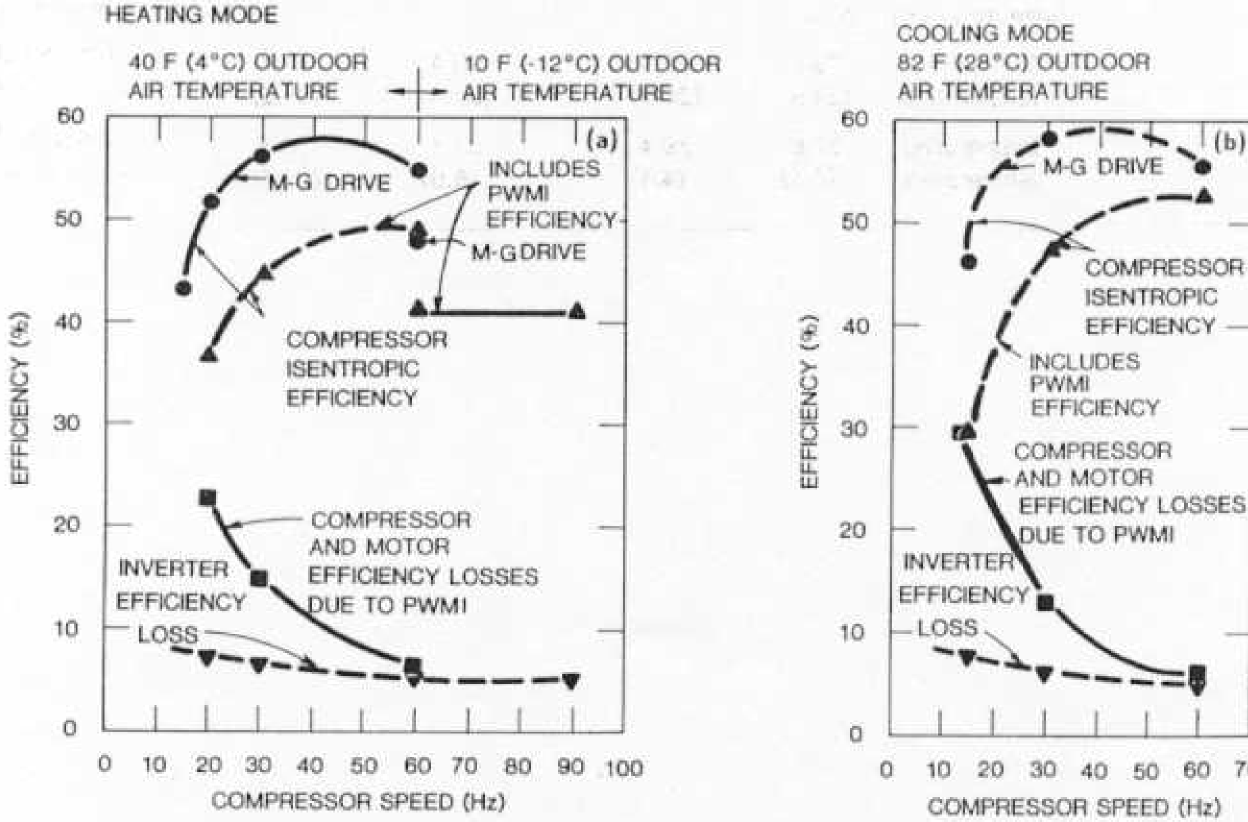

Figure 2 Compressor isentropic efficiency and efficiency losses measured during steady-state optimal COP testing of the CVSHP

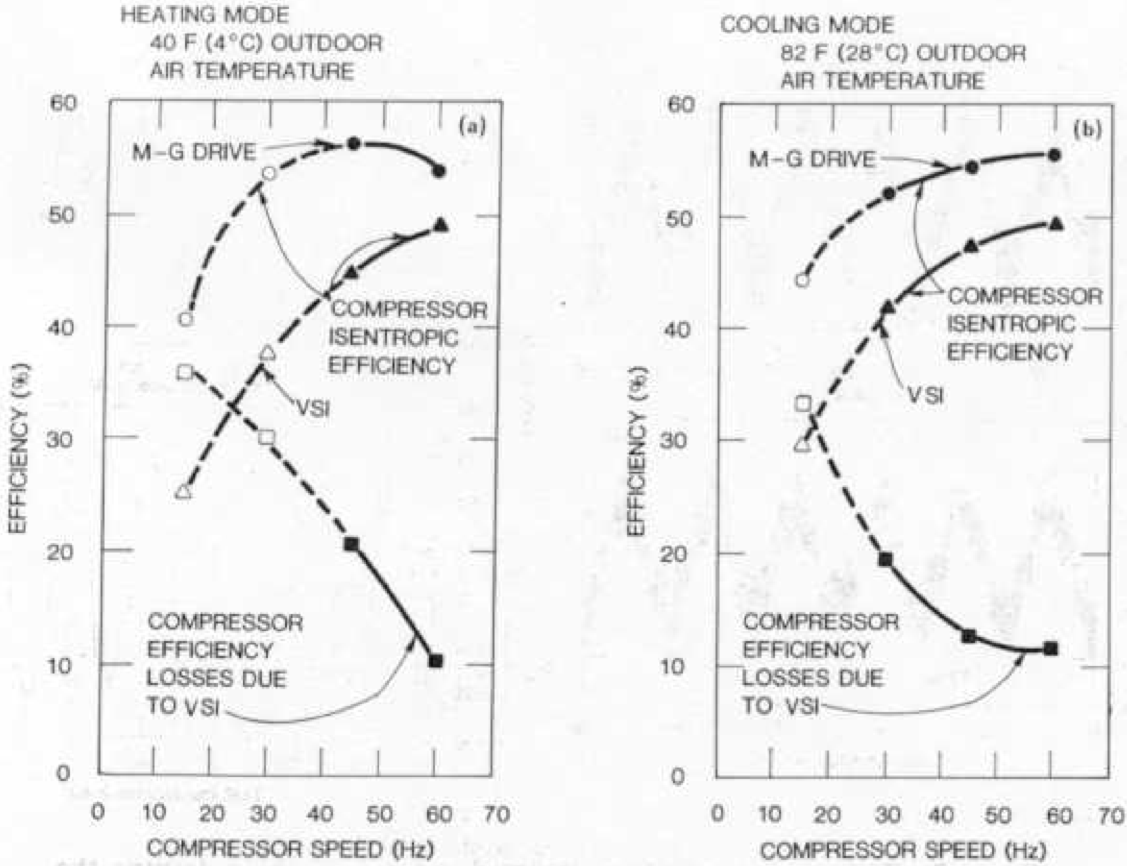

Figure 5 Compressor isentropic efficiency and efficiency losses measured during steady-state testing of the CVSHP.

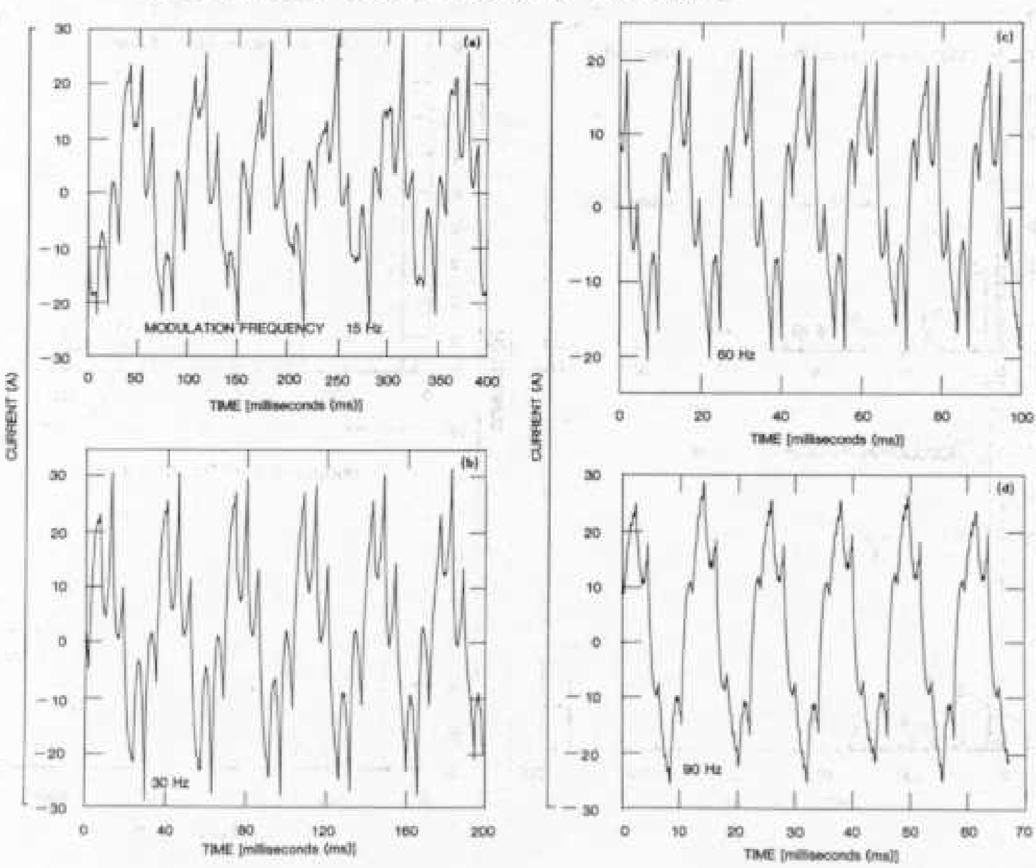

Figure 6 VSI current waveform observed under load while driving the compressor

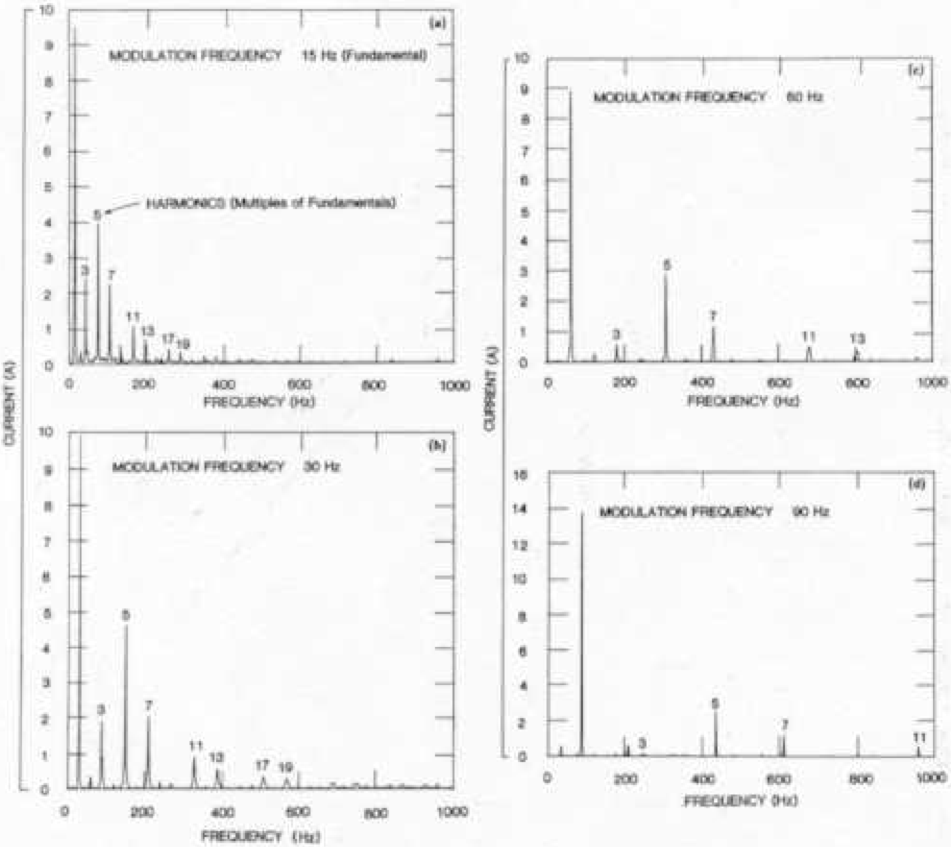

Figure 7 The VSI harmonic currents observed while the VSI powered the compressor

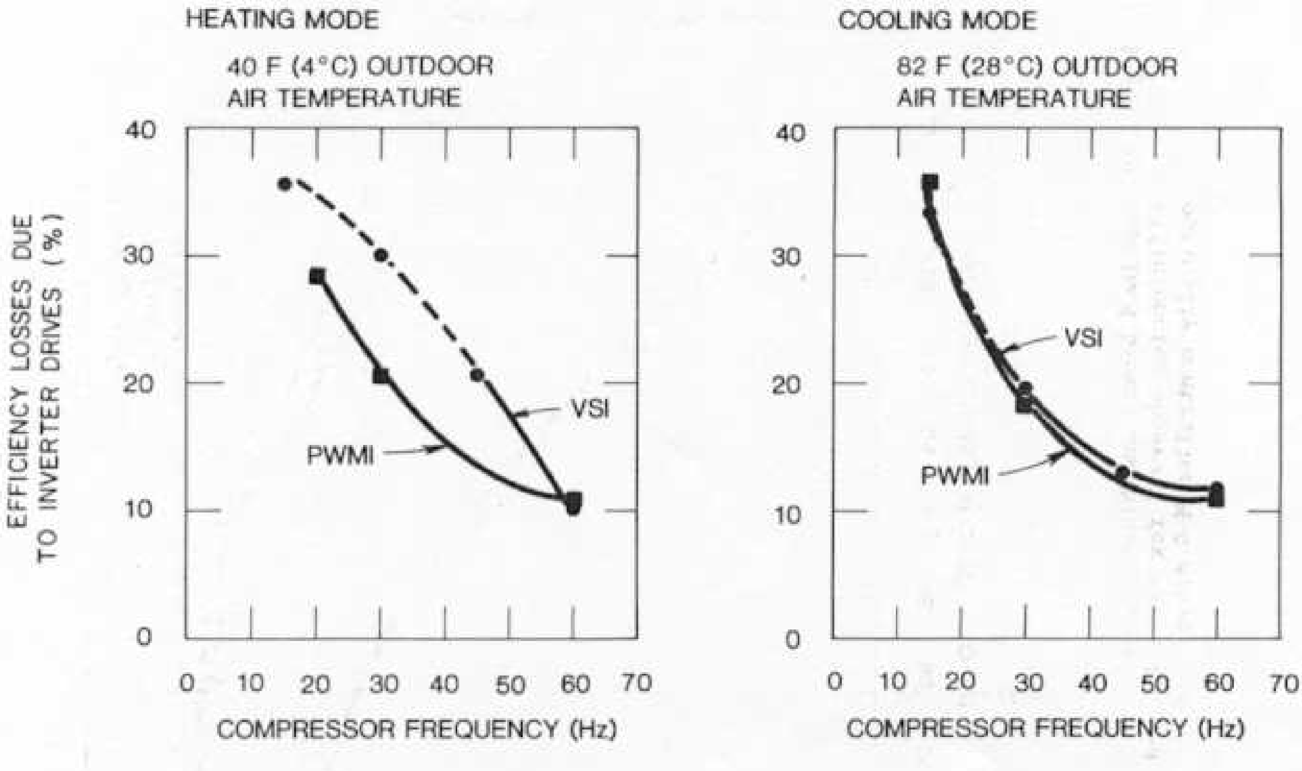

Figure 8 Comparison of combined compressor motor and inverter efficiency losses

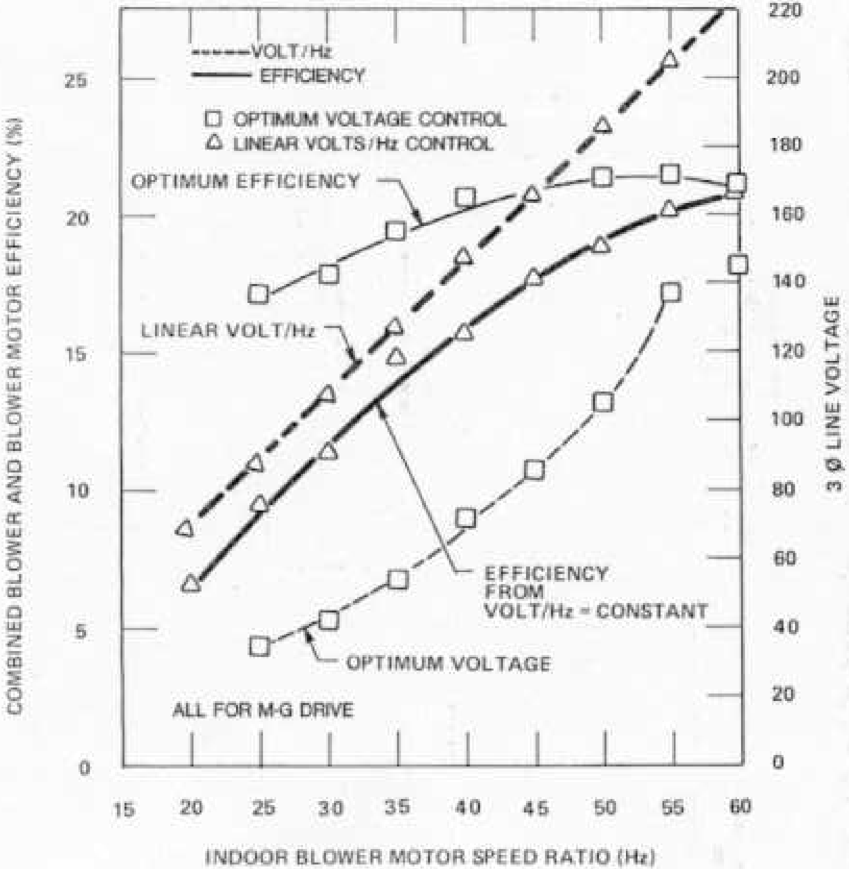

Figure 9 Combined blower and blower motor efficiency and optimal voltage control as function of modulation frequency

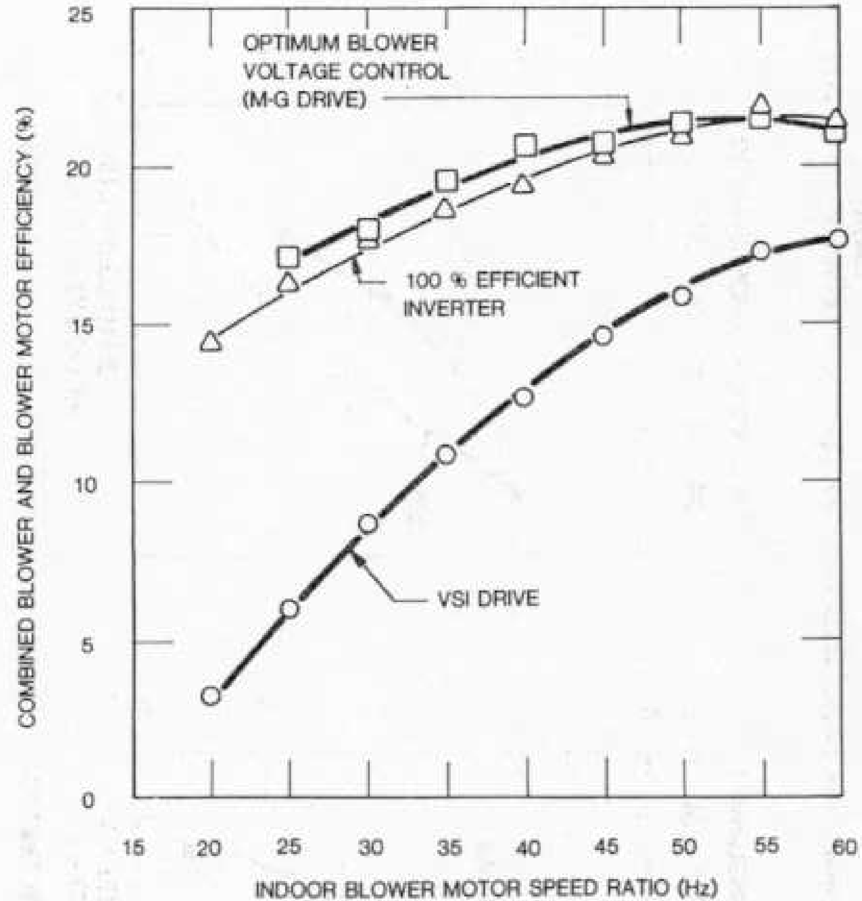

Figure 10 Combined blower and blower motor efficiencies observed for VSI drive and optimally controlled M-G drive

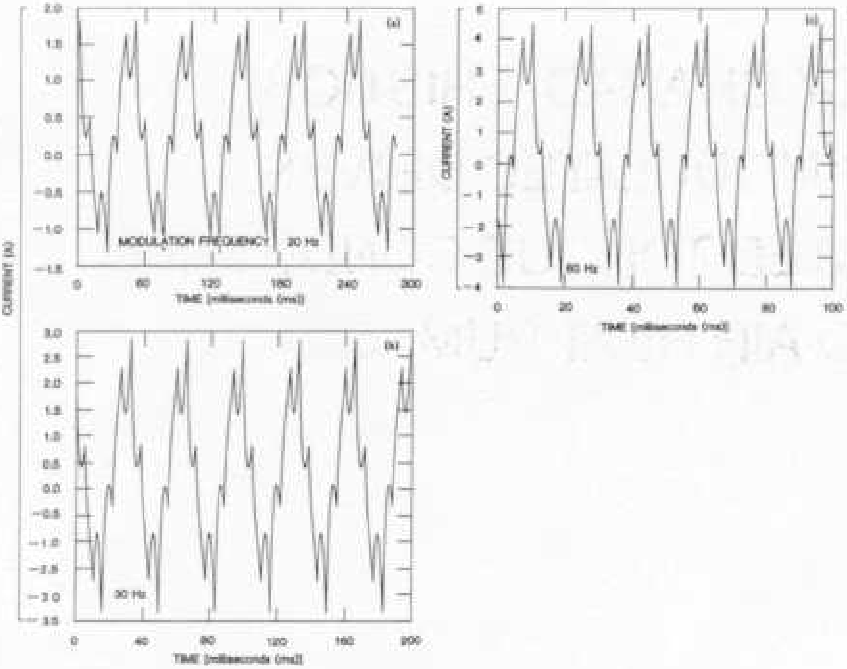

Figure 11 VSI current waveform observed while driving the indoor blower

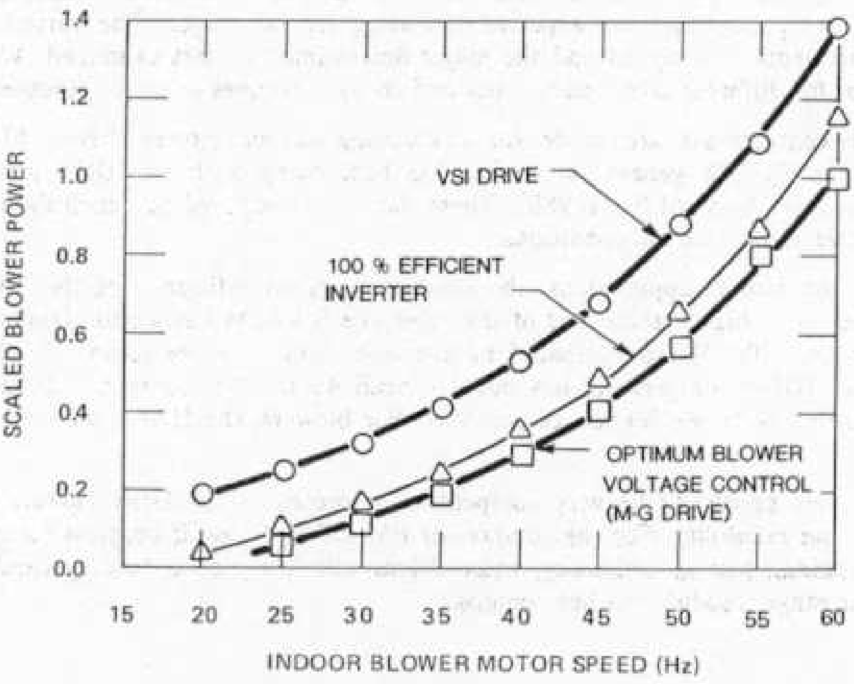

Figure 12 Power consumption of the indoor blower scaled to blower power measured at 60 Hz with optimally controlled M-G set