1994

Investigation of the Effect of Inverters on the Power Supply and the Performance of Variable Speed Refrigeration Systems

T. Q. Qureshi
Brunel University

S. A. Tassou
Brunel University

INVESTIGATION OF THE EFFECT OF INVERTERS ON THE POWER SUPPLY AND THE PERFORMANCE OF VARIABLE SPEED REFRIGERATION SYSTEMS

Mr T Q Qureshi and Dr S A Tassou
Department of Mechanical Engineering
Brunel University
Uxbridge, Middlesex UB8 3PH, UK

ABSTRACT

This paper reports the results of an experimental investigation into the characteristics and effects of a PWM inverter on the power supply and overall performance of a capacity controlled refrigeration system employing a positive displacement compressor. The results indicate that the efficiency of variable speed refrigeration systems at part load is severely affected by the poor performance of induction motors. The efficiency of the inverter was found to be high, approximately 95%, and to remain approximately constant over the speed and load range tested. The harmonic analysis showed that the total current harmonic distortion on the supply side increased with a decrease in speed and load. This can cause power quality problems and can contribute to a reduction in the power factor, resulting in high circulating current and lower efficiency. It has been found that the net efficiency gains from variable speed operation at part load conditions are not significant enough to outweigh the higher capital cost of the system and overcome the concerns about the effects of the inverter on the supply and the motor. The attractiveness of positive displacement variable speed refrigeration systems will increase considerably if motors are developed whose efficiency remains fairly constant at part load conditions.

Nomenclature

AHD	=	Current Harmonic Distortion, %
VHD	=	Voltage Harmonic Distortion, %
THD	=	Total Harmonic Distortion, %
IDC	=	Inverter Driven Compressor
MDC	=	Mains Driven Compressor
PWM	=	Pulse Width Modulation
rms	=	Root Mean Square
OF	=	Operating Frequency, Hz
Arms	=	rms Current, amps
Vrms	=	rms Voltage, volts
Vf	=	Fundamental Voltage, volts
Af	=	Fundamental Current, volts

INTRODUCTION

Traditionally, the capacity of single compressor refrigeration and air conditioning systems was matched to the load by one of a number of control methods such as on/off control, cylinder unloading and hot-gas by pass. The main disadvantage of these methods is that reduction in capacity is not accompanied by a corresponding reduction in the power consumption of the compressor. Capacity variation through the control of the compressor motor speed offers the potential for significant energy savings compared to the other methods of capacity control but its application so far to commercial refrigeration systems has produced only a variable degree of success. The main problems associated with inverter based variable speed capacity control include:

- injection of voltage harmonics to the motor which tend to heat up the motor windings and reduce its efficiency

- introduction of high harmonic contents of the input current to the supply side and emission of electromagnetic and acoustic noise
- high initial cost due to the relatively high cost of the inverter
- reduced reliability due to inadequate lubrication and cooling of the compressor at low speeds.

This paper investigates some of the effects of an inverter based variable speed drive on the performance characteristics of a commercial refrigeration system. The refrigeration system employs a suction cooled semi-hermetic compressor driven by a PWM inverter and induction motor combination. The objective is to analyze the effects of the inverter on the performance of the system and quantify overall system efficiency under variable speed and pressure ratio conditions.

EXPERIMENTAL TEST FACILITY

The investigations were carried out on an experimental test facility designed for refrigeration research in accordance with British Standard BS 3122 which is identical to the ISO 917:1989 'Testing of refrigerant compressors' [1]. The facility provides a flexible and reliable system for repeatable testing of inverters and compressors. A packaged chiller of 25 kW nominal cooling capacity was modified to incorporate a 4 cylinder suction gas cooled reciprocating compressor, a PWM inverter and associated control circuitry and to allow for variable speed operation through the inverter and for fixed speed operation directly through the mains supply. A PC based data logging system and comprehensive instrumentation enables recording of refrigerant pressures and temperatures at 4 points in the refrigeration circuit, refrigerant flow rate, and water temperature and flow rates across the condenser and evaporator in the water circuit. A power analyzer and its associated data logging system records all relevant data on power consumption. Both fundamental and true rms values of total, apparent and reactive power, voltage, current and power factor were recorded. The total harmonic distortion of the voltage and current waveforms on each phase at input and output of the inverter was determined by taking into account the initial 50 harmonics.

The performance of the inverter driven semi-hermetic compressor was investigated over an operating frequency range between 25 Hz and 60 Hz, at an evaporating temperature of 6°C, a range of condensing temperatures and a refrigerant superheat temperature of 10°C. The inverter tests were conducted at a constant switching frequency of 2.9 kHz, fixed voltage boost of 5.1% and fixed slip compensation of 0.0 Hz.

RESULTS AND DISCUSSION

Current and Voltage Waveforms with their Relative Harmonic Components

One of the important characteristics of a load is the wave shape of the current drawn from a sinusoidal supply voltage. The current and voltage waveforms with their relative harmonic components at the base frequency of 50 Hz and at a low frequency of 25 Hz were analyzed at input and output of the inverter. The waveforms on the VSD supply side at the base frequency are shown in Figure 1(a). The voltage waveform has a total harmonic voltage distortion of 2.66% of the fundamental, at a fundamental voltage of 236 V which is nearly equal to the rms voltage. The current waveform, however, was highly distorted with a total harmonic current distortion of 116% of the fundamental, at a fundamental current of 10.82 A and rms current of 16.13 A. The relative harmonic spectra are shown in Figure 1(b), which shows that the very small harmonic voltage associated with the 5th, 7th and 11th harmonics causes only a small voltage distortion, whereas the large harmonic currents associated with the 5th, 7th, 11th and 13th harmonics exceed considerably the limits imposed by BS 5406 [2]. The total harmonic current at base frequency was 11.96 A.

The waveforms on the motor side are shown in Figure 1(c). The voltage waveform shows a VHD of 2.22% of the fundamental, at a fundamental voltage of 231.2 V and rms voltage of 266.4 V. The large difference in fundamental and rms voltage indicates that the voltage waveform contains a significant proportion of high switching frequency components. The total harmonic voltage at this operating condition was 132.34 V. The current waveform on the motor side shows an AHD of 1.92% of the fundamental, at a fundamental current of 13.02 A and rms current of 13.08 A. The relative harmonic spectrum shown in Figure 1(d) indicates that almost all harmonic components within the tested range are contributing small harmonic voltage to the total VHD. The harmonic current spectrum shows that all the harmonics are well within the limits imposed by BS 5406. The total harmonic current distortion at the inverter output was nearly the same as that present on the mains (sinusoidal) supply.

Figure 2(a) shows the waveforms on the supply side at the lower operating frequency of 25 Hz. The voltage waveform shows no significant change from that at 50 Hz with a VHD of 2.65%. The harmonic current distortion, however, increased to 142% with the decrease in operating frequency at a fundamental current of 4.9 A and rms current of 8.52 A. The relative harmonic spectra on the supply side are shown in Figure 2(b) which indicate the same trend as that established at the base frequency of 50 Hz. The percentage harmonic current contribution of the individual harmonics increased at the lower frequency, however, leading to an increase in the total AHD.

The waveforms on the motor side are shown in Figure 2(c). The voltage waveform was highly distorted with a VHD of 35.16% of the fundamental at a fundamental voltage of 123.9 V and rms voltage of 209.3 V. The distortion in the current waveform was not affected by the decrease in operating frequency and shows an AHD of 1.94% of the fundamental at a fundamental current of 11.5 A and rms current of 11.58 A. The relative harmonic spectra are shown in Figure 2(d). The harmonic current spectrum on the motor side shows that all the harmonics are very small and well within the limits of BS 5406.

Total Harmonic Distortion (THD)

The total harmonic distortion (THD) for the inverter driven compressor (IDC) and the mains driven compressor (MDC) is shown in Figure 3. The THD was calculated using the following equation.

$$THD=\sqrt{H2^2+H3^2+H4^2+\dots\dots\dots\dots H50^2}$$

where, H2 is the 2nd harmonic in %, H3 is the 3rd harmonic in % and so on up to the 50th harmonic.

It can be seen that the THD is much higher for the IDC than the MDC. The THD for the IDC decreased from 124% to 110% as the pressure ratio increased from 2.5 to 5 whereas the THD for the MDC remained fairly constant at about 6% over the same pressure ratio range. The effect of speed and load on the THD are shown in Figure 4. It can be seen that at any speed the difference in THD remains fairly constant between the two loading conditions and the THD is strongly influenced by speed, increasing by about 40% as the speed was reduced from 60 Hz to 20 Hz.

Effect of Pressure Ratio on Power Consumption

The power associated with the energy that is converted and consumed by the system is referred to as true power or real power. The true power (kW) absorbed by the load with distorted waveform was measured at various operating conditions. This is the actual power that is converted into mechanical work. True power is sometimes referred as real power or active power (active power conforms to IEEE designation).

The total real power (kW) absorbed by the load increases with the pressure ratio due to the increase in load as shown in Figure 5. The percentage increase is higher in the inverter operated system (47%) compared to the mains operated system (43%). This is due to the additional power dissipation losses in the inverter. These losses, compared to mains operation, increased from 3.5% at low load (pressure ratio of 2.5), to 6.25% at high load (pressure ratio of 5), decreasing the efficiency of the inverter from 97% to 94%.

Overall Performance Characteristics

The overall COP of the IDC and MDC is shown in Figure 6. As expected, the COP decreased with an increase in the pressure ratio. The slightly lower COP for the IDC is due to the power losses in the inverter.

The effect of speed on the COP at two different loading conditions is shown in the Figure 7. It can be seen that the system exhibits maximum COP at a given speed, around 40 Hz. The decrease in the COP at speeds below 40 Hz is mainly due to increased harmonic distortion and a considerable reduction in the motor efficiency. The reduction in the COP at speeds above 40 Hz can be attributed to increased friction losses and pressure losses across the valves.

CONCLUSIONS

The investigations on the inverter driven variable speed refrigeration system have shown that the inverter generates harmonics which lead to increased losses in the motor compared to direct mains operation. The harmonic contents of the 5th, 7th, 11th and 13th harmonic number mainly contribute towards THD. The magnitude of these harmonic components varies with the frequency and pressure ratio. The THD exceeded the maximum permissible limits over the entire speed range tested. The total voltage harmonic distortion on the supply side was found to be less than the 5% and within the acceptable limits imposed by international standards.

The efficiency of the inverter remained constant at approximately 95% over the range of speeds and loads tested. The reduction in the system COP at speeds below 40 Hz was mainly due to the reduction in the motor efficiency at low speeds. This seems to be a very significant factor in the design of variable speed refrigeration systems. For maximum efficiency at part load conditions electric motors are required which exhibit a fairly constant efficiency characteristic with speed.

REFERENCES

[1] British Standard BS 3122 : Part 1 : 1990 "Methods of test for Performance".

[2] British Standard BS 5406: Part 2 : 1988 "Disturbances in Supply Systems caused by Household Appliances and Similar Electrical Equipments"

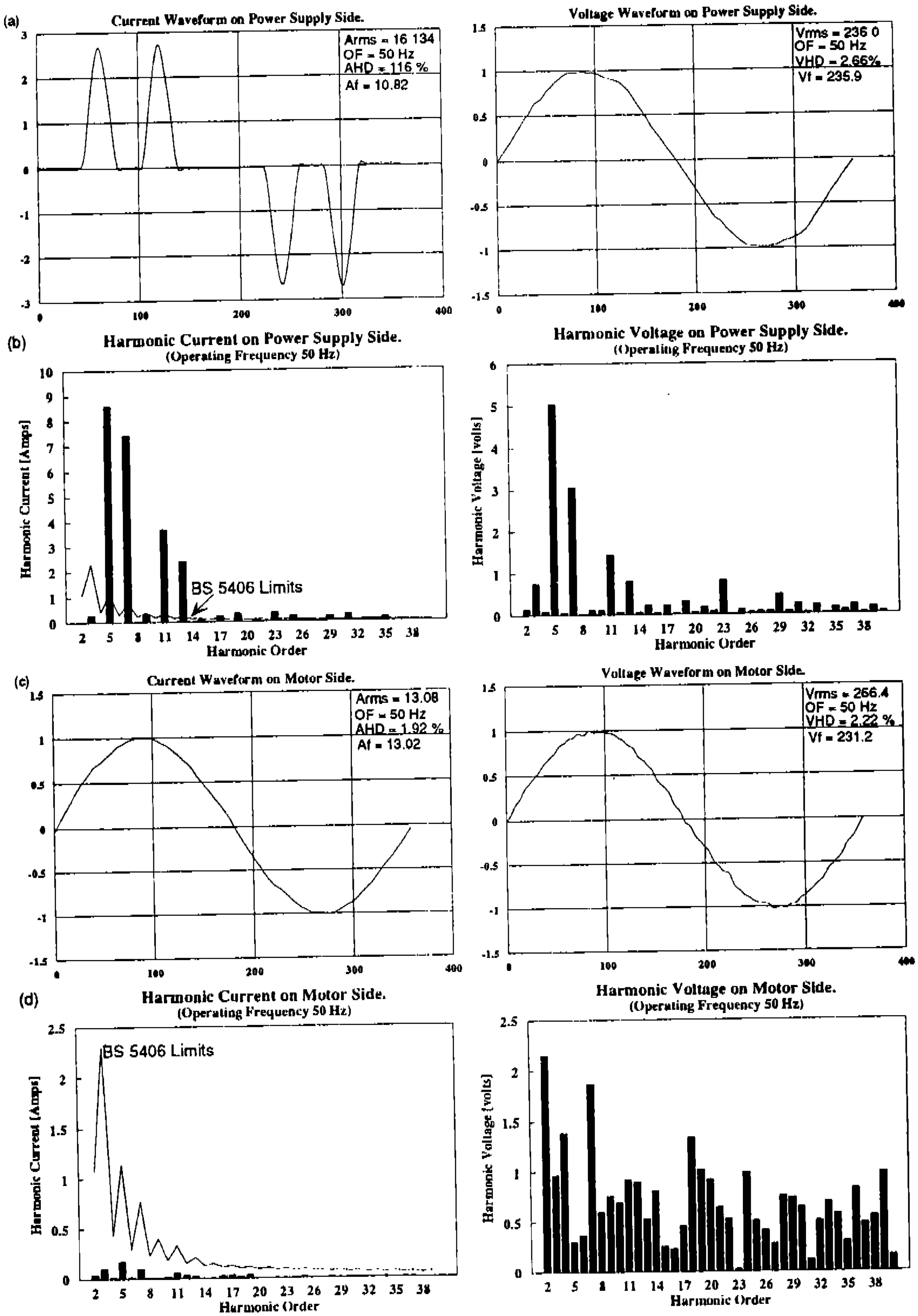

Figure 1. Current and Voltage Waveforms with Their Relative Harmonic Components at 50 Hz.

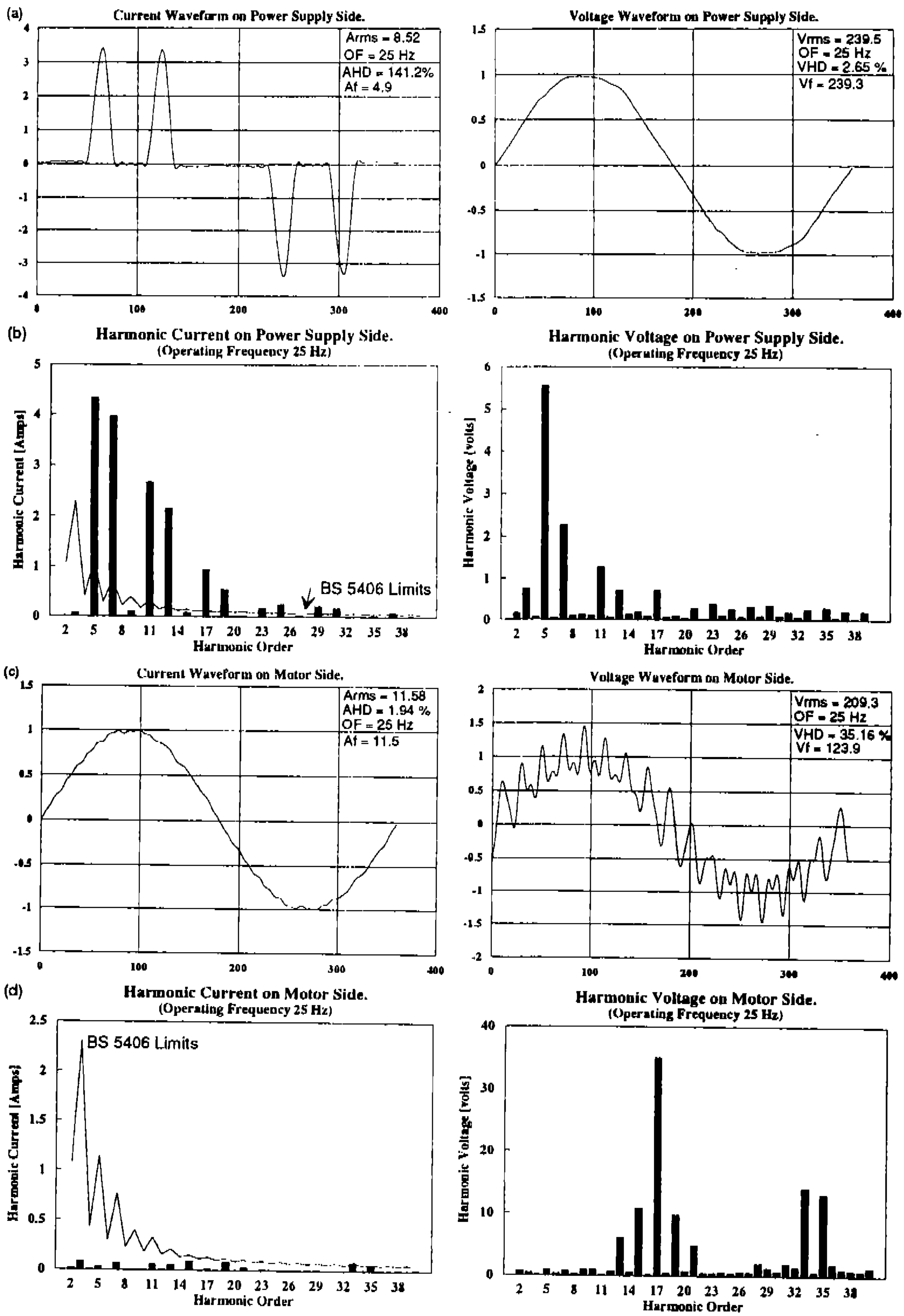

Figure 2. Current and Voltage Waveforms with Their Relative Harmonic Components at 25 Hz.

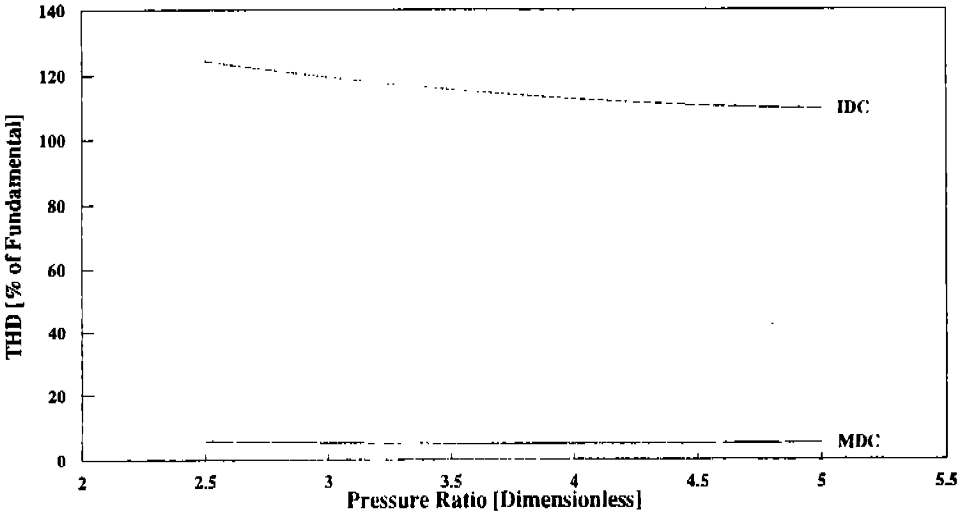

Figure 3. Effect of Loading Conditions on the Total Harmonic Current Distortion at Rated Speed.

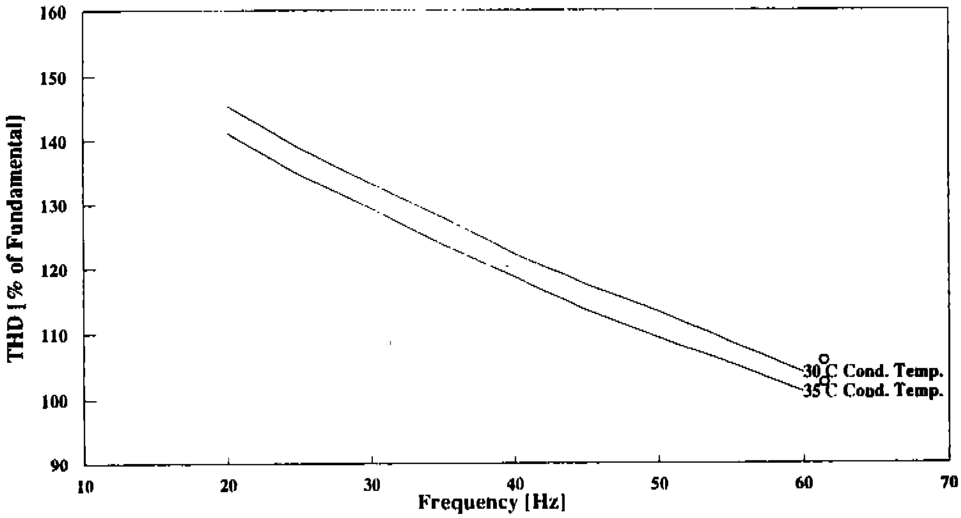

Figure 4. Effect of Operating Frequency and Loading Conditions on the Total Harmonic Current Distortion.

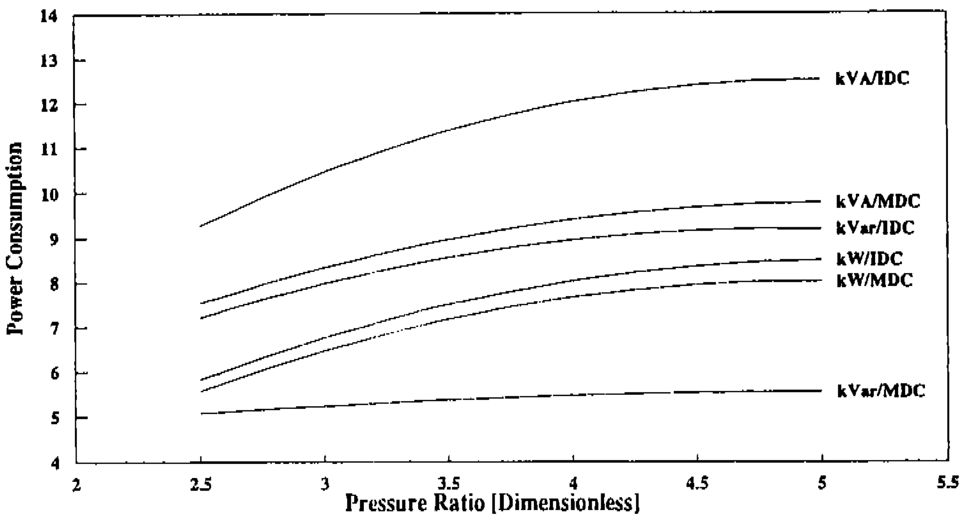

Figure 5. Effect of Loading Conditions on the Real, Apparent and Reactive Power at Rated Speed.

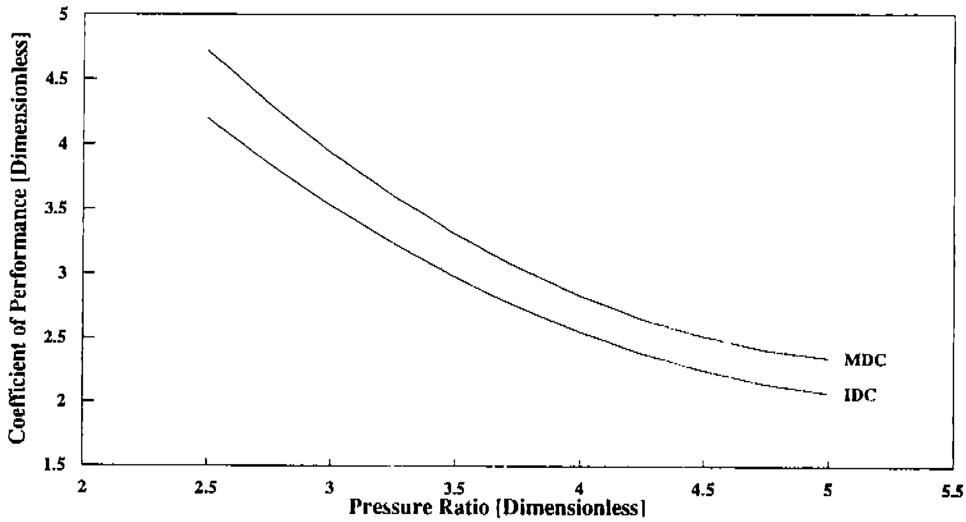

Figure 6. Effect of Loading Condition on the Coefficient of Performance at Rated Speed.

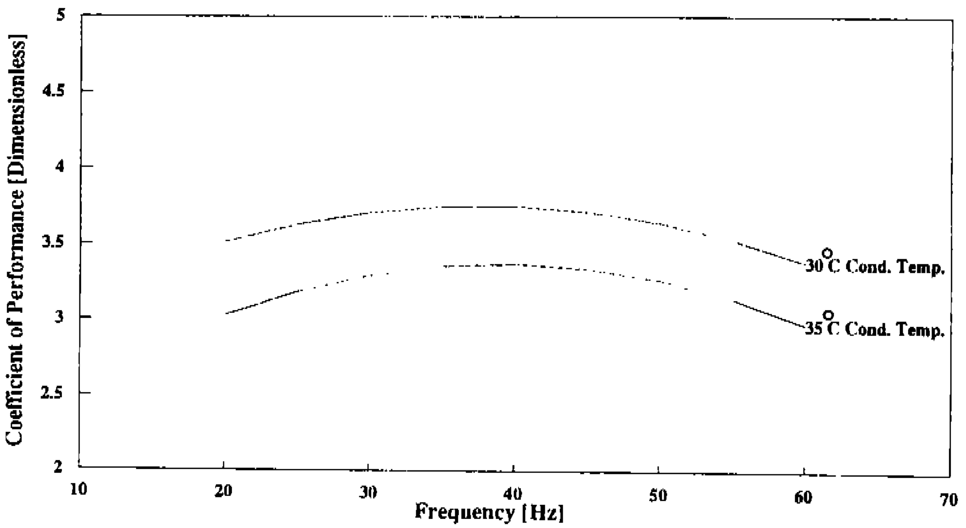

Figure 7. Effect of Compressor Operating Frequency on the Coefficient of Performance of Variable Speed Compressor.