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REVIEW PAPER

VARIABLE-SPEED CAPACITY CONTROL IN REFRIGERATION SYSTEMS

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Abstract—This paper presents a review of the application of variable-speed capacity control to refrigeration systems. The aim is to put together diversified information in a single source and to appraise recent advances in variable-speed technology. The review reveals that although variable-speed drives based on inverters have been applied successfully to control the capacity of rotodynamic machines, such as pumps and fans, their application to positive displacement machines, such as compressors, has so far been restricted to small-capacity air-conditioning units. There has been only a very small uptake of the technology in the medium-range capacity units, due to a number of problems, such as insufficient development and integration of components, poor reliability, high capital cost and the failure of demonstration installations to produce the expected energy savings. Although inverter-based variable-speed compressor technology offers the potential for energy savings, considerable research work is still required for the development of optimised and cost-effective systems.

Keywords—Refrigeration, variable-speed control, inverters.

NOMENCLATURE

EER energy efficiency ratio
SEER seasonal energy efficiency ratio
TEV thermostatic expansion valve
PWM pulse width modulation
VSI voltage source inverter
CSI current source inverter
COP coefficient of performance

INTRODUCTION

The inefficient use of electricity to drive the compressors of refrigeration and air-conditioning systems is regarded as an indirect contributor to the emission of greenhouse gases to the atmosphere. These emissions can be reduced by improving the energy conversion efficiency of refrigeration systems. One method of achieving this is through capacity control, which matches the system capacity to the load. Capacity control reduces the on/off cycling losses of the equipment and improves the steady-state efficiency of the plant due to a lower pressure differential across the compressor at part-load conditions [1].

Compressor capacity control techniques can be employed either within or outside the compressor but their basic function of varying the refrigerant flow-rate in the cycle remains the same. Capacity control methods commonly employed are: on/off control, hot gas bypass, evaporator temperature control, clearance volume control, multiple compressor control, cylinder unloading and variable speed control. Theoretical comparison of various capacity control methods at full- and part-load conditions in Fig. 1 shows variable speed as being the most energy efficient technique [2, 3].

The application of variable-speed capacity control to refrigeration and air-conditioning systems has been under consideration over the last 20 yr. Although its capacity modulation features have been proven in small-capacity systems, there are still a number of problems which impede its implementation in medium-size systems. These problems include:

1. Insufficient development and integration of compressors and variable-speed drives.
2. Relatively high cost due to the use of general-purpose variable-speed drives.

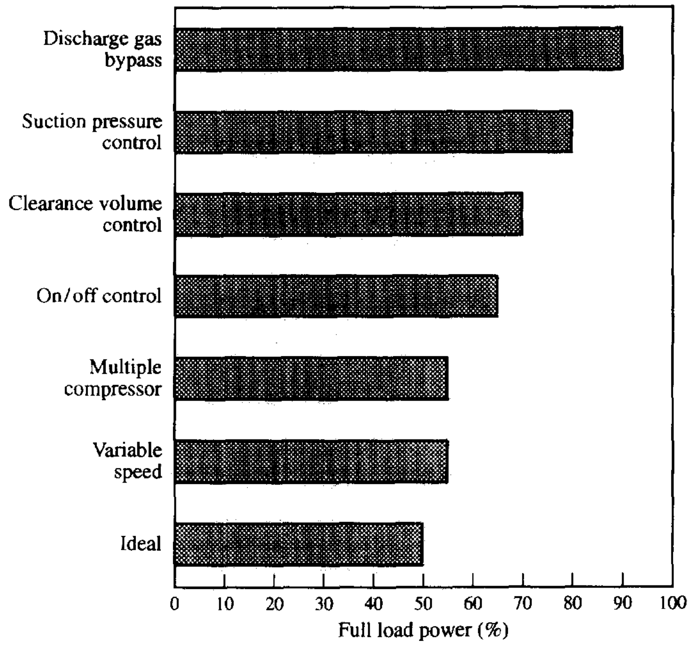

Fig. 1. Comparison of various capacity control techniques at half load.

3. Insufficient information from manufacturers on the performance characteristics of variable-speed systems.
4. Failure of demonstration installations to produce the expected energy savings.
5. Poor reliability of initial installations caused by unsophisticated and inadequately developed control systems.

Research at Brunel University aims to provide answers to some of the above uncertainties, to identify the most suitable compressor and VSD technologies for variable-speed operation and to develop control strategies for the cost-effective integration of these technologies.

This paper presents an in-depth look into the whole subject by compiling previous published information on the development of the technology. The review addresses both the mechanical and electrical aspects of variable-speed capacity control.

REFRIGERATION CAPACITY CONTROL THROUGH COMPRESSOR SPEED MODULATION

The basic difference between variable-speed refrigeration and conventional refrigeration systems is in the control of the system capacity at part-load conditions. In variable-speed refrigeration the capacity of the refrigeration system is matched to the load by regulating the speed of the compressor motor in such a way that the capacity of the system tracks the load dictated on it by varying operating conditions. Variable-speed control can be realised in a number of ways, which can be divided into two groups. Firstly, those in which the load is indirectly coupled to the motor (a constant-speed motor and a speed-control device between the motor and the load) and, secondly, those in which the load is directly coupled to the motor (a variable-speed motor). The first group further subdivides into mechanical, hydraulic and electrical systems and the second group into d.c. drives, switched reluctance drives, multi-speed motors, Ward Leonard sets and electrical variable-speed drives. The advantages and disadvantages of each group of capacity control methods have been discussed in greater detail in ref. [4]. In refrigeration applications, stepwise or infinitely variable control of the motor speed are considered to be the most flexible methods of speed control and significant energy savings have been reported through their application [5, 7–10].

Stepwise speed control can be achieved by using multi-pole electric motors. The required compressor capacity is obtained by switching a finite number of poles to achieve the desired speed.

Stepwise control is less costly than continuous speed control but step-controlled motors have lower efficiency than constant-speed motors [3]. Moreover, this method of speed control has the limitation of a fixed number of speeds, which offers restricted compressor capacity control compared to continuous stepless capacity control.

Infinitely variable capacity control can be realised by using electronic variable-speed drives to regulate the speed of the compressor motor. Since the torque–speed performance characteristics of an induction motor at low-speed operation are the same as those at rated motor frequency, frequency variation is considered to be an efficient speed-control technique.

RESEARCH INTO THE MECHANICAL ASPECTS OF VARIABLE-SPEED REFRIGERATION

Early work on variable-speed refrigeration systems was directed towards the theoretical analysis of the concept of variable-speed capacity control and the investigation of the problems associated with the mechanical design of the system. Most of the published work discusses the overall performance and benefits of the system, rather than the establishment of criteria for the integration and optimisation of compressors and variable-speed drives.

Cawley *et al.* [5] compared the part-load efficiency of two-speed compressors with compressor unloading capacity control. It was found that 49% better energy efficiency ratio (EER) could be realised by a system with a two-speed compressor, compared with a system using a cylinder unloaded compressor. The basic reason stated for this improvement was decreased power input requirements in the two-speed compressor, due to lower frictional losses at half speed.

Cohen *et al.* [6] analysed the energy conservation potential of variable-capacity compressors in domestic and small, commercial, air-conditioning systems. The authors reported the effects of using variable capacity control and identified essential modifications for the attainment of maximum efficiency gains. Although no specific technique for displacement control was recommended, it was emphasised that energy could be saved on a seasonal basis because the system would operate more efficiently at lower capacities, due to the reduced frictional losses in the compressor. Energy savings were also anticipated due to the reduced pressure ratio imposed on the compressor by the lower temperature difference at lower loads in both condenser and evaporator. Efficient refrigerant control devices which could quickly respond to wide variations of pressure ratio were also recommended for variable-capacity systems because the response of capillary tubes was found to be unsatisfactory compared to that of thermostatic expansion valves (TEVs). It was concluded that variable capacity control could provide energy savings of 28–35% on a seasonal basis, without significant changes in the system size and cost. Other projected advantages were reduced torque requirements at initial start up, low noise operation at most loads, fewer on/off cycles and stable humidity control. The investigations did not consider the practical implications of low capacities and low flow-rates on the design of the refrigerant piping and the heat exchangers.

Muir *et al.* [7] investigated various aspects of capacity modulation for general refrigeration and domestic air-conditioning systems using a rating technique, the seasonal energy efficiency ratio (SEER). This method compares the seasonal efficiency of domestic air-conditioning systems, taking into consideration the effects of on/off cycling and steady-state efficiency at several outdoor temperatures. The analysis showed that significant energy savings would be possible through capacity modulation, due to a decrease in on/off cycling losses and improvements in steady-state efficiency at lower loads than the design load. It was concluded that, in addition to investigating the costs and savings that could arise from speed modulation, more research was needed to determine the on/off cycling rates, load/capacity ratio and on/off cycling degradation coefficients for different applications.

Lida *et al.* [8] carried-out experimental investigations on a heat pump equipped with a 4 hp, (3 kW), hermetic rotary compressor. It was found that the practical limits for compressor speed variation were between 25 and 75 Hz. The results indicated improvements in EER with the inverter-driven compressor, compared to a fixed-capacity system. The reason stated for the improvement was higher efficiency at part load, which reduced the power consumption and cycling losses. Cost and SEER analyses showed a 20% increase in the total cost for the inverter-controlled system and between 20 and 26% energy savings over the single-capacity system. The cycling losses were estimated to be between 5 and 7% and the payback period was calculated to be between 3 and 4 yr. Other advantages identified for variable-speed control over fixed-speed systems included accurate temperature control, system soft-start capabilities and low noise operation at reduced loads.

The work of Shimma *et al.* [9] concentrated on the evaluation of energy savings from the application of inverters to air-conditioners and considered the effects of employing inverters in some detail. The authors proposed that maximum energy savings and better system performance could be achieved by employing better control methods and improving the performance of individual components in the air-conditioning system. Anticipated energy savings for small-capacity inverter-driven air-conditioners were in the range between 20 and 40%. These savings were attributed mainly to higher operating efficiency at lower speeds. The refrigeration effect in the low-frequency region was found to increase because of the low compression ratio operation which results from increased heat-exchanger capacity. A microcomputer-based control system was used to control the room temperature. The optimum operating frequency of the compressor was determined by the microcomputer with input values from the room-temperature sensor and heat-exchanger temperature sensor using PI (proportional and integral) control logic. The capacity-controlled system resulted in a reduction of the room temperature fluctuations to 50% of those for the conventional on/off-controlled system. In addition to this, it has been envisaged that the time required to bring the room temperature to the desired set-point temperature could be reduced by running the compressor at a higher speed at start-up. The authors pointed out various problems that needed further consideration. These included improvements in the refrigerant throttling mechanism, adoption of more effective noise suppression techniques to reduce radio wave interference noise and harmonic noise generated by the inverter, enhancement of the reliability and performance of the inverter, improvements in the overall system design to reduce noise at high-frequency operation and to overcome vibration problems at low-frequency operation. It was concluded that the cost of the inverter control system needed to be reduced further to expand its application.

Itami *et al.* [10] examined the performance and reliability factor of frequency-controlled, reciprocating and rotary compressors of the rolling piston type. They suggested modifications to ensure reliability which differ for each type of compressor. For instance, with the reciprocating compressor, a two-stage oil-pump was used over the low-frequency range to ensure proper lubrication. For the rotary compressor, a liquid injection system was used to limit overheating and a disc mechanism was adopted to prevent increased amounts of discharge oil at the higher operating-frequency range. The rotary compressor showed improvements in the volumetric and motor efficiencies when the operating frequency was increased, whereas the reciprocating compressor exhibited improvement in mechanical and compression efficiencies when the operating frequency was decreased. Between 20 and 40% improvement in the SEER was reported with the frequency-controlled air-conditioner, compared to the conventional on/off-controlled system.

In recent years, scroll compressor technology has shown promising efficiency advantages over comparable positive displacement compressors. This is due to the smooth and continuous compression characteristics of the scroll design and the elimination of valve losses. Ischii *et al.* [19, 20] compared the mechanical efficiency and dynamic performance characteristics of scroll compressors with those of rolling-piston rotary compressors. It was found that the scroll compressors exhibited better vibration characteristics than the rolling-piston rotary compressor but lower mechanical efficiency. It was anticipated that the mechanical efficiency of scroll compressors could be improved through design optimisation.

The investigations of Senshu *et al.* [21] on a small-capacity heat-pump employing a scroll compressor showed a 30% improvement in annual performance efficiency, compared with the conventional reciprocating compressor. The EER of the inverter-driven heat-pump at nominal load conditions, however, was found to be less than that of a constant-speed system, due to the inverter losses.

A feasibility and design study of a continuously variable capacity refrigeration system was carried out under the Energy Efficiency Demonstration Scheme on behalf of the Department of Energy [22]. A commercially available variable-speed system was monitored in a supermarket application with a view to first assessing the performance of an already installed conventional system and then converting these units to variable speed for overall comparison. The investigation showed a 56%

power saving with high temperature (dairy applications) and a 30% saving with low temperature (frozen-food applications). The energy savings achieved were attributed mainly to variable-speed control and fully floating head pressure.

Rice *et al.* [23–25] reported energy savings of the order of 27% for a modulating heat-pump system arising from reduced cycling losses, heat-exchanger unloading, reduced frosting/defrosting losses and reduced back-up heating. It was found that increased motor-slip losses and distorted inverter waveform decreased the conventional three-phase induction motor efficiency by up to 20%, depending on frequency and inverter type. It was suggested that a permanent-magnet, electronically commutated motor–inverter combination could reduce these losses.

ASHRAE research project RP-409 analysed a large chiller employing a variable-speed-controlled centrifugal compressor [11]. The results showed that variable-speed control led to a 1.5% reduction in the compressor power consumption at maximum load and a 40% reduction at minimum load.

Wong *et al.* [12] confirmed by experimental investigation that variable compressor speed control is more efficient compared to cylinder unloading control. With variable speed, volumetric and isentropic efficiencies and COP increased when the compressor speed was reduced, while cylinder unloading control exhibited reduced isentropic efficiency and COP. The authors evaluated the economic benefits of a variable-speed compressor in another research paper [13]. It was shown that variable-speed control leads to reduced energy consumption, but for intermittent operation it may not be economically viable due to the high capital cost of the inverter.

The work of Tassou *et al.* [1, 14–17] concentrated mainly on the capacity control of domestic-size heat-pump systems. Important issues investigated included energy conservation with capacity control, performance comparison with conventional systems, effects of capacity modulation, mathematical modelling of variable-speed systems, part-load and dynamic performance analysis of heat pumps. The investigations showed that variable-speed control could achieve a 15% improvement in energy conversion efficiency, compared to a conventional system. It was also found that superheat control with a thermostatic expansion valve was unsatisfactory during part-load operation and it was suggested that the problem could be effectively overcome by employing a microprocessor-controlled motorised expansion valve.

McGovern [18] investigated the performance of a two-cylinder, open-type, reciprocating compressor over the speed range 300–900 rpm. Performance parameters, such as mass flow-rate, shaft power and compressor discharge gas temperature showed a linear increase over the tested speed-range, whereas the volumetric efficiency was found to remain almost constant at about 66% over the speed range. The variation in mechanical efficiency with speed was found to be very small, increasing from 92 to 94% as the speed increased from 300 to 900 rpm.

ELECTRICAL ASPECTS OF VARIABLE-SPEED REFRIGERATION

Inverter-based variable-speed drive technology is presently well proven in various applications throughout all sectors of industry and several drive types are available for both energy conservation and high-performance applications. A VSD is an interface between the utility input and the compressor motor that controls the speed of the motor by changing the magnitude of voltage, current or frequency. A three-phase VSD or frequency converter, shown in Fig. 2, consists of a rectifier which converts the three-phase mains voltage, i.e. 415 V, 50 Hz, to a d.c. voltage either controlled or uncontrolled, and an inverter which inverts the d.c. voltage to a three-phase a.c. supply-voltage to the compressor motor. The voltage at the inverter output is adjustable in magnitude and frequency. A regulator is used to change the inverter switching characteristics so that the output frequency can be controlled. This may comprise a sensor which measures the control variable and sends a feedback signal to the system.

Classification of electronic VSDs

A basic classification diagram of VSDs is shown in Fig. 3. The classification criteria used are the type of semiconductor switch employed, input and output circuit topology, motor type, control strategy, power and voltage level, and regeneration capability [26]. A comprehensive technology review of the application of power electronics is given by Bose [27], which includes a discussion of power semiconductor devices, power integrated circuits, converter circuits and applications.

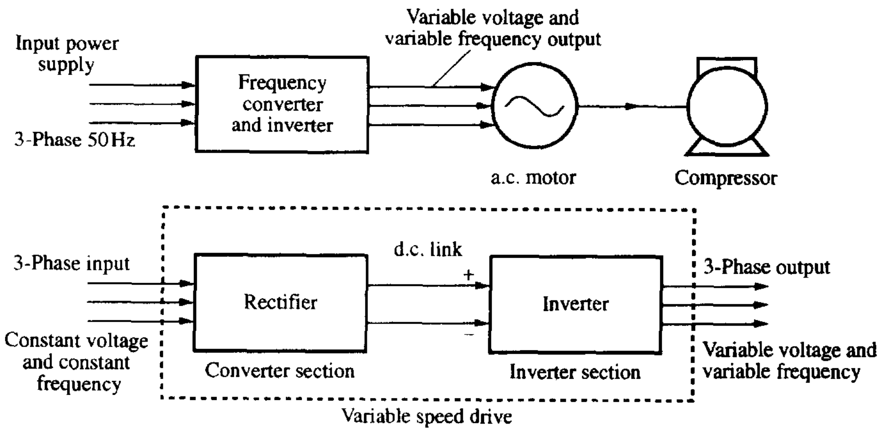

Fig. 2. Basic configuration of electronic variable-speed drive.

Currently available VSD systems can be classified into three basic inverter types: the six-step voltage inverter (VSI), the six-step current inverter (CSI) and the pulse-width-modulated voltage-source inverter (PWM). All three types have certain relative advantages and disadvantages and it is unlikely that any one will displace the others in all types of application [28]. A recent survey, however, has shown that over the last few years sales of PWM inverters exceeded those of other inverter types [29]. A report published by the Energy Efficiency Office compares typical efficiencies of six VSD types of different ratings. As shown in Fig. 4, the PWM inverter shows a slightly better efficiency over VSI and CSI [30].

The efficiency of the inverter and the motor greatly influence the energy-efficiency ratio of the refrigeration system. The efficiency of a typical inverter decreases with a decrease in speed. The combined efficiency of a conventional inverter and motor is around 86% at maximum speed and

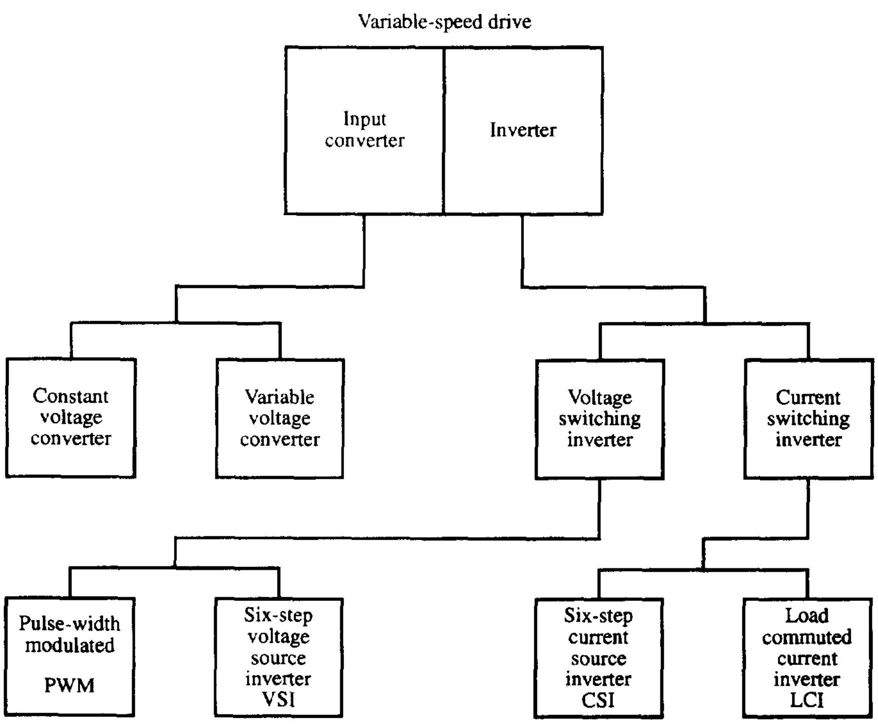

Fig. 3. Classification of electronic variable-speed drives.

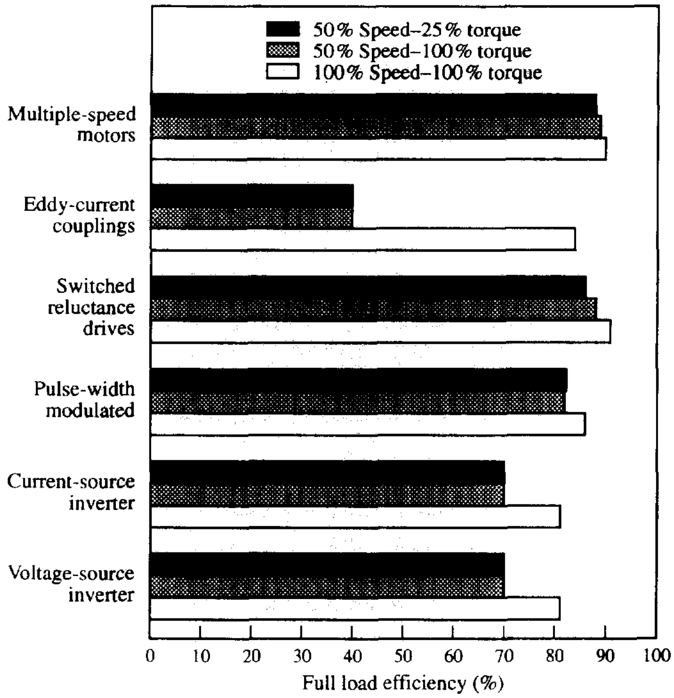

Fig. 4. Typical efficiency of various VSD types [36].

full load and falls off at reduced loads and speeds [31]. Since refrigeration systems operate most of the time at part-load conditions, considerable energy savings can be achieved by raising the efficiency of the inverter and motor combination at part-load/low-speed operation. Alternately, selection of these main driving units should be such that they operate in the high-efficiency region for most of their duty cycle.

Effects of electronic VSDs

A variable-speed inverter is liable to introduce disturbances, especially harmonics of the supply frequency, into the system to which it is connected. due to the effects of the switching mode of operation.

The negative effects of VSDs can be classified into two categories: those on the supply side and those on the motor side. The main effect on the supply side is radio-frequency interference, which may cause disturbances in the communication equipment in the vicinity of the inverter. On the motor side, the effect could be increased motor losses due to a non-sinusoidal voltage waveform, speed/torque oscillations which impose extra stresses on the windings and variation in slip which directly affects the torque of the motor.

Lloyd [32] investigated the effects of various waveforms on the efficiency of the motor and compressor. The waveforms analysed were six-step and pulse-width modulation (PWM), which were compared with pure sinusoidal waveform. The sinusoidal waveform showed higher motor and compressor efficiencies over the entire frequency range, whereas the PWM waveform resulted in a better motor and compressor efficiency over the six-step waveform at higher frequencies.

Mohen *et al.* [33] evaluated the feasibility of heat-pump capacity modulation with compressor speed adjustment using six different adjustable speed techniques. PWM and VSI drives were found to be more efficient than other adjustable-speed motor drive methods such as: square wave current source inverter (CSI), electronically-commutated synchronous motors with a permanent magnetic field (ECM), high-frequency high-speed motors using low-loss magnetic material (HCM) and pole amplitude-modulation motors (PAM). These techniques are capable of providing speed modulation in the range of at least 6:1, allowing speed to be varied above and below the rated running speed. The power factor of the PWM inverter was found to vary in the range between 60 and 80%, which is generally considered to be within permissible limits, whereas for the VSI the power factor decreased to an unacceptable value, down to 10% at low-speed operation. The efficiency of both drives was estimated to be 95% at full load. It was found that both inverter drives introduced large amounts of harmonic current into the utility system and modifications to the relevant circuitry to eradicate or lessen the harmonic current and to enhance the power factor of operation were suggested. The input distortion index was found to be in the range between 70 and 130% for both inverters.

Scholey [34] compared the performance characteristics of sine wave, six-step square wave and pulse-width-modulated variable-frequency power supplies. The induction-motor performance when subjected to complex voltage waveforms and variable-frequency supplies was also evaluated, considering winding stresses, low-speed pulsating torques, temperature rise and the effect of harmonics. It was found that the voltage-source inverter produced losses of 20%, compared to the pure sine-wave supply. The losses with the PWM inverter were not quantified but stated as being less than the VSI and dependent on the switching frequency. It was also mentioned that low-frequency pulsating torques have less effect on the PWM inverter than on the six-step VSI, due to the large number of pulses per cycle, which favour PWM when stable operation at low speeds is required. Motor temperature-rise was stated as being excessive at lower speeds for both types of inverter, due to the reduction in ventilation and additional harmonics.

Rahman [35] reviewed the efficiency of an inverter-fed induction-motor and identified various losses which may occur in the motor due to harmonics, which include copper losses, stator losses, core losses and stray losses. The power loss caused by the inverter was shown to increase with the increase in the power rating of the drive.

There are various standards that deal with the disturbances in the supply system and provide guidelines for harmonic control. The most commonly referred to standards are:

- Engineering recommendation G.5/3, 'Limits of harmonics in the UK electricity supply system' [36].
- IEEE Standard 519-1981, 'IEEE guide for harmonic control and reactive compensation of static power converters' [37].
- International Electrotechnical Commission Standard, IEC 555, 1982 [38].
- British Standard BS 5406, 1998, 'Disturbances in supply systems caused by household appliances and similar electrical equipment [39].

Harmonic currents can be controlled by various methods, such as shunt filters, phase multiplication and harmonic compensation or injection. A correctly designed input-filter can reduce the dominant harmonic to the acceptable level.

A.C. MOTORS

The type of motor fitted to the compressor is a primary consideration in selecting an electronic VSD. A number of choices are available, including both synchronous and asynchronous types, but the standard induction motor is the most widely used due to cost, reliability and availability advantages over other motor types.

According to Domijan [29], the efficiency of an inverter-fed induction-motor compared to a direct mains-driven motor is higher from start-up to no-load conditions, but decreases under part- and full-load conditions, due to increased motor losses in the presence of multiple harmonics in the current and voltage waveforms. These losses must be taken into consideration in motor design, together with the influence of motor temperature-rise, low-frequency pulsating torques, voltage stresses and harmonic torques.

High efficiency motors are a new development and achieve maximum efficiency at between 70 and 85% of full load [40]. The efficiencies of high-efficiency motors and standard induction-motors under various loading conditions are compared in Fig. 5. It can be seen that high-efficiency motors operate at maximum efficiency over a wider range of loads compared to standard induction-motors and their peak efficiency is approximately 5% higher than that of standard induction-motors, due to lower component losses. Motors utilising a higher class H insulation system are now specially designed for variable-speed operation.

REFRIGERATION COMPRESSOR

Currently, various compressor types are being driven by inverters and some are better suited to VSD operation than others, due to their better performance characteristics. The main types of positive displacement compressors likely to be used in commercial refrigeration and air-conditioning applications are reciprocating, rotary, screw and scroll. The selection of a compressor for a particular application incorporating a VSD is not quite as straight-forward as it may seem. System design has to take into account the anticipated load-profile at variable-speed operating conditions. The subject has been discussed in more detail by Mills [41]. Some of the basic requirements of a compressor for VSD applications are [42]:

(i) Proper lubrication at low- and high-speeds must be ensured as inadequate lubrication at low-speeds may increase overheating and friction losses of compressor components and ample lubrication at high-speeds may damage the seals and gaskets. An improperly designed lubrication system may reduce the performance, reliability and life of a compressor.
(ii) The compressor support frame should be designed such that the resonance frequencies are above the operating frequency range. A compressor running at fixed speed imposes vibration on its framework at a set group of frequencies. The framework is normally designed such that its natural frequency differs from the imposed frequency. A variable-speed compressor design will be more complex as each speed will impose different frequencies.
(iii) The VSD should not increase the stresses on the suction and discharge valves. Compressor valves designed to operate at fixed speed may not be suitable for variable-speed operation as imperfect valve action at various speeds may increase valve inefficiencies.
(iv) The capacity of the compressor should vary in direct proportion to speed and the efficiency of the compressor should not decrease within the required speed range.

Thermodynamically all compressor types follow the same laws but their efficiencies can vary considerably from one type to another.

Riegger [43] compared the performance of commercially available small-capacity rotary, reciprocating and scroll compressors to evaluate their performance under variable-speed operation. It was found that all three compressors were optimised for 60 Hz operation and their energy-efficiency ratio decreased above and below this rated point. The authors concluded that there is no straight-forward answer to the question of which type of compressor is most suitable for variable-speed operation because various factors, such as capacity range, operating conditions and manufacturing cost, influence their seasonal energy efficiency.

Tassou *et al.* [44] compared the performance of open-type reciprocating, semi-hermetic reciprocating and rotary vane compressors over a range of speeds and loads using a 25 kW nominal

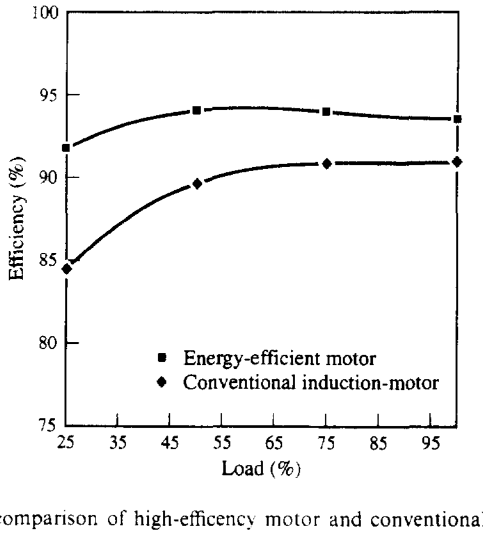

Fig. 5. Efficiency comparison of high-efficency motor and conventional induction-motor.

capacity refrigeration system. Of the three compressors, only the open-type reciprocating unit exhibited an appreciable increase in the COP with a reduction in speed. The semi-hermetic reciprocating compressor exhibited only a small improvement, due to the negative effects of reduced motor cooling and high suction temperatures, whereas the rotary compressor exhibited a reduction in the COP at low speeds, due to reduced hydrodynamic sealing between the rotating vanes and the cylinder. An analysis of the seasonal energy performance of a refrigeration system equipped with an open-type compressor and used for air-conditioning applications has shown that the system can lead to between 12 and 24% energy savings, compared to a conventional fixed-speed system, depending on climatic conditions [45].

CONCLUSIONS

In recent years, scroll compressors with VSD drives have gained an increased market share in small packaged air-conditioning systems, due to improved efficiency and reliability brought about by advancements in material and manufacturing technology and optimised design. In the medium-capacity range, reciprocating, rotary and scroll compressors are being used with off-the-shelf inverters. Research results have shown that open-drive compressors lead to better efficiency and allow smaller condensers to be fitted as the increased motor heat caused by the inverter losses is not rejected in the condenser.

Over the past few years, the price of inverters has been steadily decreasing. This trend is attributed generally to improved design, increased production and the decrease in the price of power electronic devices. The reliability of inverters is also constantly improving, due to improved technology and the availability of better components. Space requirements are also decreasing, due to improved packaging, higher efficiency, more effective heat sinks and improved circuitry.

The downward price trend and new technological developments are favourable for the increased use of VSD refrigeration in place of conventional refrigeration systems. There is also scope for achieving further energy savings by using high-efficiency motors if their present costs become competitive with standard induction-motors.

The development of an optimum variable-speed refrigeration system is a function of several design factors and more research work is needed to fully understand the interaction of the components in an integrated VSD refrigeration system. Problems to overcome are the generation of harmonics by the inverter, which affects both the supply and the motor, and the reduction of the motor efficiency at low speeds. Proper lubrication and cooling of the compressor at low speeds is also an important consideration.

New developments in inverter technology, such as vector and fuzzy logic control, require further investigation as to their application to refrigeration systems. The energy-efficiency of optimised VSD refrigeration systems should also be investigated in different applications, such as low-temperature, medium-temperature and high-temperature refrigeration.

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