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ABSTRACT

While great strides have been made in HVACR technologies in recent years, significant improvements in energy efficiency, reliability and product life have been elusive in mid-range applications. In this 50-500 TR range, the most promising potential for significant energy reduction lies in compressor integrated part load efficiency (IPLV) improvements. Although large chiller efficiencies have benefited from technology improvements like packaged variable speed drives, the far larger and less energy efficient mid-range market of rooftop packaged systems and smaller chillers has yet to benefit from these centrifugal compression related efficiencies and other available technologies. A nominal 60-90TR two-stage centrifugal oil-free R-134a refrigerant compressor utilizing integrated variable speed drive, magnetic bearings and an onboard digital control system affords major advantages for mid-market chiller and rooftop HVACR equipment.

NOMENCLATURE

HVACR: Heating, ventilation, air-conditioning and refrigeration
TR: Rated ton of refrigeration
IPLV: Integrated part load value
PWM: Pulse width modulation
DC: Direct current
PCB: Printed circuit board
VSD: Variable speed drive
IGBT: Insulated gate bipolar transistor
AC: Alternating current
IGV: Inlet guide vanes
CFC: Chlorofluorocarbon
ODP: Ozone depletion potential
GWP: Global warming potential
EXV: Electronic expansion valve
NEMA: National Electrical Manufacturers Association
KW: kilowatts
ARI: Air Conditioning and Refrigeration Institute

INTRODUCTION

Air conditioning and refrigeration (HVACR) is the largest global consumer of electric power. In commercial buildings and industrial processes, it can represent the single largest operating cost. Environmental emissions from the production of electricity contribute to global warming and climate change. Deregulating energy markets and new energy efficiency standards increasingly set new challenges in the ways organizations use and manage energy.

Within the dominant and growing commercial HVACR market for mid-range chiller and rooftop equipment, the greatest single energy consuming component and the greatest potential for energy reduction still lies in future breakthroughs in compressor technology. Significant reductions of the electric power consumption associated with HVACR are now possible with the innovative application and convergence of proven energy efficient technologies. Magnetic bearings, proven over many years in aerospace and industrial applications, enable dramatic improvement in compressor energy efficiency and operation through the elimination of mechanical friction. Variable speed drive, often used on large centrifugal-chiller compressors, enables optimal energy performance throughout a wide range of load and temperature conditions through shaft speed reduction. Onboard digital controls integrate all compressor functions within the self-contained compressor envelope while providing self-diagnostics and correction, external control and web-enabled monitoring access to the full array of performance and reliability information.

COMPRESSOR DESIGN

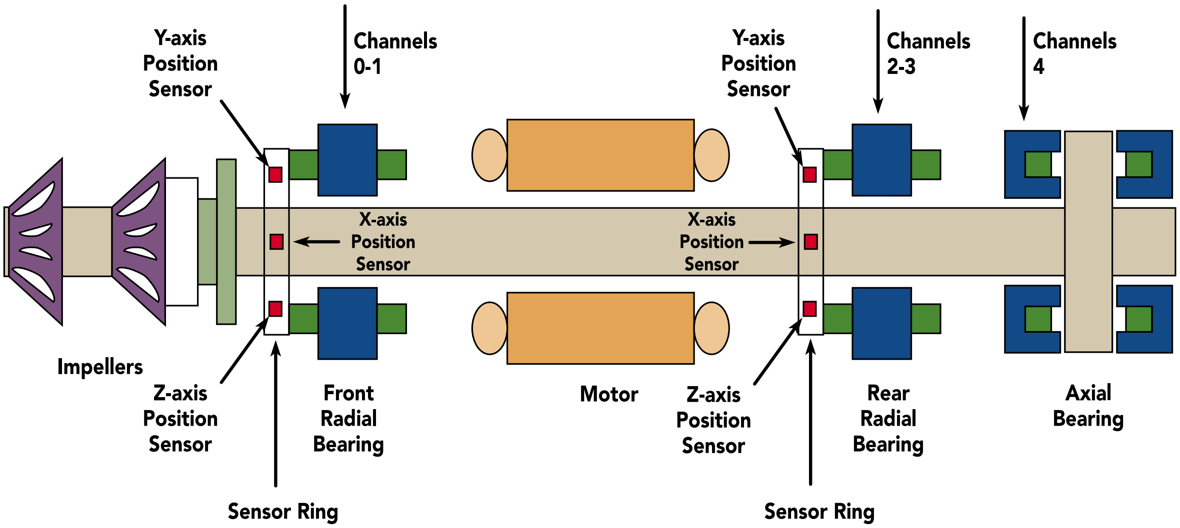
Oil free 60-90TR Centrifugal Compressor

Magnetic Bearing System

Magnetic bearings have been used in specialized applications in aerospace and large industrial machinery and have to date been limited to high-end applications where cost has not been the major consideration. The technology has been proven over the years to be a highly reliable concept and has been used in applications where energy efficiency is an issue or where conventional lubricants are not desirable. Historically, these bearing systems have been extremely expensive to develop and manufacture and have not been used in mass produced products.

The compressor's single main moving part (rotor shaft and impellers) is levitated during rotation by a digitally controlled magnetic bearing system. Rotor shaft levitation during rotation eliminates the friction losses inherent in the oil-lubricated mechanical contact bearings used in conventional refrigerant compressors. This is the first enabling step in the compressor's energy efficiency improvement differential over conventional compressor mechanical technologies.

The bearing systems is a 5 axis active control and permanent-magnet-biased design, where the bearing uses permanent magnets to do the primary work and digitally controlled electro magnets are used as a secondary trim system. Each radial bearing operates with 4 separate magnetic coils that are controlled with a digitally controlled PWM. The digital control responds to 4 separate signals sent to it from inbuilt proximity sensors that are sensitive to shaft movement of less than .00005". As the shaft moves from the center point, varying strength magnetic fields are applied to the shaft to bring it back into its required position. Typically, maximum run-out of the shaft is confined to less than .0005". Centered rotor shaft orbit and dynamic vibration are, therefore, controlled by input from bearing sensors, through a software driven bearing controller to magnetic bearing actuators in real time. The axial position of the shaft is similarly controlled, however the shaft position is controlled from the impeller end of the compressor, while the magnetic actuators apply the appropriate force to the opposite end of the shaft. Additionally, the software has been designed to auto-compensate for any out of balance the compressor may experience. Including their control electronics, this compressor’s magnetic bearing system draws 180 watts of power as compared with as much as 10,000 watts required by conventional lubricated bearings.



Cross-section of compressor rotor and magnetic bearing system

In the case of a power outage, the bearing power is fed from onboard capacitors that are primarily used to smooth out current ripple on the system DC link on the motor drive. Within a millisecond of the compressor losing its power, the motor switches into a generator mode, whereby power is fed back into the DC bus supplying the necessary power to levitate the bearings and feed the various control systems on the compressor. Should a power failure occur, the compressor is fully protected. The rotor remains fully levitated throughout coast down because the magnetic bearings are continually energized by onboard electronic capacitors, supplemented by electricity generated internally while the rotor spins. Carbon-composite touchdown bearings normally support the rotor while the compressor is off. However, they are also designed to protect the compressor in the case of a catastrophic failure such as a PCB or actuator failure.

While a typical magnetic bearing control system is housed in separate electronic enclosures and is large and expensive, in this design case the system has been miniaturized and is housed within the compressor itself, thus increasing reliability while greatly reducing costs.

Motor and Variable Speed Drive

Variable speed drives (VSD) are commonly used in large chiller HVAC installations and are well proven in their ability to improve energy efficiency. At part load and lower condensing temperatures, VSD’s dramatically reduce energy consumption by reducing compressor shaft speed, which reduces impeller tip speed to meet the adjusted requirements of lower refrigerant flow and system pressure/temperature. The energy savings related to compressor speed reduction are derived from the affinity or fans laws that depict speed as proportional to energy cubed. That is, as speed is reduced, the energy required decreases proportionally by the cube function. This improved energy performance is further complemented by integrated inlet vane capacity control that permits an operating range to well under 20% of rated capacity

The compressor variable speed drive system consists of a rectifier to convert the incoming mains power (3 ph/ 380V – 460V 50/60 Hz) to a DC current, a DC buss consisting of 4 capacitors allowing for the smoothing of current ripple, an IGBT to switch the DC current into a variable frequency AC supply for the motor and a soft-starter that significantly reduces the inrush current, (the compressor has a starting current of less than 5 amps).

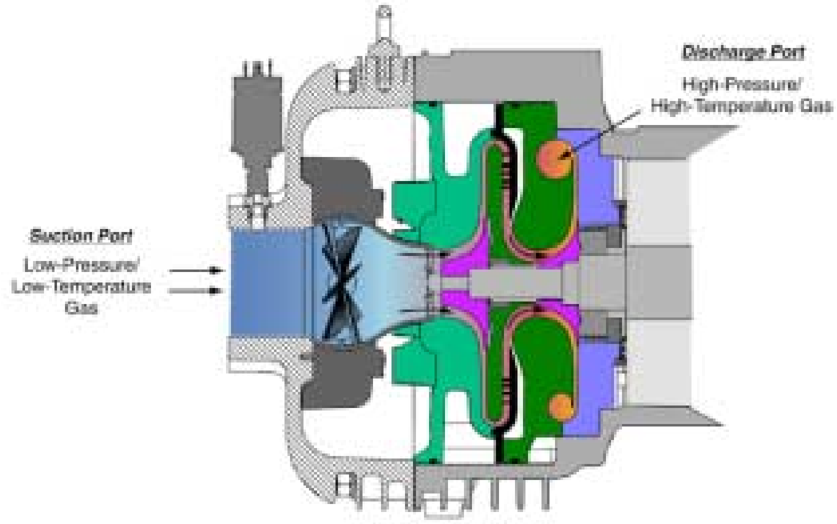
Typically, as in the case with magnetic bearings, these systems are large, separately housed in electrical enclosures and are expensive. In this case, inverter speed control has been fully integrated it into the compressor housing and has been cost reduced.

Permanent magnet, synchronous, DC motor

The motor developed specifically for this compressor is a permanent magnet synchronous DC type. Operating at speeds of up to 48,000 RPM, the 120HP motor is the same physical size as a conventional 1HP 4-pole induction motor and is refrigerant cooled. The motor cooling circuit is integrated into the compressor design and is also used to cool the key electronic components. Motor/rotor speed is controlled through load demand and pressure/temperature signal inputs to a software driven motor and compressor controller.

Centrifugal Compression and Refrigerant Selection

The two-stage fluid dynamics design uses two open impellers designed to operate both with and without an economizer system. As the gas enters the compressor, it passes through a set of pre-swirl IGV that typically remain open for most of the compressor's operating life, these vanes start to close off and are appropriately adjusted to balance the system when it starts to approach a surge condition. The gas then is directed into two investment cast impellers that pump the gas through the system. Between the 1^{st} and 2^{nd} stage impellers is a side-stream inlet port that allows the system to use an economizer circuit if required. From there, the gas passes through a purpose built discharge service / check valve. When the compressor shuts down or is not operating when installed in parallel with other compressors, the check valve closes off to stop the gas feeding back through the turbine wheels eliminating shaft/impeller reversal.



Cross-section of compressor aerodynamic section

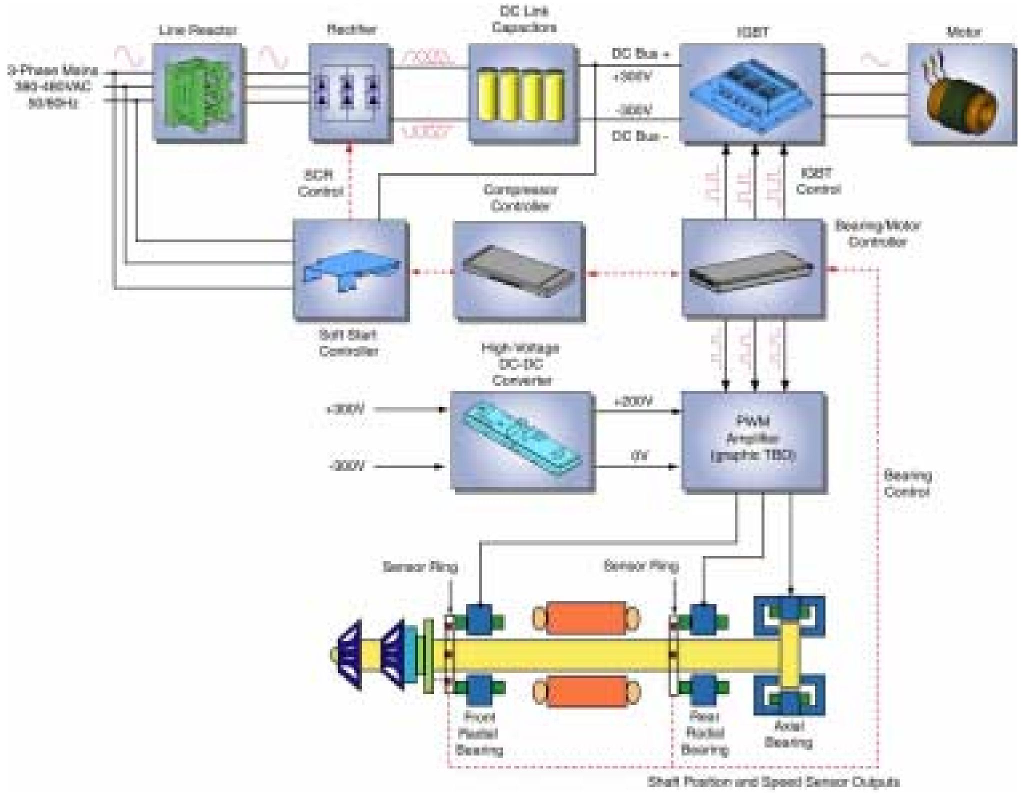
Refrigerant R-134a was selected as the basis for the compressor aerodynamics through an evaluation of design attributes focused on efficiency, cost, availability and environmental considerations. Physically, it is a medium pressure refrigerant, (180 psi working pressure at 124ºF). This affords a compact compressor size vs. low pressure refrigerants, (e.g. R–123), with a far larger swept volume /TR. Additionally, medium pressure permits pressure containing castings to be lighter and economical vs. higher pressure refrigerants, (e.g. R-410a), requiring heavy castings and face other refrigerant containment costs.

R-134a is recognized as the CFC-free alternative to R-12 for commercial and industrial HVACR applications and is also supported by the automotive industry volume. Both applications ensure wide spread use and continued commercial availability. R-134a responds to environmental concerns with zero ODP and very low GWP and has no established phase out program.

Power and Control Electronics

The compressor has been designed with fully integrated power electronics, IGBT, IGBT control, bearing and motor control, compressor control, soft starter, control power supply, PWM, smoothing capacitors, multiple EXV control, motor and electronics cooling control, IGV control and pressure transducers. The control system has been broken into two segments, the high voltage, high power section, and the low voltage, control and service section. The high voltage section is situated on top of the compressor and houses the power electronics required to drive the motor and the isolated high voltage DC/DC power supply for magnetic bearings and other low voltage system control functions. The low voltage section is situated on the side of the compressor and includes the bearing/motor control the compressor control and the low voltage DC/DC power supply. Power and sensor feed-throughs are hermetically sealed connections enabling the transfer of power to the electromagnetic bearings and shaft position and rotation signals to the control modules through the pressure-containing casing.

The bearing and motor controller computes the required shaft position signals that control the magnetic bearings and processes shaft rotation data to control motor speed. The PWM amplifier supplies power to the electromagnetic bearings. The IGBT is an inverter that converts a DC voltage into an adjustable three-phase AC voltage. Signals from the motor/bearing controller determine the inverter output frequency and voltage thereby regulating the motor speed. Capacitors provide energy storage and filter for smooth DC voltage, as well as, coast down power to the magnetic bearings, along with motor rotation, to ensure rotor shaft levitation until compressor stop in the event of an external power loss. A rectifier converts AC line power into a high voltage DC power source for motor, bearings and control operations. The DC to DC converter supplies and electronically isolates the high and low DC voltages required for the control circuits. The compressor controller is the central processor of the compressor system and is continuously updated with critical data from the motor/bearing controller and external sensors that indicate the compressor and chiller/rooftop package operating status. Software enabled, it responds to changing conditions and requirements to ensure optimum system performance.



Schematic layout and integration of principal electronic components

Miniaturization and packaging have been a key part of the electronics design and has allowed for the consolidation and elimination of many components, wiring and PCB's. The control electronics boards have been designed to be plug and play for ease of service. The injection molded thermoplastic covers serve as NEMA 4 enclosures for power and control electronics. A refrigerant cooling system has been designed to allow the electronics to operate optimally, which also increases component life and reliability.

Control boards with external cover removed

ENERGY EFFICIENCY

The application and integration of magnetic bearings, coupled with variable speed centrifugal compression, affords significant reductions in energy consumption, and the environmental emissions associated with energy production, as compared to conventional compressor technology applied in chiller and rooftop equipment. Figures 1 and 2 show an example of the compressor performance as compared to the performance of a typical oil flooded screw compressor on a 75-ton water-cooled chiller.

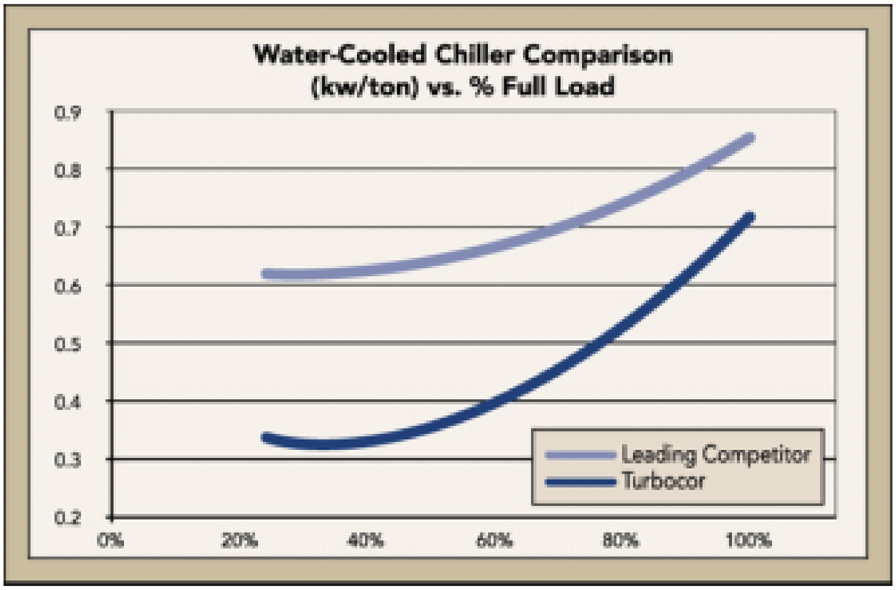


Figure 1: ARI load line comparison. Performance confirmed by Intertek Testing Services.

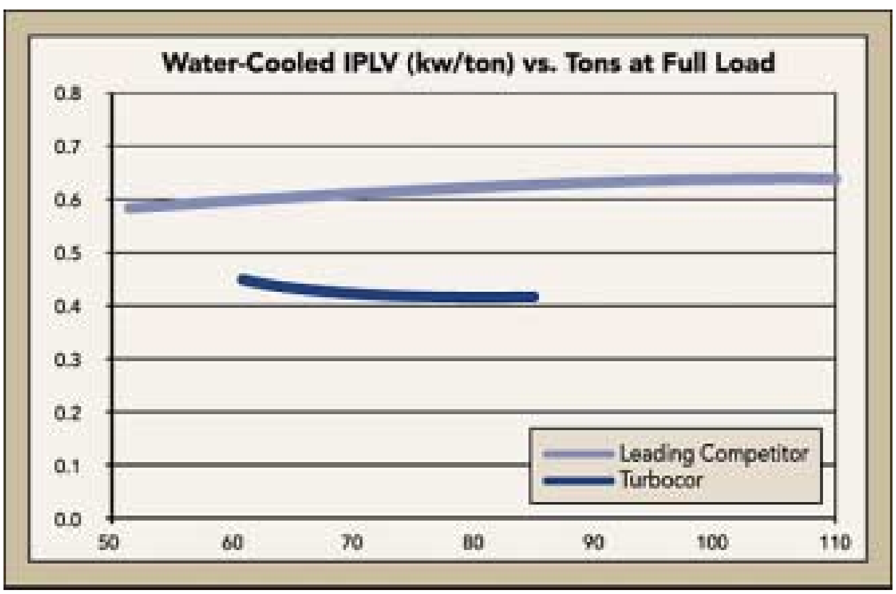


Figure 2: ARI IPLV comparison. Performance confirmed by Intertek Testing Services.

In addition to a significant improvement at full load operation, the more important comparison of IPLV yields a 35% improvement for an annual energy savings of 35,640 kw and 17,820 kg CO_2 emissions reduction. (DOE 1999)

CONCLUSIONS

The convergence of magnetic bearings, variable speed R-134a centrifugal compression and digital control technologies in a commercially viable compressor enables several significant advantages for HVACR mid range chiller and rooftop product applications:

- Improved energy efficiency and the subsequent reduction of CO_2 emissions through the elimination of friction coupled with variable speed.
- Improved reliability and reduced maintenance through the elimination of wear, oil and oil management systems.
- Low noise with virtually no structure borne vibration due to no mechanical contact, (70 dbA @ 5 feet).
- Light weight and compact package enabled through the optimization of refrigerant, compressor speed, motor design, impeller design, electronics miniaturization and materials of construction, (265 lbs, 40.25" X 25.81" X 19.26").
- Integrated digital control provides monitoring, diagnostic, and service capabilities and can eliminate many control functions previously performed by the chiller or rooftop power and control panels.

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