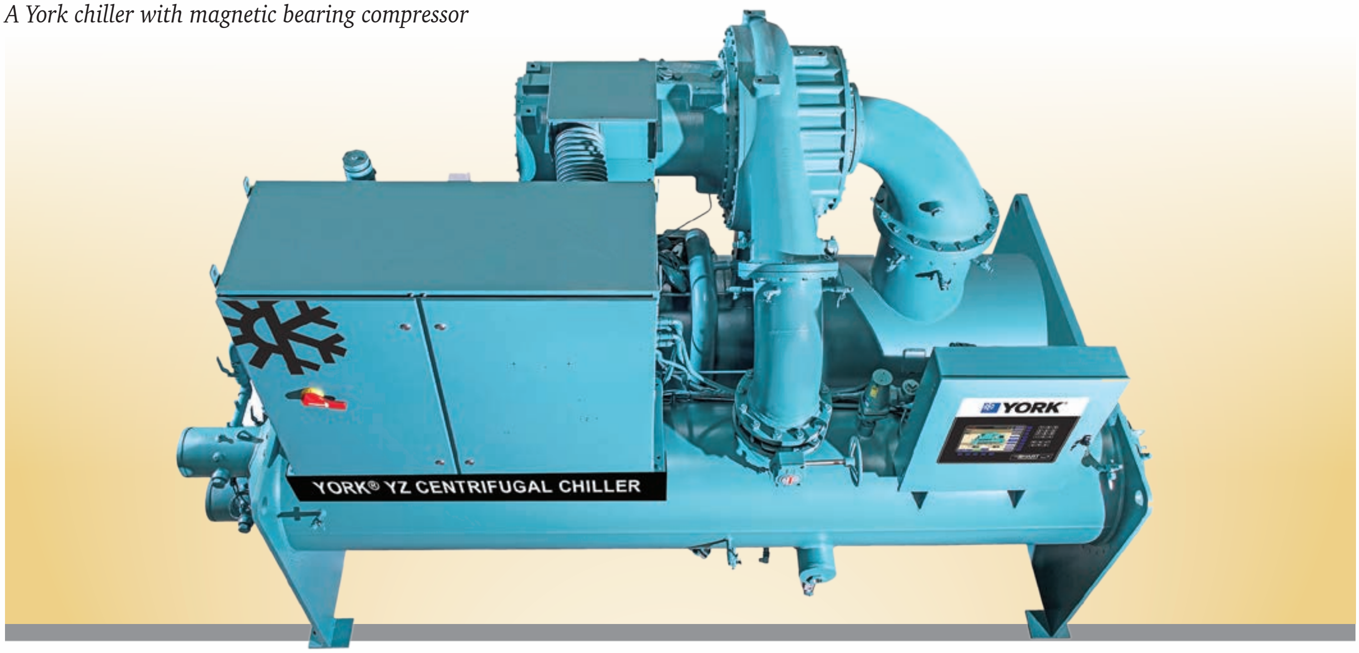
A York chiller with magnetic bearing compressor



Magnetic Bearing Centrifugal Compressors for South Asian Tropical Climate

By Seemant Sharma Director – Product Portfolio Management, Chiller Solutions – Asia, Building Technologies & Solutions, Johnson Controls, Delhi

Introduction

For decades, water-cooled centrifugal chiller technology has been the mainstay for cooling large office buildings, hospitals, data centers and high-rise buildings around the world. One reason is that in applications requiring 400 tons of refrigeration and more, a water-cooled centrifugal chiller is the most energy-efficient mechanical cooling technology.

Over the years, each component of a water-cooled centrifugal chiller system – compressor, evaporator, condenser, cooling tower, air handling unit, valves and pumps – has improved. More recently, however, the compressor driveline has received a lot of attention from engineers interested in dramatically boosting centrifugal chiller efficiency. The main focus has been using a variable speed drive (VSD) to allow the compressor to modulate speed in order to match variations in the cooling load. The ability to decrease motor RPMs during 99% of operating hours substantially lowers energy consumption when lower cooling capacity or lower operating head is needed.

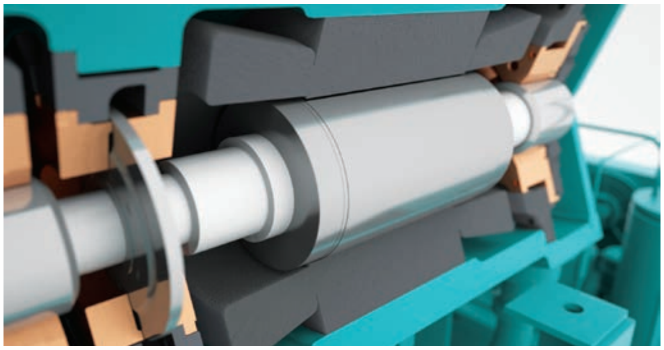


Figure 1: Magnetic bearing driveline

Consequently, the pressing engineering question has been: What is the most efficient design for a variable speed drive (VSD) centrifugal compressor? Today, the answer is: The magnetic bearing compressor. However, the question remains: Is a VSD compressor design suitable for applications in South Asian countries where a consistently high wet bulb temperature would appear to limit the efficiency benefits of a VSD chiller? To answer this, we will examine how the magnetic bearing compressor improves centrifugal chiller performance. Then we will consider how this technological advancement enhances chiller performance specifically in South Asian applications.

About the Author

Seemant Sharma has completed BE (Mechanical) from Delhi College of Engineering and Senior Management Program (SMP) from IIM Kolkata. He is a member of ISHRAE and ASHRAE, and has been associated with the air conditioning industry for over 25 years in sales, system design, projects and service of HVAC equipment, building automation and refrigeration equipment. He has been working with Johnson Controls for 18 years, and is presently Director – Product Portfolio Management for Chiller Solutions supporting Asia and Application Engineering for Middle East countries. He was Chairman – RAMA Sub Committee for ECBC2017 and was also actively involved in developing Chiller Standards on behalf of RAMA. He has presented papers on various occasions and written articles in Air Conditioning and Refrigeration Journal on VFD technology in chillers.

Benefits of Magnetic Bearing Technology for Centrifugal Chiller Applications

In recent years, magnetic bearing centrifugal chillers have produced impressive performance numbers. Our experience shows that these chillers can surpass fixed-speed and standard VSD centrifugal chillers by:

- Achieving part-load energy efficiencies below 0.1 kW/ton
- Producing leaving fluid temperatures as low as 26°F/-3.3°C (using propylene glycol)
- Utilizing cooling tower water as low as 36°F (2°C) to practically eliminate the need for economizers
- Unloading down to 10% capacity to meet a wide range of cooling loads

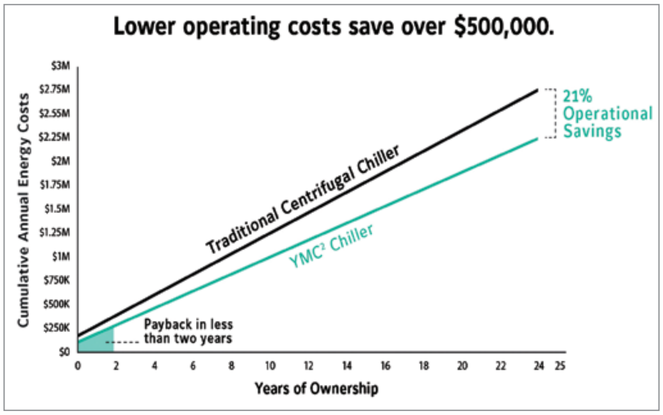


Figure 2: Operating cost of magnetic bearing vs. traditional centrifugal chiller

Advanced magnetic bearing chillers can do all of the above without nuisance trips, extreme modification of building control strategies, or energy-wasting cooling tower bypass and hot gas bypass, which are commonly required with conventional centrifugal chillers operating in off-design conditions.

These accomplishments are made possible by advancements in magnetic bearing compressors for VSD centrifugal chillers.

By combining the inherent efficiency of VSD technology with the advantages of a lubrication-free magnetic bearing motor, magnetic bearing centrifugal chillers provide the highest energy efficiencies in their tonnage range. Compared to a positive displacement constant speed chiller at the same part-load capacity, they are anywhere from 42% to 80% more efficient. This efficiency advantage is available over a wide range of off-design operating conditions, even when building loads are very low and tower water is very cold.

Moreover, magnetic bearing compressors provide other benefits, including:

- Eliminating the costs of bearing lubrication and maintenance
- Running more quietly
- Providing superior control and monitoring
- Lowering the electric demand profile

These benefits and others make it worth examining how magnetic bearing compressor technology improves centrifugal chiller performance.

Areas where Magnetic Bearing Compressors Enhance Centrifugal Chiller Performance

Limitations of Fixed-Speed Compressors

A chiller compressor has two basic functions: 1) Lowering pressure in the evaporator, which causes the refrigerant to boil and absorb heat from water, 2) Raising the pressure of the refrigerant gas, which is then discharged into the condenser.

A centrifugal compressor operates by dynamically compressing refrigerant gas by rotating an impeller at 10,000 RPM or faster.

Compressors are sized to satisfy the 'worst case' cooling load – usually the hottest days of the year. But 99% of operating hours are not at design conditions. Consequently, with fixed-speed chillers, capacity must be reduced by using a number of techniques (such as inlet guide vanes and/or hot gas bypass, which are discussed later), but the compressor still operates close to full RPMs. This is like pushing the accelerator pedal in your car to the floor, and adjusting the car's speed by using the brake.

Advances and Limitations of Conventional VSD Compressors

To improve energy efficiency, VSD centrifugal compressors were introduced for water-cooled chillers nearly four decades ago. A VSD compressor can reduce motor speed in relation to chiller load and working lift/head. A conventional VSD centrifugal compressor is a significant advancement over constant-speed chillers, but there is room for significant improvement using magnetic bearing technology.

To understand why, consider how a VSD centrifugal compressor's components – variable-frequency drive (VFD), impeller, inlet guide vanes, capacity control or variable geometry diffuser – are used.

- A VFD, also known as an 'inverter', converts the electric current's AC signal into a DC signal using rectifiers, and then converts that DC signal back to AC. VSD intelligence can then modulate the AC signal frequency to change motor speed. The same capability is used in magnetic bearing compressors.
- An impeller is used in all centrifugal chillers to compress refrigerant gas by dynamic compression. The rotating impeller wheel accelerates the gas to the tangential velocity at the edge of the impeller. The resultant compression increases the pressure difference between the refrigerant in the evaporator and the condenser.

This difference, known as 'lift' or 'head' pressure, moves the refrigerant through the vapor compression cycle. Obviously, the higher the head, the higher the impeller speed, which requires higher energy input. However, the head conditions may change as the load pattern and outside ambient temperatures change – for example, when cooler weather reduces cooling tower/condenser water temperatures. In this case, a constant-speed compressor will over-accelerate the refrigerant, which wastes energy. A VSD compressor, on the other hand, can reduce impeller speed as the head drops, even if building load remains constant. This moves the compressor into a higher efficiency region in the compressor map, allowing a VSD compressor to use less energy at part load conditions. The map for a magnetic bearing compressor can cover a larger area, as will be discussed.

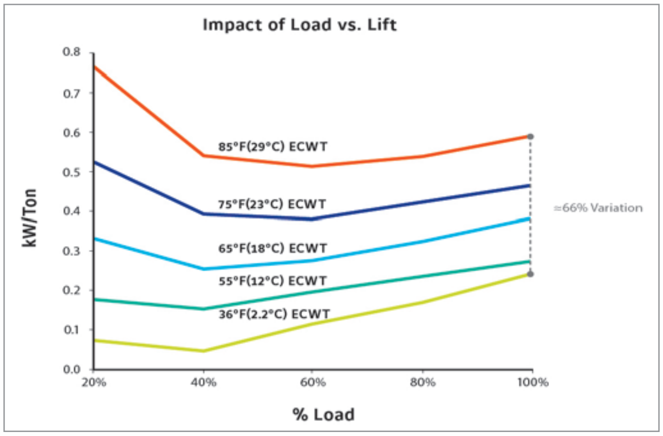


Figure 3: Impact of load vs. lift

- *Inlet Guide Vanes* (IGV) are vanes located at the inlet of the compressor to throttle refrigerant flow. When the guide vanes move from fully open to slightly closed, compressor efficiency can actually improve because the guide vanes 'pre-swirl' the refrigerant entering the impeller. However, as the vanes continue to close, the vane action quickly becomes a restriction, losing the pre-rotation effect and reducing the compressor capacity and efficiency.

A VSD compressor can slow the compressor speed to match the head conditions without closing the guide vanes. Keeping the guide vanes open improves the compressor's operating efficiency.

Consequently, it helps to use both IGV and speed control to optimize efficiency by keeping the compressor within the efficiency islands on the compressor map (*Figure 4*). This combination also allows better tracking of off-design conditions.

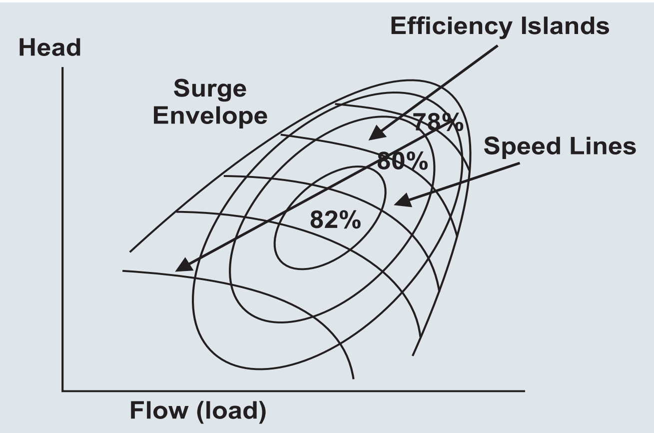


Figure 4: VSD centrifugal compressor map

(Another method of capacity control – hot gas bypass (HGBP) – is an option that can unload the chiller to zero load. While there are operational benefits of using HGBP to prevent cycling the chiller on and off at ultralow loads, it is normally used for loads below 10% because otherwise it is an inefficient way of turning down capacity.)

- *VSD Capacity Control* is the intelligence that regulates capacity and refrigerant flow. Impeller rotation drives the refrigerant compression cycle by establishing the pressure differential that the chiller needs for proper operation. This differential is referred to as 'lift'. The pressure difference is a function of the leaving chilled liquid temperature and the leaving condenser liquid temperature, as well as the heat transfer between those liquids and the refrigerant. Speed must always be maintained above the minimum necessary to create the required lift (pressure difference) between the condenser and evaporator, regardless of load. VSD capacity control reduces motor speed as much as possible while maintaining chilled liquid temperature and sufficient lift/head pressure to prevent gas surge in the compressor.

By optimizing compressor speed to more closely matched load requirements, VSD capacity control reduces chiller power consumption. With a magnetic bearing compressor, VSD capacity control handles a wider range of conditions.

- *Variable Geometry Diffuser* (VGD) is used when speed cannot be reduced further due to the lift required for the specified leaving chilled water temperature setting. Consequently, the available cooling to the condenser and capacity must be further reduced. In this case, VGD is employed at the exit of the impeller to reduce refrigerant gas flow. The VGD not only controls capacity, but also serves to mitigate 'stall'. Stall is an effect caused by slow refrigerant gas passing through the compressor at reduced flow rates during low-capacity operation. With a magnetic bearing VSD centrifugal compressor, the VGD can be fine tuned for very precise control.

Of the various capacity control techniques employed in VSD chillers, advanced magnetic bearing chillers only use VGD and speed. At certain operating points, some magnetic bearing chillers will increase speed and close VGD to control capacity.

Moving VSD Chiller Efficiency Forward with Magnetic Bearing Compressor Technology

Depending on the chiller manufacturer, magnetic bearing compressor technology can be integrated into a VSD chiller design to boost efficiency and handle a much wider capacity and lift range (operating envelope) than a standard VSD centrifugal chiller.

A magnetic bearing compressor that uses neither oil nor refrigerant lubrication dramatically improves VSD chiller performance through enhanced motor efficiency and eliminating gearbox energy losses.

To appreciate how this is done, it helps to understand the components of a magnetic bearing compressor.

- *The bearing rotor and stator* use electromagnetic forces to levitate the shaft in a magnetic field without the need for conventional contact bearings or brushes. The magnetic field can be produced either by using rare-earth magnets that are permanently embedded in the rotor, or by passing an AC current through stator windings to produce magnetic forces that repeal and attract the rotor into motion.

- *Impeller* is integrated with the rotor and is overhung from the end of the motor shaft. No gearbox is employed.
- *Position sensors* identify the position of the shaft in several axes. Forces of magnetic attraction are modulated to levitate the rotor shaft into a precise position in the magnetic field.
- *Compressor controller* regulates the current sent to the magnetic bearing stator to keep the shaft at a predefined position. The controller applies the optimum current to the coils by monitoring the position signal from the positioning sensors to keep the shaft at the desired position throughout the operating range of the machine. The controller maintains the air gap between the rotor and stator.
- *Chiller control* with a VSD compressor involves a lot of data, but a magnetic bearing compressor processes even more. The chiller control continuously monitors several operating conditions, such as chilled water, chilled water set-point, refrigerant pressures and the actual motor speed. This information is then fed to a microprocessor that determines the most efficient way to operate. The frequency of the power input to the motor is optimized to consume the least amount of energy.

Advantages of Advanced Magnetic Bearing Compressor Technology

The inherent design advantages of an advanced magnetic bearing compressor translate into numerous operational and performance benefits.

No Oil Lubrication System Needed

There are no gearboxes and no surface-to-surface contact between bearings and shaft, which eliminates mechanical friction losses. (Bearings are included in the motor, but only engage when shaft rotation stops, thereby providing a safe touchdown for the shaft during chiller shut-down or loss of power.)

Without mechanical bearing friction, no lubrication system is needed. Several benefits results:

- No need for an additional lubrication circuit and ancillary heat exchangers and piping, which reduces auxiliary power, capital costs and maintenance issues.

- No need to maintain pressure differential between the evaporator and condenser to circulate the lubricant – whether oil or refrigerant type – as it goes through the bearing system, which increases operating range.

- No cooling subsystem is needed, because the hermetic motor can be cooled by refrigerant suction gas.

Expanded Operating Envelope

One parameter that determines a chiller's operating envelope is entering condenser water temperatures (ECWT). Based on city and month of operation, the wet bulb temperature (WBT) can vary significantly from design weather conditions. It is recommended that for every chiller installation a full weather analysis is carried out to see how many hours are available at different entering condenser water temperatures. Even warm tropical climate cities like Mumbai have a large reduction in WBT from design monsoon conditions compared to other months.

A magnetic bearing chiller can operate as long as it is within the acceptable lift range for the impeller and is not limited by any other factor, such as motor cooling or oil loss to evaporator. *Figure 5* shows the operating envelope of an advanced magnetic bearing chiller demonstrating performance at the 100% load point with varying ECWT down to 36˚F (2˚C). It is possible to achieve 100% load at 40˚F (4˚C) condenser entering fluid temperature (CEFT) for 0.2 kW/ton. A tropical climate may not see such low WBT or cooling tower (CT) water temperatures. Nevertheless, similar lower lift conditions occur with higher chilled water (CHW) temperatures of 60˚F (15˚C) to 70˚F (21˚C) used in data center applications or in a dual loop system using chilled beam or radiator cooling. In these cases, the sensible load is addressed by a cooling system having high chilled water temperature.

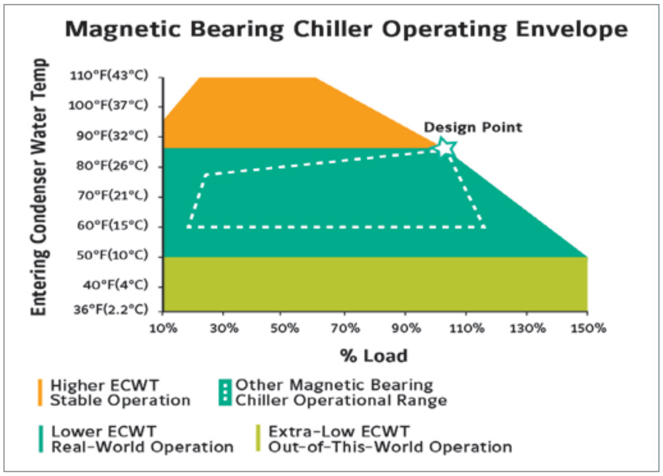


Figure 5: Operating envelope of a magnetic bearing chiller

If a chiller can utilize lower ECWT or high leaving CHW temperature, it is possible for the chiller to run in an 'inverted' manner. In this situation, ECWT is below the leaving chilled water temperature (LCHWT). Certain magnetic bearing compressor designs can handle ultralow ECWT by continuing to spin the impeller to maintain a pressure differential that moves refrigerant from the condenser to the evaporator. A magnetic bearing chiller's ability to utilize extremely low ECWT lets the operator take advantage of using cold outdoor conditions for indoor cooling without the need for waterside economizers/free-cooling heat exchangers, which saves space and capital expense. Low ECWT, for example, is available in northern cities of India like Delhi.

Now, let us briefly look at high ECWT. Based on how the capacity control is designed, some magnetic bearing centrifugal chillers can be used as heat pumps if there is a very high ECWT above 90˚F (32˚C).

Lifespan

Magnetic bearings have a theoretically infinite lifespan. There is no routine maintenance, inspection or teardown schedule required. The expectation is that magnetic bearings will be operational for the life of the chiller. For that reason, the magnetic bearing design has been successfully used in turbo-machinery for decades – even in centrifugal chillers on board submarines – where replacement at sea is not feasible.

Quieter Operation

Magnetic bearings have quieter operation with less vibration. Sound as low as 73 dBA has been measured on magnetic bearing centrifugal chillers. Vibration detection is accomplished with an accelerometer incorporated into the compressor for lubricated chiller designs. The magnetic bearing control system constantly monitors the position of the shaft at very high sampling rates to optimize rotor position. This function is different from accelerometers used on contact-bearing chillers that simply detect increasing vibration as a warning system.

Figure 6: A magnetic bearing chiller installation

Low Amperage

Low amperage draw provides many electrical benefits. With a VSD compressor, power is initially applied for startup at a very low frequency and then gradually increased, minimizing motor slip. With a magnetic bearing compressor, startup amps can be as low as 2 amps compared to over 500 amps for a constant-speed compressor. Moreover, the inrush current for the motor never exceeds 100% full load amps (FLA). Other soft starters, such as Star-Delta or Solid State starters, have 200 to 400% FLA as the inrush current at startup. Consequently, a magnetic bearing VSD is an ideal starter for applications with limited inrush capabilities, such as emergency generator systems. Also, the generators and cabling can be downsized, because they do not need to carry the extra current for startup.

Other Electrical Benefits

Fast Startup if Power is Lost

Adding to the soft start benefit, a magnetic bearing chiller may enable a fast restart if power is lost compared to a half-hour or more with conventional centrifugal chillers.

High Power Factor

Like other VSD centrifugal compressors, a magnetic bearing compressor enables a high power factor up to 95% at all operating conditions. A normal centrifugal chiller or screw chiller has a power factor of 0.85 at 100% load which further reduces at part load and can go down to as low as 0.60. With lower power factors, many utilities require correction or impose financial penalties.

Power Demand Limit Feature

When a demand limit feature is incorporated into a magnetic bearing chiller, the user has the flexibility to set electrical load limits. For example, a 200 TR (700 kW/TR) chiller with a full power load of 100 kW can be powered by just 50 kW to manage the electric load. Maximum current and ramp rates can also be adjusted.

Considering Real World Applications

Given the general advantages of magnetic bearing compressors, are they beneficial when applied to water-cooled centrifugal chillers in South Asian applications?

Because magnetic bearing compressors provide more flexibility in the operating envelope than oil-lubricated compressors, designers can handle more challenging applications such as data centers or green buildings where high chilled water supply temperatures of 60˚F (15˚C) to 70˚F (21˚C) can be utilized in a dual loop system.

The higher chilled water temperature (CHWT) required in lubricated (oil or refrigerant) compressor designs with a semi-hermetic motor necessitates a higher ECWT: 70˚F (21˚C) to 80˚F (27˚C). Each 1˚F (0.56˚C) increase in CHWT limits the minimum ECWT proportionately. Such limitations result in excess power consumption, which does not occur in magnetic bearing chillers that can utilize lower ECWT.

Coastal tropical cities in Southeast Asia may not see lower condenser water temperatures of 55˚F (13˚C). But many sites operating with higher design CHWT and the intention of saving power actually employ a cooling tower interlock to limit the reduction of ECWT – a necessity that increases power consumption. Magnetic bearing chillers can be designed to totally eliminate this limitation and save kWh in these real-world operating conditions.

Conclusion

In the real world, a chiller's performance is a factor of how it operates in off-design conditions. Magnetic bearing compressors have pushed the operating envelope and efficiency of VSD centrifugal chillers to new levels.

Even in warm tropical climates, efficiency models show that a 400TR magnetic bearing centrifugal chiller can provide annual energy savings of 15 to 25% compared to high-efficiency fixed-speed centrifugal or positive-displacement screw chillers, depending on city weather data and operating hours. A magnetic bearing chiller outperforms conventional VSD chillers by 5% to 8% based on capacity and operating conditions. Consequently, even for challenging South Asian applications, magnetic bearing chillers have an advantage in reducing a facility's energy consumption and carbon footprint, and providing a quick payback and return on investment that is particularly attractive for facilities requiring continuous cooling, such as hotels, hospitals, call centers, software centers and universities.