Permanent Magnet Technology within Direct Drive Cooling Tower Motors Creates System Energy Savings

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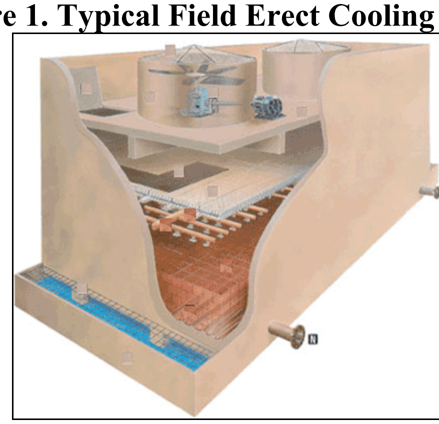
ABSTRACT

At a time were energy efficiency is of utmost importance recent developments in motor technology have changed the playing field within cooling tower HVAC systems. This new permanent magnet / laminated frame motor technology allows for the removal of all the mechanical components such as gearboxes, drive shafts, disc couplings and existing motors and replaced them with one direct drive CTPM motor. With the removal of these mechanical components you also remove their mechanical energy losses decreasing your overall system energy demands. Not to mention the higher motor efficiency gains with PM technology over standard induction motor efficiencies. A case study will be presented where an existing tower was refurbished utilizing the developed Motor Technology with a focus on energy and efficiency gains.

Introduction

To more fully understand the benefits of this technology an understanding of the cooling tower application is important to clarify. There are typically two types of cooling towers found in the industry, Cross flow towers and counter flow towers. These are defined by what direction the air passed over the waste water. A cooling tower is defined as a structure which extracts waste heat from a process and distributes it to the atmosphere. The most common method is to let heated water fall through a moving air stream created by a fan located at the top of the tower. This is an evaporative process which takes a large amount of heat from the process. The heated water is distributed over a "fill" material which increases surface area that the water travels on and increases the cycle time within the tower. The water is cooled as it descends through the fill. The cooled water is then collected in a cold water basin below the fill from which it is pumped back through the process to absorb more heat. A typical tower arrangement is shown in Figure 1.

Figure 1. Typical Field Erect Cooling Tower



Commonly, the size of a tower is identified by the diameter of the fan. Fan sizes range from 6 to 40 feet, with the most common applications in the 10 to 26 foot range. The speed of the fan is typically limited by industry standards for stressing which are typically rated as a max fan tip speed of 12,000 fpm. This max tip speed typically generates a fan speed in the range of 147-382 rpm. As the fan diameters become smaller or larger than the 10-26 ft sizes the fan speeds can differ. The most common solution for driving the fan in current cooling tower designs utilizes an induction motor, driveshaft, disc couplings, and gearbox arrangement, as shown in Figure 2. Few changes to this design have been made in the last thirty years.

Figure 2. Typical Fan Drive Arrangement

The motor used is normally a standard NEMA induction motor. Cooling tower applications follow fan affinity laws which state that HP varies by the cube of the fan speed. To reduced energy consumption, two speed motors have been applied for use when full fan speed is not required due to decreased heat load. When the heat load decreases enough, the drive motor can be run at half speed. This lowers the horsepower required to only 12.5% of the rated value. However, when any air flow even slightly above that provided by half speed operation is required, a two speed motor must be run at rated horsepower as there is no other speed available. Two speed motors do provide some energy savings, but still must be cycled on and off to maintain the desired water temperature. This cycling involves many "across the line" starts drawing high amps and placing unnecessary strain on the mechanical components of the system.

The use of variable frequency drives (VFDs) has become much more commonplace in recent years within the industry on new construction due to the energy savings associated with the fan affinity laws. Additionally, most towers being upgraded or refurbished are also being equipped with VFDs. These drives have the advantage of a soft mechanical start, no large starting current draw, and the ability to run the fan at any desired speed from zero to the maximum design speed for the application. The energy savings realized by using a VFD are well recognized and documented.

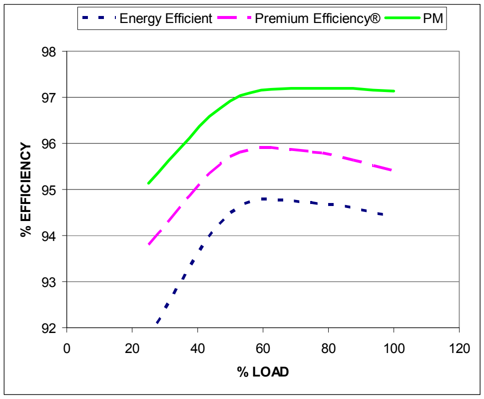
Historically, the mechanical components of the fan drive system, specifically the right angle gearbox, have been the largest maintenance issue for cooling tower installations. Gearbox failures, oil leaks, oil contamination, failed drive shafts, misaligned drive shafts and excessive vibration are all significant problems related to this type of fan drive system.

In this paper, recent developments in motor technology are presented. It is demonstrated how these innovative designs can be used to improve the reliability and reduce maintenance associated with today's cooling tower installations. The design and installation of a 208 rpm, 50 horsepower PM motor for a retrofit application is discussed in detail. The possibility of improved efficiency and lower energy consumption with the proposed solution is discussed.

Improvements in Motor Technology

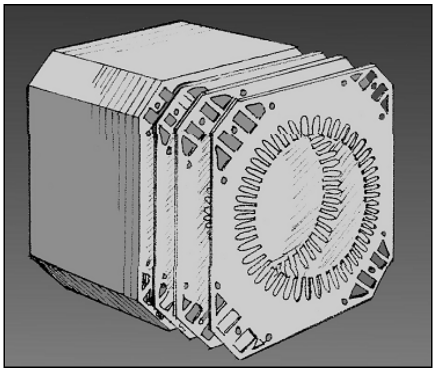
Increased efficiency and improved power density are being demanded in the motor industry. To achieve these goals, along with lower noise and adjustable speed operating capability, other technologies beyond simple induction motors should be considered. PM motors have long been recognized as providing higher efficiencies than comparable induction motors. However, limitations in terms of motor control, as well as magnet material performance and cost, have severely restricted their use. Due to dramatic improvements in magnetic and thermal properties of PM materials over the past 20 years, synchronous PM motors now represent viable alternatives. Figs. 3 shows a efficiency comparison for various motor types.

Figure 3. Typical Partial Load Efficiencies of 75 HP, TEFC, 1800 RPM Motors



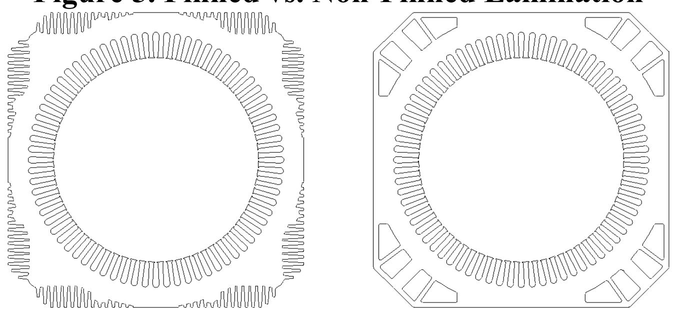
Another innovation which merits discussion is the laminated frame motor technology used in this design. Laminated frame motors consist of a stack of laminations permanently riveted under controlled pressure. The cast iron outer frame normally associated with a NEMA motor is eliminated, allowing more room for active (torque producing) magnetic material. Fig. 4 below is a representation showing how the stator frame is constructed.

Figure 4. Laminated Frame Construction



Another advantage of this construction is that the air used to cool the motor is in direct contact with the stator laminations. There is no thermal resistance path which exists in a traditional cast iron frame with contact to the stator lams. The heat transfer mechanism in a cast iron frame motor is highly dependent upon the stator to frame fit. Laminated frame construction eliminates this issue. In recent years, industry drivers have forced the development of an optimized, finned, laminated motor design. To improve the cooling and increase power density, fins have been added to the exterior of the stator laminations. The addition of the optimized cooling fins increases the surface area available for heat dissipation. The result is improved heat transfer and a power increase of 20-25% is typical for a given lamination diameter and core length. Fig. 5 shows the increased surface area achieved by including these cooling fins.

Figure 5. Finned vs. Non-Finned Lamination



It is this improved cooling method, along with the higher efficiency with the PM technology that allows for increased power density in these motor designs. Power density is the key for being able to match the height restriction of the existing gearbox.

Case Study

The case study involves the retrofit of an existing cooling tower constructed in 1986 at a university in the Southeast. The tower information is as follows:

Fan Diameter:	18 ft
Flow Rates:	4,250 gallons per minute (GPM) per cell - 8,500 GPM total
Motor Information:	Frame – 326T
	HP – 50/12.5
	Speed – 1765/885 rpm
Gearbox:	Size – 155, Ratio – 8.5:1

As shown in the previous data, this tower is comprised of two identical cells. For this study, one cell was retrofitted with the new slow speed PM motor and ASD while the other was left as originally configured. This allowed for a direct comparison of the two fan drive solutions. Fig. 6 below shows Cell #1 in the original configuration, while Fig. 7 shows the PM motor installed in place of the gearbox in Cell #2.

Figure 6. Original Installation

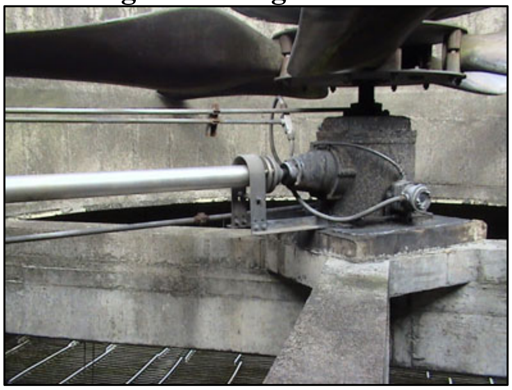


Figure 7. PM Motor Installed

Prior to the installation, the current being drawn by the two original induction motors was measured with the fans running at full speed. An ammeter was used and the current was measured to be forty seven (47) amps, rms on both induction motors. As the induction motors are identical, this is a good indication that both cells were operating under the same load conditions. After the PM motor and ASD installation was complete, the current was again re-checked and found to be only forty one (41) amps for the PM motor. The induction motor on the original, identical, tower was still drawing forty seven (47) amps.

A power meter was used to measure the input power to both solutions. The fans were both running at 208 rpm. Data was taken at both the input and output of the drive to allow for a direct comparison of the induction motor / gearbox combination to the PM motor. The results of the measurements are shown in Table 1.

Table 1. Power Consumption Comparison Original (9°) Blade Pitch, Manufacturers Data

Location	Volts, mean	Amps, rms	Input kW
Input to Induction (Cell #1)	477	46.7	31.5
Input to ASD, PM (Cell #2)	477	44.5	28.5
Input to PM (Cell #2)	459	40.9	28.0

From this data, it was determined that both cells were running at less than full load and that the load should be increased on each cell. To this end, the pitch of the blades on each fan was increased to 12°. This change of pitch caused the fans to draw more air, thus increasing the load on each motor. Further, the increased air flow improved the effectiveness of the overall tower performance. Again, power measurements were made and a third party testing service was engaged to verify the manufacturer's results. The data is shown in Tables 2 & 3 below.

Table 2. Power Consumption Comparison 12° Blade Pitch, Manufacturer's Data

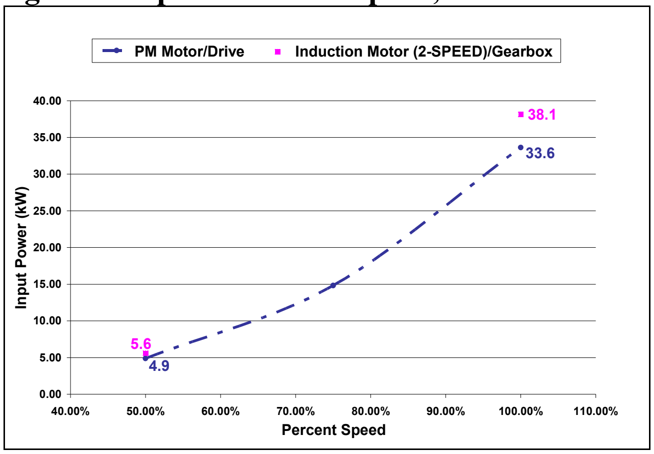
Location	Volts, mean	Amps, rms	Input kW
Input to Induction (Cell #1)	477	54.8	38.1
Input to ASD, PM (Cell #2)	477	49.8	33.6

Table 3. Power Consumption Comparison 12° Blade Pitch, Testing Service Data

Location	Volts, mean	Amps, rms	Input kW
Input to Induction (Cell #1)	478	54.3	37.9
Input to ASD, PM (Cell #2)	477	49.8	33.0

For the final blade pitch of 12°, 4.5 kW less power consumption was observed on Cell #2 with the PM motor installed. In order to document the savings realized at various speeds on this application, input power was recorded at intermediate speeds for the PM motor cell. Fig. 8 below shows the actual measured input power for the induction motor / gearbox solution and the PM motor solution at various speeds.

Figure 8. Input Power vs. Speed, 12° Blade Pitch



As shown in Tables 2-3, the PM motor solution requires less input power for the given blade pitch setting. Fig. 8 shows the total input power in kilowatts for each solution over a range of operating speeds from 50-100%. Again, the PM motor has an advantage over the induction motor / gearbox combination. Using an average price of $.08/kWh, the annual cost savings for various applications and duty cycles are shown in Table 4. This table does not account for the additional savings achieved by using an ASD and having the ability to run at speeds between 50% and 100% of rated.

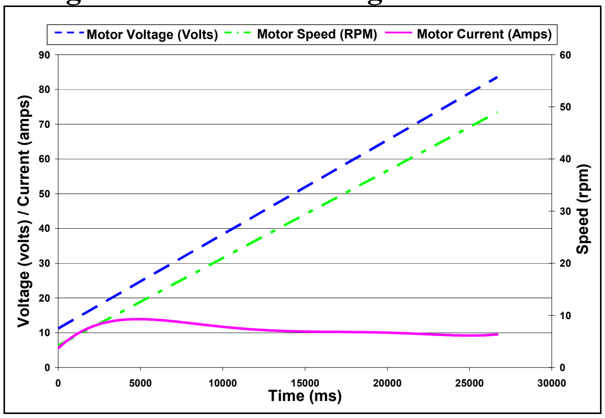
Table 4. Annual Energy Savings Based on Various Duty Cycles

		Annual Savings (%High Speed/%Low Speed)		
Application	Daily Use	100 / 0	75 / 25	50 / 50
Cooling Tower	24 hrs.	$3154	$2488	$1822
	18 hrs.	$2365	$1866	$1367
	12 hrs.	$1577	$1244	$911

Electrical Considerations

In addition to the PM motor design features already detailed, another challenge of this application was that the PM motor had to be run sensorless. There was no room to install a speed feedback device, such as an encoder or resolver, and still meet the height restriction of the existing gearbox. In this harsh environment, a feedback device would be a liability as far as reliability is concerned. Therefore, a sensorless PM control scheme was developed to satisfy the requirements of this application. Several things had to be considered when forming this algorithm. One challenge was the inertia of the fan. This was taken into account to prevent the motor from falling out of synchronism when starting and changing speeds. Figure 9 is a portion of a typical start from rest. Note the smooth acceleration and low starting current required. A typical 480 volt induction motor started across the line would draw 347 amps, compared to 12 amps for this PM design started on the VFD.

Figure 9. Motor Starting Performance



Braking and Condensation Control

The use of a VFD also provides the opportunity to offer some additional features that across the line systems do not. The drive may be configured to apply a trickle current to the motor windings to act as a brake during down time. This prevents the fan from free wheeling due to nominal winds or adjacent cooling tower turbulence. However, a mechanical locking mechanism should be using during any maintenance procedures. This trickle current also acts as an internal space heater by raising the winding temperature, preventing condensation when the motor is not running.

Insulation System

Inside the fan stack is an extremely humid environment. Therefore, the insulation system on the stator windings must be robust and highly moisture resistant. To this end, an insulation system derived from a system originally developed for use by the US Navy was employed. This system utilizes an epoxy compound applied via a vacuum pressure impregnation (VPI) system. The VPI system is widely recognized as a superior insulation system for harsh applications such as this. This particular system has been successfully employed on "open" motors in tough applications such as oil platforms operating in the North Sea.

Mechanical Considerations

Shaft Seal

Due to the harsh environment inherent with a cooling tower application, the motor's drive end is protected by a metallic, non-contacting, non-wearing, permanent compound labyrinth shaft seal that incorporates a vapor blocking ring prevent an ingress of moisture. This seal has been proven to exclude all types of bearing contamination and meets the requirements of the IEEE-841 motor specification for severe duty applications. This type of seal has been successfully used in cooling tower gearboxes for many years.

Maintenance

Another consideration is overall system maintenance. For motor / gearbox combination drives, the lubrication interval is determined by the high speed gear set. The recommended lubrication interval for this type of gear is typically 2500 hours or six months, whichever comes first. In addition, gear manufacturers recommend a *daily* visual inspection for oil leaks, unusual noises, or vibrations. As these units are installed in areas which are not readily accessible or frequented, this is an unreasonable expectation and burden on maintenance personnel. When a gear is to be idle for more than a week, it should be run periodically to keep the internal components lubricated because they are highly susceptible to attacks by rust and corrosion. When being stored for an extended period, it is recommended that the gearboxes be completely filled with oil and then drained to the proper level prior to resumed operation. Because the high speed input has been eliminated with the slow speed PM motor design, the lubrication cycle can now be extended up to two years. The PM motor need not be inspected daily for oil leaks, as the motor contains no oil. As mentioned previously, the VFD can provide a trickle current to heat the stator windings to a temperature slightly above ambient to prevent moisture from forming inside the motor.

Vibration

With the elimination of the high speed input to the gearbox, the system dynamics from a vibration standpoint have been simplified. There are no longer any resonance issues with the driveshaft. The maximum rotational excitation is now limited to the rotational speed of the fan. The number of bearings in the drive system has been reduced from six to two for a single reduction gearbox and from eight to two for a double reduction gearbox. This reduces the number of forcing frequencies present in the system.

Noise Level

Many cooling towers are in locations where airborne noise can be an issue, such as hospitals and universities. To this end, a third party testing company was engaged to conduct comparative sound tests between the two cells. Data was taken at both high speed and low speed for both cells. The induction motor cell was designated as Cell #1 while the PM motor cell was designated as Cell #2. Sound level measurements were taken on Cell #1 while Cell #2 was turned off. There were twelve 30-second readings taken at high speed and twelve 30-second readings taken at low speed around the perimeter of the tower and the fan motor. As there was no motor outside of the fan stack on Cell #2, only nine readings were taken on Cell #2 with Cell #1 turned off. A single point measurement was taken where the old induction motor was mounted on Cell #2 in order to have some reference to Cell #1. It was not possible to turn off the water flow for either cell at any time so there was a significant amount of background noise, but as this condition was the same for both cells, it should not affect the comparative data. Average A-weighted sound pressure results are shown in Table 6 for both high speed and low speed operation.

Table 6 – Sound Pressure Data

	A-weighted Average	
Cell	**High Speed**	**Low Speed**
Induction	**82.3 dBA**	**74.4 dBA**
PM	**77.7 dBA**	**69.0 dBA**

At high speed, the PM motor cell was 4.6 dBA lower than the induction motor cell. For low speed operation, the PM motor cell was 5.4 dBA lower. Although there may be some slight differences in the background noise for each cell, these likely do not account for all of the noise level reduction realized with the PM motor solution. The removal of the high speed induction motor from the outside of the fan stack appears to have the biggest influence on the noise level of the tower itself.

Conclusions

Cooling tower fan drives have changed very little over the past two decades. Failures of the gearbox, driveshaft, or disc couplings have been the biggest reliability issue facing tower manufacturers and end users. Increasing energy costs have placed a premium on power consumption for all motors and applications.

Many of the problems associated with cooling tower maintenance and reliability are solved with the PM motor design. The relatively high speed (typically 1750 rpm) induction motor has been eliminated. The motor itself has not historically been a problem, but the associated resonances and potential vibration concerns have been an issue. The driveshaft and associated disc couplings have been removed, thus eliminating problems associated with misalignment, improper lubrication, natural frequencies, or delaminating of the driveshaft itself. The right angle spiral-beveled gearbox has been removed. Difficult maintenance associated with changing the oil, proper oil fill levels, contamination of the oil, oil leaks, and gearbox failures is no longer a concern.

New motor technology now provides an alternative solution, the direct drive of cooling tower fans. PM motor technology combined with the finned, laminated frame design now allows the construction of low speed, compact motors for use in place of the existing gearbox. Data obtained to date indicates this solution will eliminate the problems associated with the right angle gearbox and drive shaft design. By eliminating the gearbox, which is a significant source of loss in the system, improved system efficiencies can be realized.

Acknowledgements

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