Improve Reliability and Reduce Maintenance with Direct Drive for Cooling Tower Fans

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Abstract – Cooling towers are in use at over 200 major electrical generating plants in the United States. Operation of these towers is vital to both nuclear and fossil-fired facilities. Improving reliability of these towers has been a major focus of the power generation industry for the last several years. Most large towers are constructed using a single or two-speed motor and right angle gearbox combination. Maintenance or failure of the right angle gearbox and associated components (drive shaft, couplings, etc.) has been problematic in these applications. This paper presents recent developments in motor technology that allow for the direct drive of cooling tower fans. Reduced maintenance and improved reliability can be achieved by using a slow speed, direct drive motor solution. A case study will be presented and the viability of this technology in large horsepower towers will be discussed.

I. INTRODUCTION

An open circuit cooling tower distributes heated water over a labyrinth-like packing or "fill." 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 [1]. Many towers are made up of multiple “cells”, with each cell having its own fan. A typical tower arrangement with two cells is shown in Fig. 1.

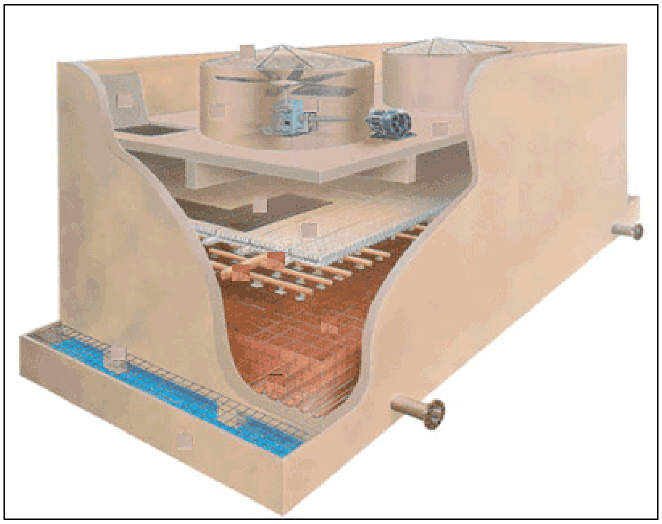

Fig. 1 Typical Tower Arrangement with Two Cells

For more than thirty years, the most common solution for driving the fan has used an induction motor, driveshaft, disc coupling, and gearbox arrangement, as shown in Fig. 2. Few changes have been made during this time.

Fig. 2 Typical Fan Drive Arrangement

Historically, the mechanical components of the fan drive system have been the largest maintenance issue for cooling tower installations [2]. 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 [3], [4]. In this paper, recent developments in motor technology are presented. It is demonstrated how these innovations can be used to improve reliability and reduce maintenance costs associated with today’s cooling tower installations. Plant implications are considered. The design and installation of a 50 horsepower, 208 rpm PM motor for a retrofit application is discussed in detail.

II. MOTOR TECHNOLOGY

A. Permanent Magnet Rotors

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. Permanent Magnet (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 & 4 show the efficiency and power factor for various motor types [5].

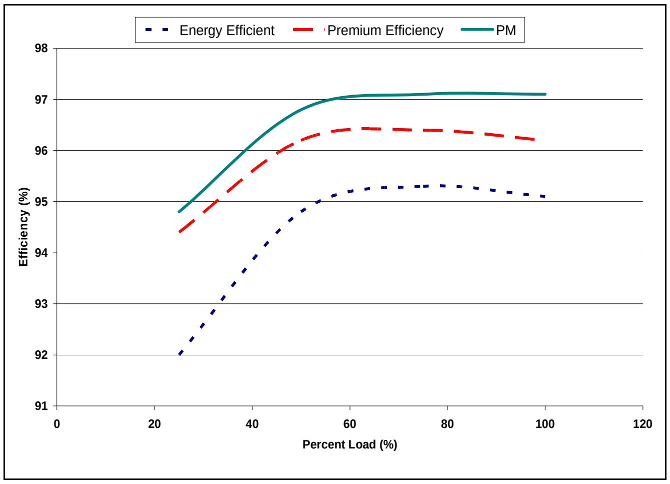

Fig. 3 Typical Partial Load Efficiencies of 150 HP, TEFC, 1800 RPM Motors

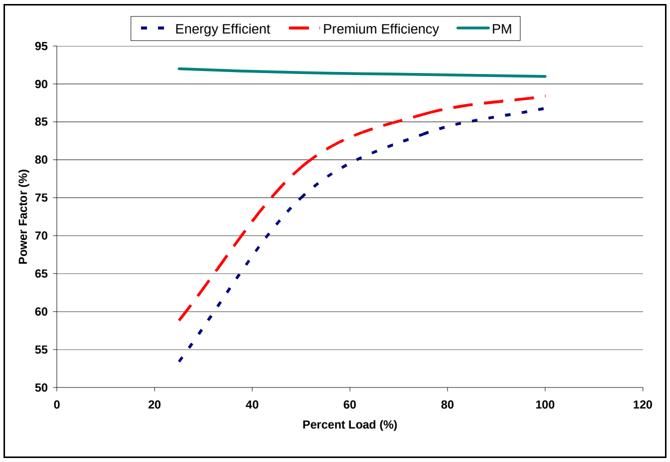

Fig. 4 Typical Partial Load Power Factors of 150HP, TEFC, 1800 RPM Motors

B. Laminated Frame Construction

Another innovation which merits discussion is laminated frame motor technology. 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) material. An added advantage of this construction is that the air used to cool the motor is in direct contact with the stator laminations. 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.

To further improve 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 is a representation showing how the stator frame is constructed. Fig. 6 shows the increased surface area achieved by including cooling fins.

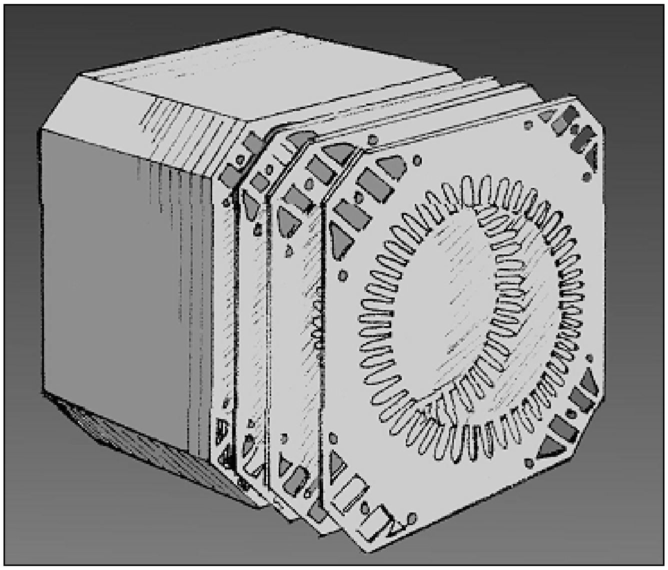

Fig. 5 Laminated Frame Construction

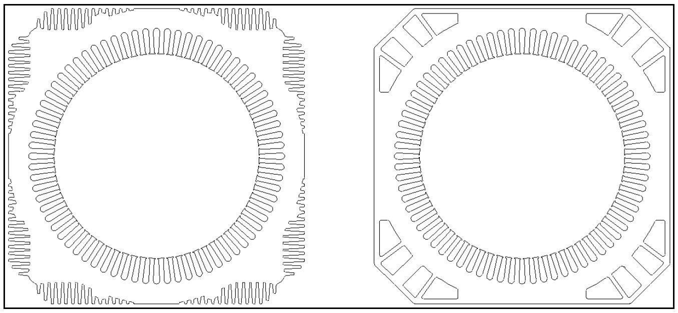

Fig. 6 Finned vs. Non-finned Lamination

C. Water Jacket Cooling

For higher horsepower ratings an alternative to air cooling is water cooling. With this method, the stator core is shrunk into a tubular steel frame that has a water jacket on the outside diameter of the frame. Cooling water is then introduced into this jacket and the stator core heat and losses are then transferred to the water for dissipation. This method of cooling has been popular for many years in the mining industry for motors 100 horsepower and above. Approximately 10 gallons per minute (GPM) through the water jacket are needed to provide the necessary cooling. This water can be taken from the make-up water supply necessary to replace the approximately 1% of water lost due to evaporation in an open tower design. For closed loop towers, a small portion of the water ethylene glycol mixture can be diverted through the water jacket prior to entering the cooling medium.

III. POWER DENSITY

It is these improved cooling methods, along with the higher efficiency achieved with the PM rotor technology that allows for increased power density in this type of motor design. This increased power density offers the opportunity to fit a low speed motor in the same space as the right angle gearbox in cooling tower applications and keep the weight at a reasonable level. For comparison, a study was performed to determine the approximate sizes and weights of various motor types for possible use in a cooling tower. The results are shown in Table 1 below. The rating is 120 horsepower at 180 rpm. Each motor was designed for the same temperature rise.

TABLE 1
MOTOR SIZE COMPARISON

Motor Type	Height (in.)	Width/ Diameter (in.)	Wt. (lbs.)
Cast Iron Frame Induction	45	40	10433
Finned, Laminated Frame PM	31	31	4411
Water-Cooled PM	26.75	26	2529

IV. MECHANICAL CONSIDERATIONS

A. Mounting

The motor is mounted using a flange located on the opposite drive end. In many cases, the motor mounting holes can match the bolt hole pattern of the existing gearbox. In other instances, an adapter plate can be used to mount the motor to an existing base design. On new towers, this would not be an issue, however it should be considered for retrofit installations.

B. 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 multi labyrinth shaft seal that incorporates a vapor blocking ring to prevent 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 [6]. In addition, a slinger is used on the drive end to further protect the seal from direct spray of moisture. There are only two ingress points for water into the motor, the shaft and the conduit box. By choosing the right seal and conduit box configuration, an IP56 protection rating can be achieved.

C. Corrosion and Paint

The environment inside the cooling tower is well known to be highly corrosive and is a concern for any equipment installed within. High levels of chlorides and sulfides are not uncommon in cooling tower water and any piece of equipment operating inside the fan stack is subject to a constant mist of water containing these chemicals. For this reason, it is important to address corrosion resistance as it applies to a motor being employed in this application.

As with any severe duty application, the user must specify the type of environment in which the motor will operate so the manufacturer can provide an appropriate paint system. Many different products are available for coating of the motor to withstand the harsh chemicals that may be present in the water of a cooling tower. The authors acknowledge the existence of multiple solutions to this problem, but offer the following as guidance in the selection process.

One option would be to coat the steel portions of the motor, such as the stator laminations, with an epoxy resin or other suitable corrosion preventing material. The cast iron parts may be e-coated (an electrically applied paint coating), which is a process that provides superior adhesion and corrosion resistance. Finally, a multi-layer epoxy top coat may be applied. If corrosion of the motor shaft is a concern, stainless steel shaft material can be used.

V. ELECTRICAL CONSIDERATIONS

A. Permanent Magnet Control Algorithm

This type of PM motor must be used with an adjustable speed drive (ASD) and cannot be started across the line. Data from a noted cooling tower manufacturer indicates that ASDs are being installed in the majority of all new towers being constructed. Additionally, most towers being upgraded or refurbished are also being equipped with ASDs. Adjustable speed drives have the advantages 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 [7]. The energy savings realized by using an ASD are well recognized and documented, so no further discussion will be introduced here [8].

One obstacle of this application is that the PM motor has to be run sensorless. There is often no room to install a speed feedback device, such as an encoder or resolver, and still meet the height restriction of the existing gearbox. Also, in this harsh environment, a feedback device would be a reliability concern. 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 is the inertia of the fan. This was taken into account to prevent the motor from pulling out of synchronism when starting and changing speeds. A typical 50HP, 480 volt induction motor started across the line would draw 347 amps [9], compared to 12 amps for this PM design started on the ASD.

B. Improved Process Control

As mentioned earlier, the addition of the ASD allows the user to more accurately and efficiently control the process. Fig. 7 shows a portion of the motor voltage, speed, and current for a typical start from rest. Note the smooth acceleration and low starting current required. Fig. 8 shows how the motor speed is changed automatically with control logic as the heat demand on the system changes with time.

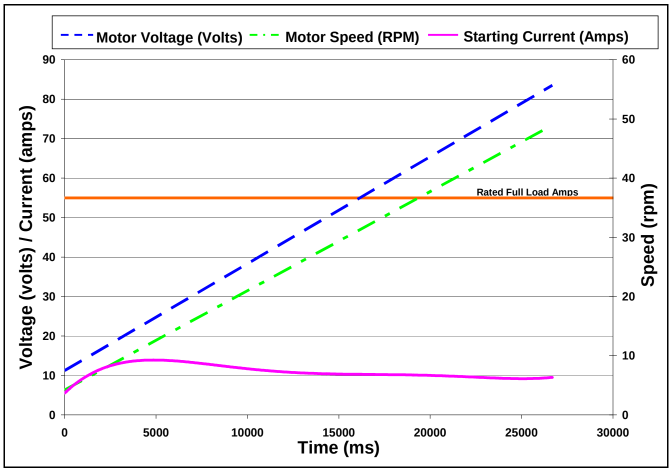

Fig. 7 Motor Starting Performance

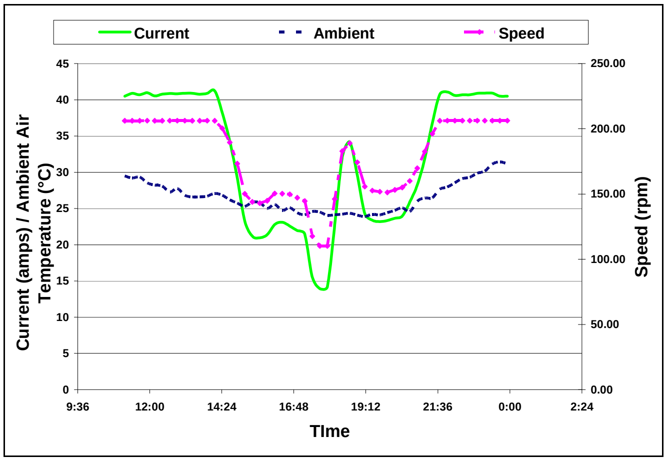

Fig. 8 Motor Speed Variation with Changing Heat Load

C. Braking and Condensation Control

The use of an ASD 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 wind milling due to nominal winds or adjacent cooling tower turbulence. However, a mechanical locking mechanism should be employed during any maintenance procedures, as is commonly used with the existing technology. This trickle current may also be used as an internal space heater by raising the winding temperature and preventing condensation when the motor is not running.

D. 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. It is recommended that an insulation system utilizing an epoxy compound applied via a vacuum pressure impregnation (VPI) system be employed. The VPI system is widely recognized as the superior insulation system for harsh applications such as this.

E. Insulated Bearings

The magnetic fields present inside the running permanent magnet motor are no greater in magnitude than the fields present in a comparable induction motor. As with all inverter fed motors, shaft currents may be present depending upon a number of factors including cable type, lead length, switching frequency of the adjustable speed drive, etc. Insulated bearings may be applied when the particular installation warrants. The authors have elected to include this section to emphasize that permanent magnet motors are no more or less susceptible to shaft currents than similar induction motor designs.

F. Generating Capability

A permanent magnet motor will act as a generator when the shaft is driven by a mechanical means, such as wind milling of the fan. The voltage generated at the terminals on open circuit is typically in the range of 1-2 Vrms line-to-line per revolution per minute (1-2 Vrms/rpm). This is not a particularly high voltage at low rpm, but it is necessary for maintenance and other personnel to be made aware of the potential of generated terminal voltage even on a disconnected motor.

VI. IMPROVED RELIABILITY AND REDUCED MAINTENANCE

The question of how this type of direct drive PM motor can help reduce maintenance cost and decrease downtime can be answered with one word - "simplicity". The installation of the low speed motor in place of the gearbox greatly simplifies the installation and reduces the number of moving parts. Not only is there a reduction of moving parts, but now the "high speed" parts are only operating at a fraction of the relatively high speed induction motor, bearings, driveshaft, couplings, and input gears on the planetary gearbox found on the geared design. In traditional fan drive designs, the gear ratio is typically from 4:1 to 12:1, resulting in speeds of mechanical rotation from 4-12 times that of the fan rpm.

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 that 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 resuming operation [10].

Because the high speed input has been eliminated with the slow speed PM motor design, the lubrication cycle can now be extended to one year. Once more field data is collected, it is believed that this interval can be increased, but a cautious approach is being taken until more history is developed. The PM motor need not be inspected daily for oil leaks, as the motor contains no oil. 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. For added protection, a vibration switch can be used as with typical gearbox installations. To this end, a flat pad may be incorporated on the side of the motor, which can be drilled and tapped to accept commonly used vibration sensors.

VII. PLANT IMPLICATONS

A. Reduced Maintenance Costs

In order to quantify the potential benefits of using the direct drive motor solution, two facilities with multiple cooling towers were audited to determine maintenance and repair costs over a six year time period. There were 16 towers with a total of 102 cells. The total six year maintenance cost associated with these towers was $3,189,957. This equates to an average maintenance cost of $531,660 per year. Unplanned maintenance accounted for 79% percent of this total. The data obtained to date indicates that approximately 81% of the unplanned maintenance was caused by problems inherent with the traditional fan drive solution. Further, some users manually adjust the fan blade pitch depending on the season. The use of an ASD would eliminate the need for this planned maintenance as well, because the speed of the fan could be increased or decreased to optimize air flow rather than using manual adjustment of the fan blades. A breakdown of the maintenance costs is shown in Table 2 below.

TABLE 2
FAILURE DATA

Facility	Number of Cells	Electrical Repairs	Mechanical Repairs	Total
A	82	$626,845	$994,800	1,621,645
B	20	$462,899	$1,105,413	1,568,312
Total	102	1,089,744	2,100,213	3,189,957

B. Maximize Cooling and Reduce Energy Consumption

It is well known that colder water temperatures result in increased condenser production at lower unit cost [11]. In fact, “enthalpy charts indicate that for every one degree F of colder water returning from cooling tower within operating range of compressors, 2½% less energy will be required by the compressor to produce the same cooling results.” [12] Elimination of the gearbox and associated component losses (typically 4-6%) may result in the ability to increase the blade pitch and generate more air for the same input horsepower. More air flow could result in lower cold water temperatures, thus positively affecting the condenser performance and reducing energy consumption.

C. Serviceability

With the installation of PM motors becoming more commonplace, the question of serviceability often arises. Rewinding the stator, bearing replacements, etc. are all possible for a PM motor just as with a typical induction motor, although some precautions must be taken due to the magnetized rotor assembly. In fact, the rotor assembly is the only real difference between this type of PM motor and induction motors historically used in most industrial applications.

The stator windings are generally lap wound, as with a common induction motor. Therefore, rewinding of the stator core is no more complex than for an induction motor. No special tools or processes are needed.

There is a magnetic force holding the rotor in the stator. The magnitude of this force will vary depending upon the rotor diameter and core length of the motor. When removing or installing the rotor, it is important to guard against the rotor pulling itself against the coil head and damaging the stator windings. Simple fixtures may be used as guides during the removal or insertion of a magnetized rotor.

Another often asked question is “what happens if the rotor becomes demagnetized?” The rotor can be demagnetized if the temperature capability of the magnets is exceeded. However, there are many different grades of magnets available, and by choosing the right one, the motor manufacturer can avoid this problem. Generally speaking, the rotor temperature will be lower than that of the stator windings due to the low rotor losses achieved by the use of permanent magnets. Also, the allowable operating temperature of the magnets can be selected to be greater than that of the winding insulation. Thus, by using winding temperature detectors or thermostats, both the windings and magnets will be protected.

VIII. 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’-0"
Flow Rate:	4,250 gallons per minute (GPM) per cell - 8,500 GPM total
Original Motor Information:	Frame – 326T induction HP – 50/12.5 Speed – 1765/885 rpm
Gearbox:	Size – 155, Ratio – 8.5:1

As shown above, this tower is comprised of two identical cells. For this study, one cell was retrofitted with a slow speed, direct drive 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. 9 shows Cell #1 in the original configuration, while Fig. 10 shows the PM motor installed in place of the gearbox in Cell #2.

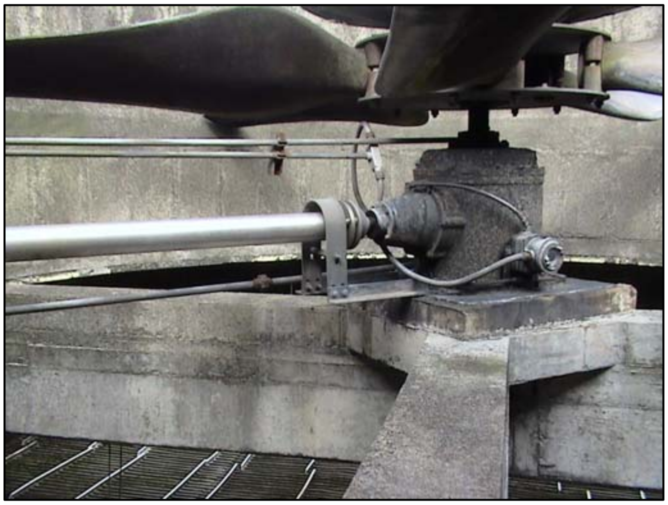

Fig. 9 Original Installation

Fig. 10 PM Motor Installed in Place of Gearbox & Driveshaft

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. Power measurements were made and a third party testing service was engaged to verify the manufacturer's results. The data is shown in Tables 3 & 4. For the final blade pitch of 12°, 4.5 kW less power consumption was measured on Cell #2 with the PM motor installed.

TABLE 3
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 4
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

Many cooling towers are in locations where airborne noise can be an issue. 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 at the location 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 [13]. Average A-weighted sound pressure results are shown in Table 5 for both high speed and low speed operation.

TABLE 5
SOUND PRESSURE DATA

	A-weighted Average	
Cell	High Speed	Low Speed
Induction (Cell #1)	82.3 dBA	74.4 dBA
PM (Cell #2)	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 higher speed induction motor from the outside of the fan stack appears to have the biggest influence on the overall noise level of the tower itself.

IX. 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 a direct drive, low speed, PM motor. 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 [14]. The right angle spiral-beveled gearbox has been removed. Difficult maintenance issues associated with changing the oil, proper oil fill levels, contamination of the oil, oil leaks, and gearbox failures are no longer a concern.

New motor technology now provides an alternative solution, the direct drive of cooling tower fans. PM motor technology combined with a finned, laminated frame or water jacket design makes possible 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 may be realized. There is no reason this technology cannot be applied to towers requiring 200 horsepower or more. The biggest concern may be the weight of the motor as compared to the gearbox, but with the use of the cooling methods discussed, weight can be kept to a minimum.

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XI. VITA

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