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## RECENT DEVELOPMENTS IN MOTOR TECHNOLOGY ALLOW DIRECT DRIVE OF LOW SPEED COOLING TOWER FANS

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**Abstract - Improved reliability of cooling tower fan drives is now possible due to new advancements in motor technology. This paper discusses the development of low speed, permanent magnet motors and how they can be used in direct-drive applications to eliminate the gearbox, NEMA motor, driveshaft, and disc couplings from cooling tower designs. A case study is presented where a tower was refurbished using a direct-drive motor designed to fit the exact footprint and height of the existing gearbox. Design considerations, performance data, maintenance, and efficiency comparisons will be discussed.**

## I. INTRODUCTION

The most common solution for driving the fan in current cooling tower designs utilizes an induction motor, driveshaft, disc coupling, and gearbox arrangement, as shown in Figure 1. Few changes to this design have been made in the last twenty years.



**Figure 1: Typical Fan Drive Arrangement**

The motor used is normally a standard NEMA induction motor. For reduced energy consumption, two speed motors have been applied for use when full fan speed is not required due to decreased heat load. As the horsepower required to drive the fan varies as the cube of the fan speed, it is advantageous to reduce the fan speed when possible. 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 [1]. 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 [2]. While providing some flexibility in the tower control logic, two speed motors are not optimal when it comes to maximizing energy savings during times of reduced heat load.

The use of variable frequency drives (VFDs) has become much more commonplace in recent years. Data from a noted cooling tower manufacturer indicates that VFDs are being installed in the majority of all new towers being constructed. 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 [3]. The energy savings realized by using a VFD are well recognized and documented, so no further discussion will be introduced here [4]. Several factors that must be considered when applying a VFD are any critical speeds of the mechanical system, the cooling ability of the induction motor at low speed, and the proper lubrication of the gearbox at slow speeds. For practical purposes, the fan is generally not run at speeds below 30% of the nominal design speed.

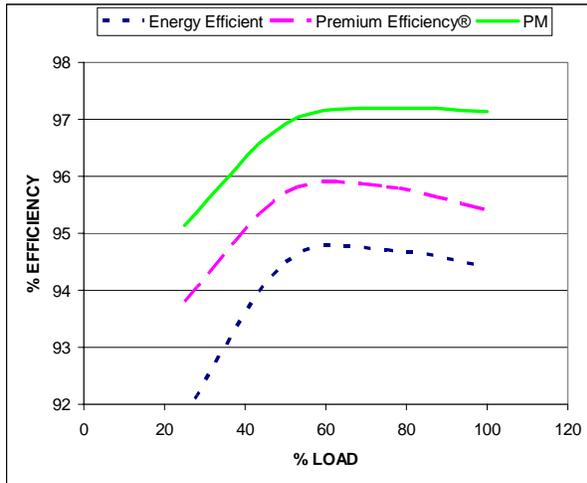
Historically, the mechanical components of the fan drive system, specifically the right angle gearbox, have been the largest maintenance issue for cooling tower installations [5]. Gearbox failures, oil leaks, oil contamination, failed drive shafts, misaligned drive shafts and excessive vibration are all significant problems related to this type of fan drive system [6], [7].

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.

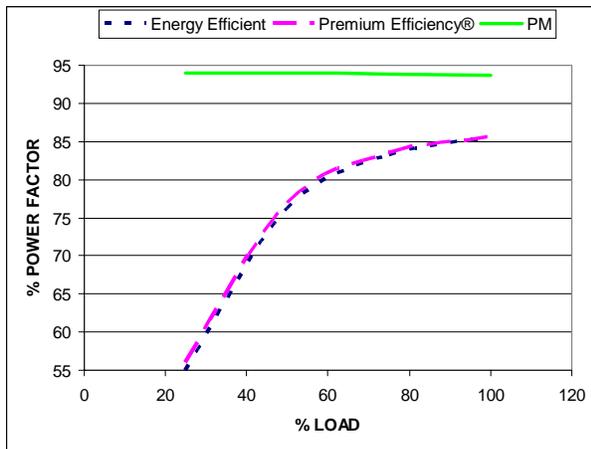
## II. IMPROVEMENTS IN MOTOR TECHNOLOGY

Increased efficiency and improved power density are being demanded in the motor industry. To achieve these goals, along with lower noise and variable 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. Figures 2 & 3 show typical efficiencies and power factors for various motor types [8].

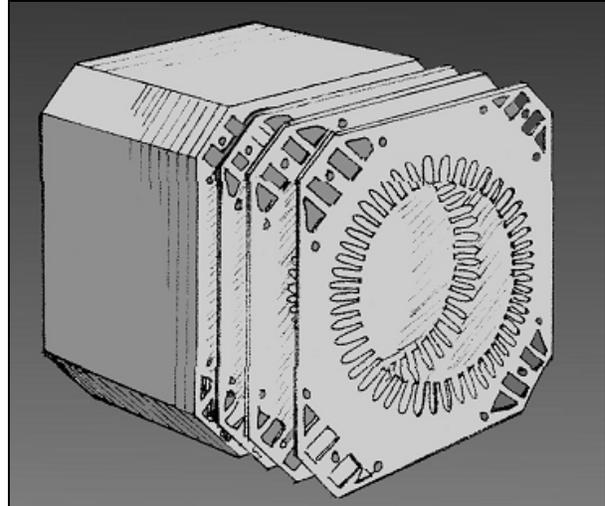


**Figure 2 - Typical Partial Load Efficiencies of 75 HP, TEFC, 1800 RPM Motors**



**Figure 3 - Typical Partial Load Power Factors of 75HP, 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 is eliminated, allowing more room for active (torque producing) magnetic material. Figure 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 electrical steel. There is no thermal resistance path as that 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. Figure 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 and power factor achieved 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. For comparison, a paper study was performed to determine the approximate sizes and weights of various motor types for use in this application. The results are shown in Table 1 below. The rating is 50 horsepower at 208 rpm. Each motor was designed for the same temperature rise.

Motor Type	Height (in.)	Width (in.)	Width (in.)	Wt. (lbs.)
Cast Iron Frame Induction	41	28	28	3950
Finned, Laminated Frame Induction	28	22	22	2320
Finned, Laminated Frame PM	22	22	22	1670

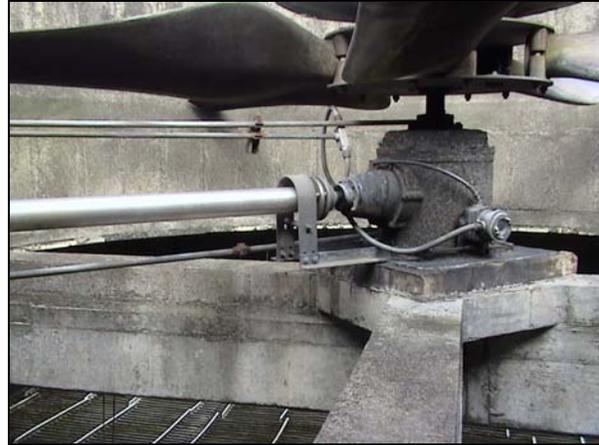
**Table 1 – Motor Size Comparisons**

### III. CASE STUDY

The case study involves the retrofit of an existing cooling tower constructed in 1986 at Clemson University in South Carolina. The tower information is as follows:

- Fan Diameter: 18'-0"
- 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 above data, this tower is comprised of two identical cells. For this study, one cell was retrofitted with the new slow speed PM motor and VFD while the other was left intact as originally constructed. This allows for a direct comparison of the two fan drive solutions. Figure 6 below shows Cell #1 in the original configuration, while Figure 7 shows the PM motor installed in place of the gearbox in Cell #2.



**Figure 6 – Original Installation**



**Figure 7 – PM Motor Installed in Place of Gearbox & Driveshaft**

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 VFD 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 running at the same speed. 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 2 below.

Location	Volts, mean	Amps, rms	Input kW	Power Factor (%)
Input to Induction	477	46.7	31.5	81.7
Input to VFD, PM	477	44.5	28.5	77.6
Input to PM	459	40.9	28.0	86.1

**Table 2 – Power Consumption Comparison, Original blade pitch, manufacturer data**

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 3 & 4 below.

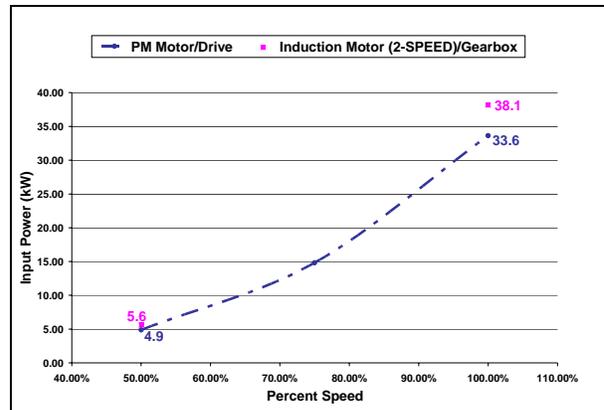
Location	Volts, mean	Amps, rms	Input kW
Input to Induction	477	54.8	38.1
Input to VFD, PM	477	49.8	33.6

**Table 3 – Power Consumption Comparison, 12° blade pitch, manufacturer data**

Location	Volts, mean	Amps, rms	Input kW
Input to Induction	478	54.3	37.9
Input to VFD, PM	477	49.8	33.0

**Table 4 – Power Consumption Comparison, 12° blade pitch, testing service data [9]**

For the final blade pitch, 4.5 kW less power consumption was observed on the cell 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. Figure 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 2-4, the PM motor solution requires less input power for each load point (blade pitch). Figure 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 solution. Using an average price of \$.08/kWh, the annual cost savings for various applications and duty cycles are shown in Table 5. This table does not account for the additional savings achieved by using a VFD and having the ability to run at speeds between 50% and 100% of rated.

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

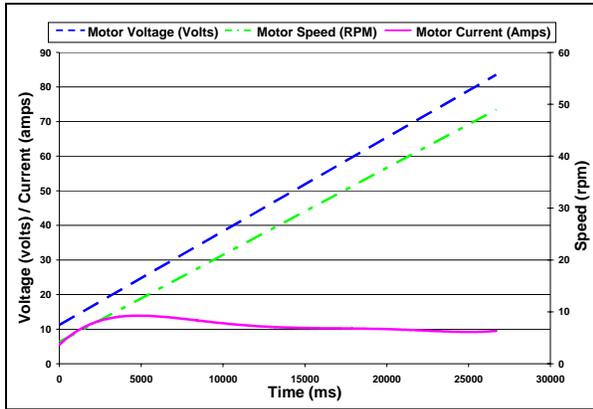
**Table 5 – Annual Energy Savings Based on Various Duty Cycles**

#### IV. ELECTRICAL CONSIDERATIONS

##### PM Control Algorithm

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

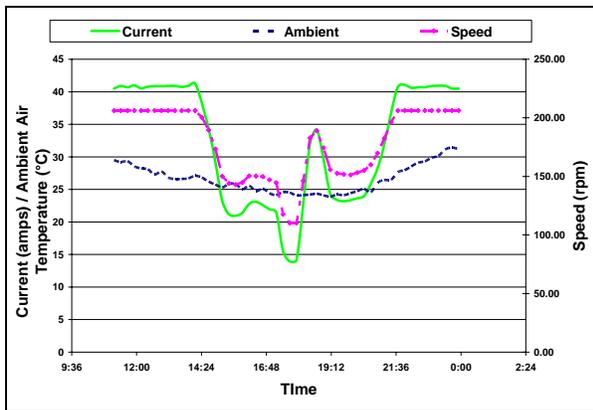
when starting and changing speeds. Figure 9 is a portion of a typical start from rest. Note the smooth acceleration and low starting current required. A typical 480 volt induction motor started across the line would draw 347 amps [10], compared to 12 amps for this PM design started on the VFD.



**Figure 9 – Motor Starting Performance**

### Improved Process Control

As mentioned earlier, the addition of the VFD allows the user to more accurately and efficiently control the process. Figure 10 shows how the motor speed is changed automatically with control logic as the heat demand on the system changes with time.



**Figure 10 – Motor Speed Variation with Changing Heat Load**

### 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.

## V. 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 [11].

### 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 [9]. Average A-weighted sound pressure results are shown in Table 6 for both high speed and low speed operation.

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

**Table 6 – Sound Pressure Data**

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.

## VI. 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 [12]. 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.

## VII. ACKNOWLEDGEMENTS

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