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DIRECT DRIVE COOLING – PRACTICAL SOLUTIONS

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ELECTRIC TORQUE MACHINES

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Abstract
The promise of direct drive cooling tower fans with Permanent Magnet (PM) motors is not new, but so far this approach has not seen significant adoption. This paper reviews the advantages of direct drive and the requirements for successful direct drive implementation, including performance and economic gaps that have impeded adoption. Efficient torque at the low speeds required for direct drive has been a critical constraint. Crossing this gap can be achieved by increasing motor pole count without increasing coil resistance. This combination has not been practical with PM Radial Flux (RF) motors, given their fundamental design and construction. An emerging motor type known as Transverse Flux (TF) offers promise to both increase pole count and simultaneously reduce coil resistance, a combination which is unique to this motor type. TF motors, originally invented in the 1980's, have now been successfully commercialized in several markets including direct drive pumps and fans.

I. INTRODUCTION

The last 20 years have seen broader adoption of permanent magnet (PM) motors within the heat rejection equipment industry. Compared to AC induction motors, the compact, high efficiency nature of PM motors has led to broad use in sub-10 horsepower fan drives. However, despite the availability of larger PM motors designed for direct drive, fans requiring greater than 10 HP continue to be driven predominantly by AC induction motors with either gearboxes or belts. See Figure 1. This design has been essentially unchanged for over 50 years. This paper reviews the reasons for legacy drive persistence and offers a promising approach to direct drive with a recently commercialized motor technology known as Transverse Flux.

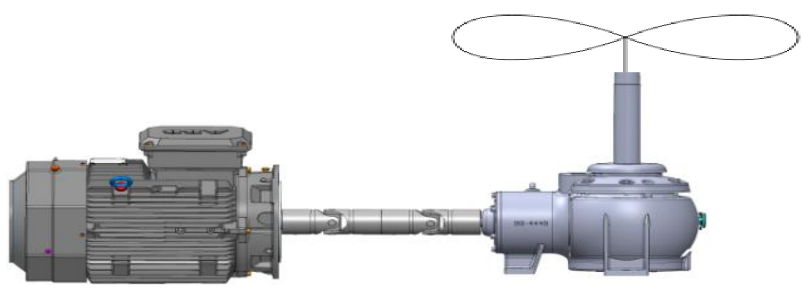


Figure 1: Conventional Fan Drive with AC Induction Motor, Driveshaft and Right-Angle Gearbox.

II. HISTORY OF DIRECT DRIVE IN COOLING SYSTEMS

The introduction of large direct drive fan motors in cooling systems is highlighted by a 2009 CTI paper presented by Baldor Electric [1]. This paper describes the following advantages of direct drive PM motor driven fans in cooling systems:

- Energy savings over 10%, depending on the use profile.
- Reduced acoustic emissions
- Simplified installation by eliminating the need for drivetrain balance and alignment.
- Reduced current draw in both starting and operating
- Reduced maintenance associated with the gearbox.
- Reduced vibration with lower rotating mass and fewer components

Fast forward 10 years to a 2019 paper by SPX Cooling Technologies which highlights 2 key challenges for PM direct drive motor adoption in fans over 10HP: a) purchase cost, and b) motor size and weight. [2]

Table 1 – Comparison of Cooling Tower Power Transmission Technologies				
	Belt Drive	Gear Drive	Direct Drive	
			EC	PM
Applicable Power	<100 HP	No Limit	<10 HP	<250 HP
Applicable Fan Diameter	<14 feet	No Limit	<4 feet	<30 feet
First Cost	$	$$	$$$	$$$$
Operating Cost	$$$	$$	$	$
Energy Efficiency	+	++	++++	+++
Weight	+	++	+	+++
Sound				
VFD Required?	No	No	Yes, Integral	Yes, External

Table 1: Cooling Tower Power Transmission Comparison. [2]

Quotes from the SPX paper:
"Initial costs can be two to three times more than a gearbox. Due to the high first cost, payback can extend to 10 or more years."
And
"PM Direct Drive motors are bigger and heavier"

Given that a motor's cost is generally proportional to motor's mass, especially its electromagnetic materials, the correlation of these two factors is not surprising.
These concerns are highlighted in Table 1.

III. DIRECT DRIVE CHALLENGES

Taking a closer look at the barriers to create practical direct drive motors, we see that as required fan power increases (often due to increasing propeller size), motor RPM decreases and torque increases. This non-linear interaction is affected by several variables such as cooling system type, max allowable propeller tip speed and fan pressure. This relationship is shown in Figure 2.

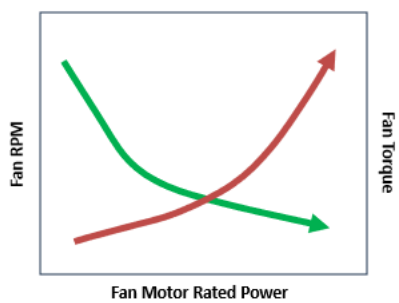


Figure 2: As Direct Drive Fan Motor Rated Power Increases, RPM Decreases and Torque Increases

Using two hypothetical cooling tower fan examples, a 20 HP fan motor operating at 1000 RPM produces 140 Nm, while a 150 HP fan motor spinning at 180 RPM needs to produce 5800 Nm. Due to speed reduction, the 7.5X power increase requires greater than 40X increase in torque. Given that motors are generally sized proportional to torque, this creates an increasing burden on motor suppliers to create cost effective direct drive motors for larger heat rejection systems.

IV. MOTOR PHYSICS

To better understand these challenges, we'll take a brief dive into the relevant physics operating within an electric motor.

Faraday's Law of Induction, shown Equation 1, states that EMF (Electromotive Force) per turn is equal to the change in magnetic flux over the change in Time.

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

Equation 1: Faraday's Law of Induction.

Where

ε is Electromotive Force

Φ_B is Magnetic Flux

t is time

If this is divided by the speed of rotation, it becomes the well known motor characteristic k_e or voltage constant. $k_e = \frac{\varepsilon N}{\omega}$, where N is the number of turns per phase and ω is the speed of rotation. The frequency of the motor is entirely determined by the pole count and rotational speed in the form $\left(\frac{1}{dt}\right) = 2\pi p\omega$, where p is the pole count of the motor. This allows Equation 1 to be rewritten in terms of the voltage constant of the motor in the form $k_e = 2\pi N\Phi_B p$. Taking this one step further, we can introduce the concept of k_m, motor constant, which is a fundamental measure of a motor's ability to efficiently produce torque. Specifically, it is the ratio of torque per unit root coil loss, or $k_m = \frac{k_e}{\sqrt{RN^2}}$, where R is the resistance of a single turn motor. Substituting in the equation for k_e above we have an equation that represents the ability of a motor to make torque, based on its fundamental structure

$$k_m = \frac{2\pi\Phi_B p}{\sqrt{R}}$$

Equation 2: Motor Constant in Terms of Fundamental Motor Characteristics

Where

k_m is Motor Constant

p is the Number of Poles

R is the Single Turn Winding Resistance

This equation offers three options for increasing torque:

1. Increase flux
2. Decrease resistance
3. Increase pole count

Let's take a closer look at these three options.

1. <u>Increase Flux:</u> For the vast majority of motors using electrical steel as a flux conductor, and neodymium magnets, flux for a given motor size is limited by steel saturation and magnet remanence. Thus, the only way to significantly affect this parameter is to increase overall motor volume. This has the obvious but unfortunate consequence of increasing the motor's overall size, weight and cost.

2. <u>Decrease resistance:</u> While there have been some academic demonstrations of superconducting motors, for the foreseeable future the vast majority of applications will continue to use copper as a conductor. Given this, and the constraints of providing sufficient flux pathway, the ability to decrease resistance is limited to various strategies for increasing

the density of copper in the available spaces using various tricks of construction and geometry.

3. Increase pole count: Given the constraints listed above, the most important factor that can be varied is pole count. While flux and resistance can be increased by perhaps 10-30% using a variety of increasingly complex and expensive means, pole count can, depending on the motor size, conceivably be increased by 10X or more. However, for all conventional motor types there is a direct tradeoff between increasing pole count and increasing resistance. This is explained in Section V. However, as discussed in detail in the following sections, TF motors decouple the winding geometry (and resistance) from the number of poles in the motor – unlocking this potent variable for the efficient production of torque. Figure 3 illustrates this effect. [4]

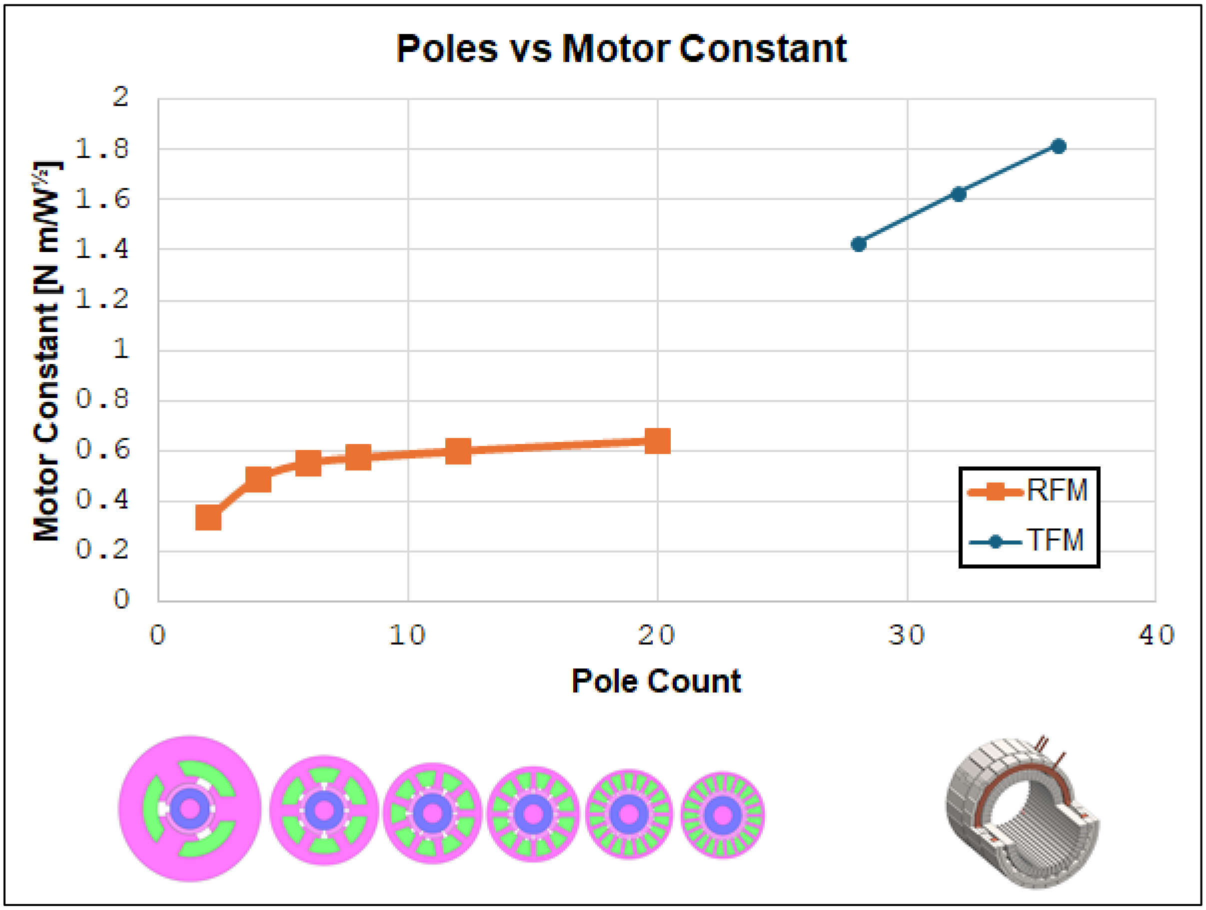


Figure 3: Motor Constant Increases with Pole Count, but is Offset by Increases in Resistance for Non-TF Motors

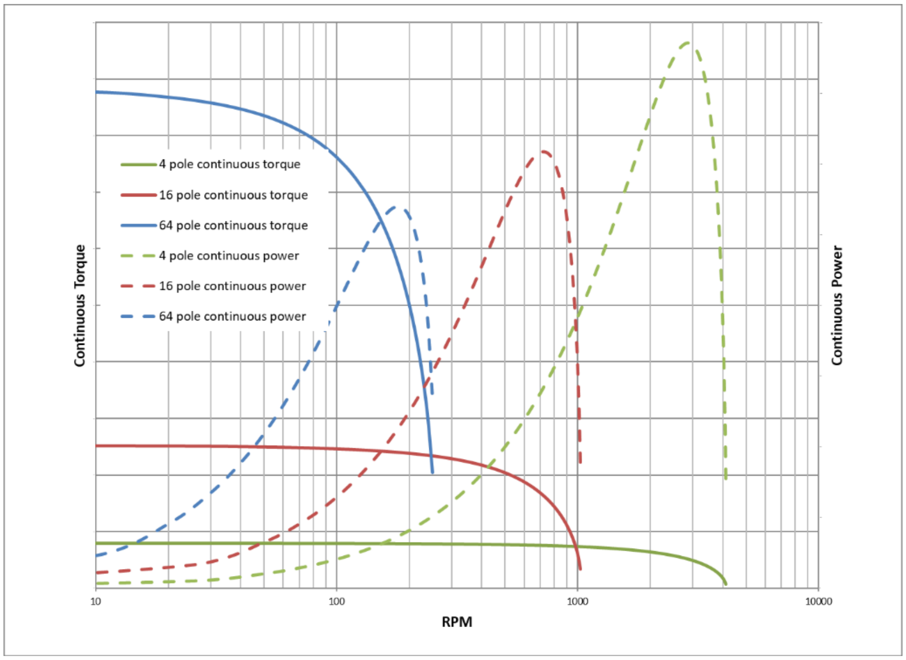


Figure 4: For a Given Motor Size, Increasing Motor Pole Count Increases Low Speed Torque and Decreases High Speed Power. [4]

Increasing Pole Count is Key

Pole count increase and the accompanying effects on torque and power are demonstrated by simulation in Figure 4 [4]. As shown in this graph, where motor size, weight and form factor are normalized, available motor torque increases with pole count. Note that maximum motor power *decreases* with higher pole count machines, which the motor designer must consider given the motor's intended application. For low speed, direct drive applications, higher pole count motors offer superior torque density.

Conventional direct drive PM motors over 10 HP typically have 4-8 poles, roughly the same pole count as 1800 RPM induction motors seen in conventional geared fan drives. Because direct drive motors operate at much lower speeds, their operating frequency is less than ideal for optimal torque production.

A recently commercialized motor type known as Transverse Flux (TF) offers much higher pole count motors and takes advantage of the accompanying low speed torque increase. As shown in Table 2, Transverse Flux motors may have 48 and 108 poles for 40 and 75 HP sizes respectively.

	Radial Flux	Transverse Flux
40 HP	4-8 Poles	48 Poles
75 HP	4-8 Poles	108 Poles

Table 2: Pole Count Comparison for Radial and Transverse Flux Machines. [5]

V. MOTOR TYPES

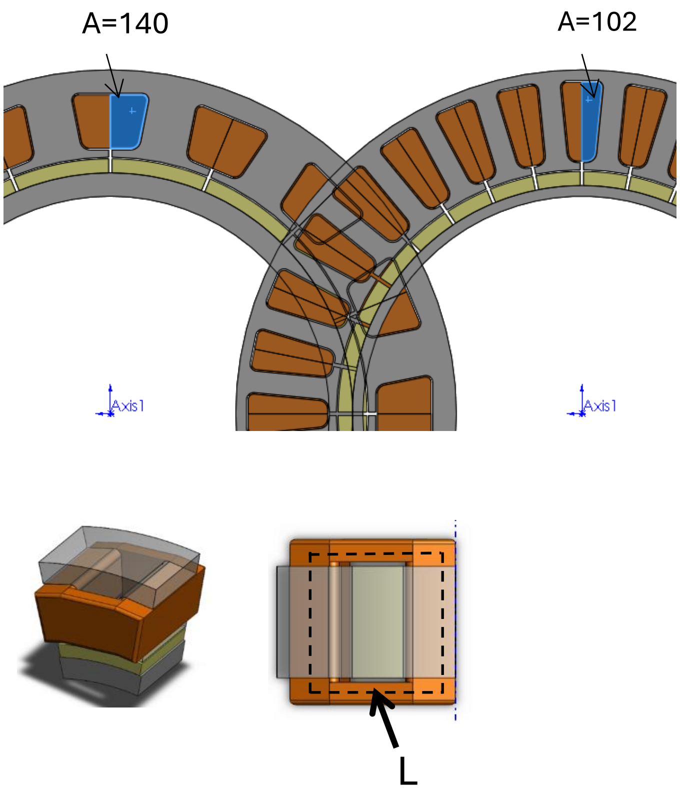
To better understand the differences in pole count and coil resistance seen in different motor types, we'll examine the stator construction for 2 different PM topologies: Radial Flux and Transverse Flux.

Radial Flux Motors

Radial Flux (RF) motors are by far the most common PM motor type. In RF motors, stator windings are characterized by wire that passes back and forth through slots in the stator as shown in Figure 5.

Figure 5: Radial Flux Stator.

For conventional RF motors, winding resistance tends to increase proportionally with the number of magnetic poles. This is explained in Figure 6.



$$R = \rho \frac{L}{A}$$

Where
R is Coil Resistance
ρ is the Wire Resistivity per Length
L is the Coil Wire Length for 1 Slot Pair
A is the Cross-sectional Area of the Slot

Figure 6: Relationship Between Poles/Slots and Winding Resistance for Radial Flux Stators.

Applying this relationship between stator slots and winding resistance, we see that doubling the motors poles (and therefore slots) more than doubles the resistance. This creates an “uphill battle” for the direct drive RF motor designer.

	Reference	2X pole count
Poles/slots	16	32
Area	140	102
Circumference	116	88
R	13.26	27.61
	Ratio:	**2.08**

Table 3: Doubling the Number of Poles/Slots in a Radial Flux Stator More Than Doubles the Coil Resistance.

This increase in resistance is one challenge RF motor designers face when increasing pole count for low speed direct drive applications.

Transverse Flux Motors

Transverse Flux (TF) motors, recently commercialized for heat rejection systems, offer higher pole count and lower coil resistance, ideal for low-speed direct drive fans.

TF motors have the unique property of independence between poles and winding as shown in Figure 7 [6]. These images show ¼ sections of TF motor models in 2 configurations: 20 Poles and 40 Poles. The winding (and winding resistance) is identical in these 2 configurations, demonstrating a unique feature of TF motors where the winding resistance is independent of pole count. This enables the TF motor designer to create exceptionally high pole count, low resistance motors, ideal for low speed, direct drive fan applications.

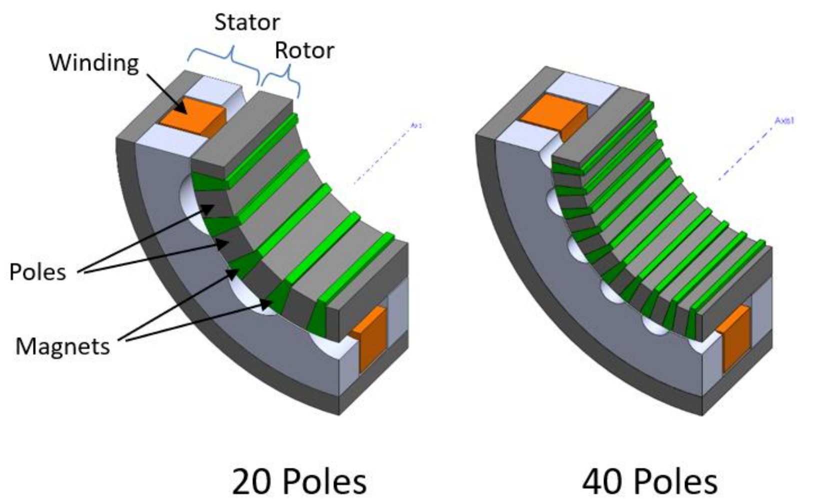


Figure 7: Quarter Section of a Transverse Flux Motor Showing Independence Between Pole Count and Winding

VI. PERFORMANCE COMPARISON

Given that torque per weight is an important figure of merit for direct drive motors, comparing the published values for RF and TF motors provides valuable insight. Figure 8 provides a comparison of the weight of direct drive motors RF and TF motor types as a function of torque. This graph shows the torque density advantage provided by TF motors. This improvement in torque density is important to minimize motor support related structural changes needed in the cooling equipment. Lighter motors can also reduce the challenges associated with field installation, especially in the highest torque motor sizes.

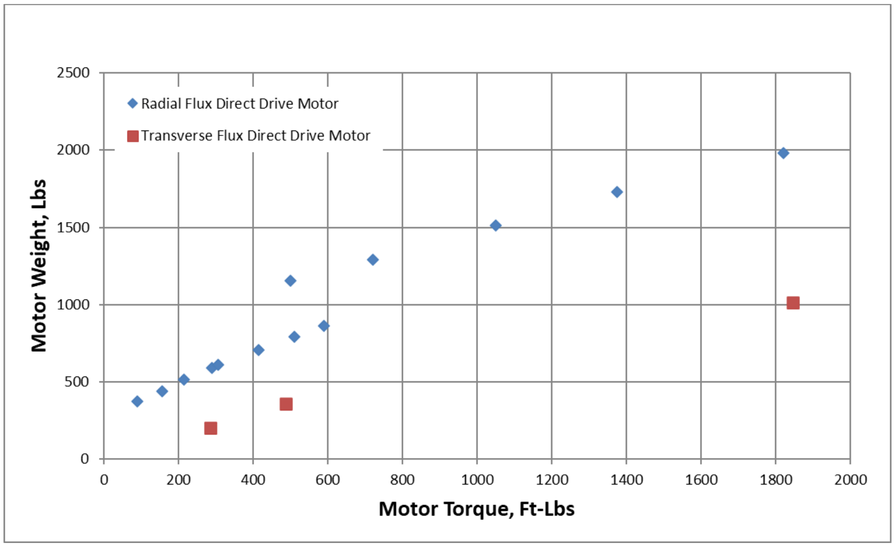


Figure 8: Torque vs. Weight Comparison for Radial Flux and Transverse Flux Direct Drive Motors.

Motor Size

Converting heat rejection equipment from belt and gear transmissions to direct drive typically requires the motor to move inside the airstream, often to a location that was previously occupied by a gearbox or belts and sheaves. The more compact the direct drive motor, the less re-engineering is needed to make this change. Compact direct drive motors also offer a more feasible approach to retrofit existing cooling systems with transmissions.

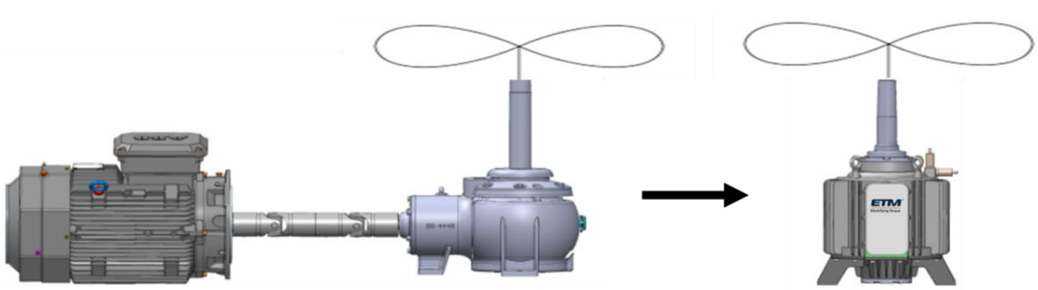


Figure 9: The Ideal Direct Drive Motor Size for Cooling Towers.

The ideally sized direct drive motor fits within the spaced vacated by the gearbox as shown in Figure 9.

VII. COST EFFECTIVENESS

<u>Transverse Flux Reduces Motor Mass</u>

Historically, direct drive motors have been difficult to manufacture cost effectively, partly due to costs that are proportional to electromagnetic material mass. As explained above, this results from the relatively high torque and low speeds needed for fans over 10 HP. The higher pole counts and reduced winding resistance in TF motors offers to reduce material mass, directly improving cost effectiveness. TF motors are also made with the same materials (magnets, windings and lamination steel) as conventional PM motor types.

<u>Transverse Flux Motor Assembly Related Costs and Recent Commercialization</u>

Early TF motor designs suffered from electromagnetic assembly complexity and associated manufacturing challenges [7]. Over the last several years, significant investments in Design for

Manufacturability (DFM) for TF motors have resulted in commercialization into several high volume, cost sensitive markets. Two examples are paint sprayers and positive displacement pumps with products shown in Figures 10 and 11 [8] [9]. The automated manufacturing lines supporting these products deliver 10's of thousands of units annually, demonstrating cost-effective TF motor supply to cost sensitive markets. The factories, developed by Graco Inc, parent company of a leading TF Motor developer, Electric Torque Machines (ETM), include tooling and automation specific to TF Motor assembly.

Figure 10: Paint Sprayer with Direct Drive Transverse Flux Motor [8]

Figure 11: Positive Displacement Pump with Direct Drive Transverse Flux Motor [9]

Transverse Flux Motors for Heat Rejection Equipment

TF motors have recently been introduced to the heat rejection equipment industry. Application specific testing and evaluation have validated the size and weight advantages described in this paper. Figure 12 shows a 40 HP TF motor mounted in a direct drive fan test stand. This motor is designed to fit within the space previously occupied by the gearbox.

Figure 12: 40HP Direct Drive Transverse Flux Motor on a Test Stand

VIII. Further Direct Drive Considerations

<u>Environment</u>
The environmental challenges for direct drive motors used in heat rejection equipment include temperature extremes, high humidity, condensing moisture, vibration and corrosive alkalinity. Moving from transmission based designs to direct drive increases the environmental challenge as the motor is typically moved from outside the airstream to within the airstream where temperature and humidity excursions increase.

Design features such as shaft seals, fully encapsulated electromagnetics, integrated space heaters and drain ports are commonly required for direct drive motors, regardless of electromagnetic type. A key step in direct drive motor qualification includes environmental testing. References such as IEEE 841 can provide guidance in this area, although PM motor types are specifically excluded from this standard. Refer to Industry Standards section below.

Some cooling system customer sites include exposure to volatile flammable liquids or gases and require hazardous location certification such as Class 1, Division 2. Third party certification companies such as UL can provide hazardous location testing and certification.

<u>Reliability</u>
Cooling towers, dry air coolers and similar systems typically support mission-critical facilities where reliability is paramount. Although cooling system redundancy can help minimize risks associated with downtime, any new technology introduction such as direct drive motors demands reliability assessment and testing.

Direct drive motors bring inherent reliability advantages by eliminating the leading cause of cooling system failures: gears and belts. [1]

<u>Motor Cooling</u>
Geared and belted motors are often specified as TEFC (Totally Enclosed Fan Cooled) whereas direct drive motors are typically TEAO (Totally Enclosed Air Over). This means the motor’s cooling air supply, rather than being controlled by the motor manufacturer via an on-board fan, is

subject to airflow differences from system to system. Qualification for new direct drive motor systems should include temperature rise testing on equipment with representative airflow.

Efficiency

Efficiency gains and energy savings associated with the move from fixed to variable speed, and the elimination of gearbox and belt/sheave losses have been previously established [1]. Additional efficiency gains within the motor itself are helpful to reduce internal motor temperature rise, especially with higher ambient temperatures and variable cooling airflow. The low resistance coils used in TF motors are helpful in these situations.

Acoustic Signature

Heat rejection equipment is often installed in locations such as hospitals, schools and hotels where acoustic noise is a concern. Direct drive motors need to be tested acoustically by the equipment manufacturer in a representative system. In general, the motor should not be heard over the fan noise created by turbulent air. Direct drive systems are often quieter given the elimination of rotating components such as driveshafts, belts and sheaves.

Power Factor

Motor Power Factor is the ratio between real and apparent power between the motor and VFD [11]. As motor Power Factor declines, more current must be supplied to the motor from the VFD. The primary concern with low motor Power Factor is the potential need to upsize the VFD which increases system cost. PM motor designers need to include Power Factor in their design inputs. A good rule of thumb for the motor specifier is to ask whether an upsized VFD is needed to achieve rated motor performance.

Motor Power Factor should not be confused with VFD Power Factor, which concerns the electrical load presented by the VFD to the utility grid. This type of Power Factor may be regulated by the local power utility.

VFD Bypass

In the event of VFD failure, geared and belted induction motor systems have the advantage of operating at a fixed speed on grid power via a bypass circuit. This circuit is installed parallel to the VFD and when connected, feeds grid power directly to the motor. This can provide a valuable backup capability. There is a key difference with PM direct drive motors that is not compatible with bypass systems: induction motors are asynchronous and have magnetic “slip” whereas PM motors are synchronous and do not have slip. Induction motor slip allows the motor to accelerate the fan’s inertia while fed by fixed grid frequency (50 or 60 Hz depending on country) and eventually reach nominal operating speed. Because they have no slip, PM synchronous motors are not able to start on grid power. For critical applications, cooling system OEMs may consider a parallel backup VFD, ready to engage when needed.

Industry Standards

Specifications developed for motors used in heat rejection systems have not yet been widely adapted to the PM motor market.

One example is IEEE 841 “IEEE Standard for Petroleum and Chemical Industry— Premium-Efficiency, Severe-Duty, Totally Enclosed Squirrel Cage Induction Motors from 0.75 kW to 370 kW (1 hp to 500 hp)”. The 2021 version of this specification excludes PM motor types:

14.5 Options that do not allow a motor to reference IEEE 841 in any way
The characteristics and features in this subclause note examples of variations from this standard that preclude a motor from being labeled either “IEEE Std 841-2021,” “IEEE Std 841-2021 Features” or to reference IEEE 841. This list is not intended to be all inclusive.

b) Alternate motor technology (e.g., permanent magnet, synchronous, synch. reluctance, etc.)
[10]

Further specification development is needed to include new direct drive motor technologies and enable cooling system OEMs to procure and supply motors that meet standards specific to the cooling system industry.

IX. CONCLUSION

The advantages of direct drive PM fan motors in cooling systems have been well established, but direct drive systems over 10 HP have not yet proven practical due to motor weight and initial cost. Conventional Radial Flux PM motors have struggled with the torque density and low speed requirements needed for practical direct drive. Transverse Flux, a recently commercialized motor topology offers the promise of closing this practicality gap with smaller, lighter motors that take advantage of higher pole counts and lower coil resistance. Transverse Flux Motors have seen recent commercial success in other markets, further demonstrating commercial viability of this motor technology.

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