High Efficiency Evaporator Fan Motors for Commercial Refrigeration Applications

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ABSTRACT

Evaporator fan motors used in commercial refrigeration applications are fractional horsepower in size, responsible for moving air across the evaporator coil, and typically run at one speed. Historically, shaded-pole motors have been the most commonly used evaporator fan motors in commercial refrigeration equipment and beverage vending machines. Electronically commutated (EC) motors, also known as brushless DC motors, became widely commercialized in the late 1980s, and their use in commercial refrigeration applications has increased within the last 10 to 15 years because of economic incentives and regulatory requirements. Another motor type, the permanent split capacitor (PSC) motor, offers a mid-point between shaded-pole and EC motor price and efficiency levels.

A permanent magnet synchronous (PMS) AC motor that can directly use grid-supplied AC current without the need to rectify to DC, has recently been commercialized. This new motor has the potential to significantly reduce the energy consumption of evaporator fans in commercial refrigeration equipment.

In this paper, the results of field demonstrations, consisting of side-by-side measurements of the power consumption of the new PMS motor technology versus shaded-pole, PSC, or EC evaporator fan motors in identical refrigerated display cases, are presented. Measured quantities include fan motor power, current, power factor, display case discharge and return air temperatures, and ambient store temperature. Initial results from the field demonstrations indicate that the new PMS motor technology is approximately 34% more energy efficient than existing EC motors and nearly 79% more energy efficient than shaded-pole motors. In addition, the new motor exhibits a power factor of approximately 0.83, which is on average 40% greater than that of existing evaporator fan motors.

1. INTRODUCTION

The US Department of Energy Building Technologies Office (DOE BTO) estimates that the commercial sector uses approximately 18% of all primary or source energy consumed in the United States, or 18.3 exajoules (EJ) (NCI, 2013). "Primary" or "source" energy refers to the sum of the energy consumed at the site (site energy) plus the energy required to extract, convert, and transmit that energy to the site, and "site" energy refers to the energy directly consumed at the site, typically measured with utility meters (Deru and Torcellini, 2007). The DOE estimates that the conversion from site to source electric energy is 3.16 units of source energy per unit of site energy (DOE,

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2011). Therefore, the 18.3 EJ of primary energy consumed by the US commercial sector equates to approximately 5.07×10^{12} kilowatt hours (kWh) of primary energy, which in turn converts to 1.60×10^{12} kWh of site energy, valued at approximately $170 billion (EIA, 2015).

Of that 18.3 EJ of primary energy, DOE BTO estimates that the primary energy consumption of electric motor-driven systems in the commercial sector is 5.14 EJ and that the motors in central commercial refrigeration and beverage vending machines account for 6.7% and 3.6% of that 5.14 EJ, respectively (NCI, 2013). This equates to approximately 96×10^9 kWh of primary energy for central commercial refrigeration, which in turn converts to 30×10^9 kWh of site energy, valued at approximately $3.2 billion. For beverage vending machines, this equates to 52×10^9 kWh of primary energy, which in turn converts to 16×10^9 kWh of site energy, valued at approximately $1.7 billion. Thus, although the evaporator fan motors used in commercial refrigeration are only fractional horsepower in size, due to their wide proliferation, they are a significant consumer of electrical energy in the United States.

Although higher-efficiency motors have been increasingly used in central commercial refrigeration and beverage vending machines, the installed base of smaller 9–12 W evaporator fan motors continues to be dominated by lower-efficiency shaded-pole motors. Over the past 10 years, the higher-efficiency electronically commutated (EC) motor has begun to penetrate the market. While EC motors are significantly more efficient than shaded pole motors, newly available permanent magnet synchronous (PMS) motors offer even greater efficiency at a comparable first cost. In addition to transforming electrical energy into mechanical energy more efficiently than EC motors, PMS motors have higher power factors, meaning that they accept energy from the grid more efficiently. The resulting reduced current draw means that the electric utility can reduce the amount of energy that it needs to supply to the grid.

This paper provides background information on various fractional-horsepower electric motor technologies used for evaporator fan applications in commercial refrigeration and summarizes data from a DOE-sponsored evaporator fan motor demonstration project.

2. EVAPORATOR FAN MOTOR TECHNOLOGIES

Evaporator fan motors are fractional horsepower in size, responsible for moving air across the evaporator coil, and typically run at one speed. The manufacturer will match the motor size and blade design to the evaporator coil to meet the expected load on the case under most conditions. Higher-efficiency evaporator fan motors reduce energy consumption by requiring less electrical power to generate the same motor shaft output power (NCI/PNNL, 2011).

Historically, shaded-pole motors have been the most commonly used evaporator fan motors in commercial refrigeration equipment and beverage vending machines. The shaded-pole motor, a type of single-phase AC induction motor, is the simplest and least expensive type of fractional-horsepower motor. It is also the least efficient in terms of converting electrical energy into mechanical energy. The 9–12 W sizes commonly used for evaporator fans in these systems are typically 20% efficient (NCI/PNNL, 2011). Given that motor efficiency losses are released as heat, this inefficiency also increases the refrigeration load, further increasing the overall refrigeration system energy consumption (Fricke and Becker, 2015).

Electronically commutated (EC) motors, also known as brushless DC motors, were conceived in 1962 (Wilson and Trickey, 1962) and first became widely commercialized in the late 1980s, after higher-quality rare-earth permanent magnets became more readily available (de Almeida and Greenberg, 2004). The use of these premium-priced EC motors for commercial refrigeration fan applications began in earnest 10 to 15 years ago, and their use has increased because of economic incentives and regulatory requirements. Another motor type, the permanent split capacitor (PSC) motor, which holds a limited share of the market, offers a mid-point between shaded-pole and EC motor price and efficiency levels. The Department of Energy (DOE) reports that for commercial refrigeration evaporator fan motor applications, state-of-the-art EC motors are 66% efficient and PSC motors are usually about 29% efficient (NCI/PNNL, 2011).

All electric motors function as converters of electrical energy to magnetism and then to mechanical rotating motion. The operation of all electric motors is based on the interaction between a field magnet and a magnetic rotor. The electromagnetic interactions between these two magnets cause the rotor to rotate. The different types of motors result from the manner in which the rotating magnetic fields are generated.

In an induction motor, the AC current is fed into the stator coil, which creates a rotating magnetic field around the stator. This rotating magnetic field in the stator induces a current in the rotor coil, which in turn, generates a magnetic field around the rotor. The magnetic fields of the rotor and stator interact. As the magnetic field in the stator rotates, the rotor follows it and torque is generated.

Single-phase induction motors suffer from a serious shortcoming in that they only produce an interaction of two rotating magnetic fields when the rotor is rotating. Simply powering the electromagnet is not sufficient to start such a motor. One of the most significant differences among various types of single-phase induction motors is the way they handle this start-up problem (NCI/PNNL, 2011).

Nearly all inexpensive fan motors are either shaded-pole or PSC induction motors. In a shaded-pole motor, a shading ring, typically a single short-circuited turn of thick copper, surrounds one side of the stator poles. Most of the magnetic flux from the stator crosses the air-gap to the rotor. However, a small portion of the flux passes through the shading ring and induces a current in the ring. The resulting magnetic flux in the ring reaches a peak after the main flux, thereby producing a rotation of the flux across the face of the stator poles. This shift in the flux across the face of the stator poles is required to start the motor. Incidentally, the side of the stator poles where the shading ring is placed dictates the direction of rotation of the motor (Hughes and Drury, 2013). Because a portion of the electrical energy input is used to induce the magnetic field of the shading ring, and since the imbalance between the shaded and unshaded portions of the stator poles remains throughout operation, shaded-pole motors are inefficient.

In a PSC motor, a smaller start-up winding is present in addition to the main stator winding. The start-up winding is electrically connected in parallel with the main stator winding and in series with a capacitor, which causes a phase-shift of the current in the two windings. At startup, the interactions between the magnetic field generated by the start-up winding and that generated by the main winding create a rotating magnetic field that induces rotation of the rotor. As the motor reaches steady state, the start-up winding becomes an auxiliary winding, thereby approximating two-phase operation at the rated load point. For that reason, PSC motors are more energy efficient than their shaded-pole counterparts (NCI/PNNL, 2011).

The EC motor, also known as the brushless permanent magnet motor, is more energy efficient than either shaded-pole or PSC motors. In the EC motor, the grid-suppled AC current is rectified to DC current. The stator is composed of individual windings. The DC current to these windings is electronically commutated (switched) by digital signals from simple rotor position sensors. As the DC current is switched to the various stator windings, a rotating magnetic field is created. This rotating magnetic field creates a torque by pulling the permanent-magnet rotor. This combination permits the motor to develop a smooth torque, regardless of speed (de Almeida and Greenberg, 2004).

A permanent magnet synchronous (PMS) motor can directly use grid-supplied current without the need to rectify to DC. Synchronous motors are so named because the rotation of the motor's shaft is synchronized with the frequency of the supplied current. Previously, synchronous motors have been prohibitively expensive for commercial refrigeration evaporator fan applications because of the high cost of the electronic control circuit that is required to bring the synchronous motor up to synchronous speed. However, the PMS motor makes use of a new patented controller that is simpler and lower in cost than previous synchronous motor controllers or EC motor controllers, making the PMS motor a cost-effective alternative in the commercial refrigeration market (Flynn and Tracy, 2016).

The PMS motor technology includes a split-wound stator coil as well as a motor controller with a Hall effect sensor to detect rotor position. Upon startup, or when the Hall effect sensor detects that the motor is not running at synchronous speed, the motor controller modifies the frequency of the AC current delivered to the stator coil to bring the motor to synchronous speed. When the frequency detected by the Hall effect sensor matches the frequency of the input AC, the motor is running synchronously. If the motor is running synchronously, the motor controller is not needed and is switched off until either the motor falls out of sync or the motor is stopped and restarted. If the motor slows below synchronous speed, then the motor controller will control the motor timing as it does for startup. Using this method improves overall motor efficiency and the expected lifetime of the components in the circuit (Flynn and Tracy, 2014).

As a result, PMS motors use less energy to provide the same power output, compared with EC and shaded-pole or PSC motors. Since the PMS motor is a permanent magnet motor, it requires less current than an induction motor to produce the same power because no magnetizing current is necessary. Furthermore, compared with an EC motor, the PMS motor does not need to rectify AC to DC, thereby eliminating power-consuming electronics. Moreover, because they can use AC power directly from the grid, PMS motors have much higher power factors than EC motors. While the higher power factor does not mean that the motor uses less power on site, it does mean that the utility is able to supply less power to the grid per unit of output of the motor. Another inherent advantage of PMS motors is that the field coils are energized before the electronic controller, thereby protecting the electronics against power surges. Finally, the elimination of the electronics from the circuit while the motor operates at synchronous speed is expected to increase the reliability and service life of PMS motors.

3. FIELD EVALUATION OF FAN MOTOR TECHNOLOGIES

The U.S. DOE has recently supported a field demonstration to quantify the energy savings realized by switching from shaded-pole, PSC, or EC evaporator fan motors to PMS motors. The demonstration consists of side-by-side measurement of the power consumption of PMS and shaded-pole, PSC, or EC evaporator fan motors in identical refrigerated display cases. The measurement and verification plan includes provisions for measuring fan motor power, current, and power factor, as well as display case discharge and return air temperatures and ambient store temperature.

At each test site, either one display case was used, in which an equal number of incumbent and PMS evaporator fan motors were installed (with one motor type in each half of the display case) or two identical display cases were used, in which case one display case contained the incumbent fan motors while the other case contained an equal number of PMS fan motors. During the retrofit of PMS fan motors at each test site, care was taken to match the airflow rate between the incumbent fans and the PMS fans to within 5% by using appropriately pitched fan blades on the PMS motors.

A total of six test sites were used for the field evaluation of the various evaporator fan motor technologies. The location of each test site as well as display case descriptions and motor types evaluated are summarized in Table 1. The motors evaluated included shaded pole motors from one manufacturer, EC motors from three manufacturers (denoted as types “A”, “B” and “C”) and PMS motors from one manufacturer.

Table 1: Summary of field test sites

Number and Type of Fan Motor				
Electrical Circuit A	**Electrical Circuit B**	**Display Case Type**	**Data Collection Duration**	**Location**
Two shaded-pole	Two PMS	One 4.9 m long medium-temperature open multi-deck case	Four months	Kansas City, MO Site #1
Four EC, type A	Four PMS	Two 3.7 m long medium-temperature open multi-deck cases	Four months	Kansas City, MO Site #2
Two EC, type B	Two PMS	Two 2.4 m long medium-temperature open multi-deck cases	Four months	Lee’s Summit, MO
One EC, type B	One PMS	One 2.4 m long medium-temperature open multi-deck case	Two months	San Diego, CA
Three EC, type C	Three PMS	Two 3.7 m long medium-temperature open multi-deck cases, retrofit with doors	Four months	San Antonio, TX Site #1
Two EC, type C	Two PMS	One 3.7 m long medium-temperature open multi-deck case, retrofit with doors	Three months	San Antonio, TX Site #2

Measured quantities at each test site included fan motor power, voltage, current, and power factor, as well as display case discharge and return air temperatures and ambient store temperature. Quantities were measured every 30 seconds and then averaged and recorded every two minutes. Table 2 list the specifications of the instrumentation used in this study.

Table 2: Instrumentation specifications

Instrument	Measured Quantity	Instrument Range	Accuracy
Power Meter	Fan power, current, voltage and power factor	Power: 0 to 600 W Current: 0 to 5 A Voltage: 90 to 600 V	Power: 0.2% Current: 0.4% Voltage: 0.4%
Resistance Temperature Detector (RTD)	Display case discharge and return air temperature	-50 to 260°C	±0.20°C

4. FIELD EVALUATION RESULTS AND DISCUSSION

Figure 1 shows an example of the fan motor energy performance data obtained from one of the Kansas City test sites, where the performance of two shaded pole and two PMS evaporator fan motors in one 4.9 m long medium-temperature open multi-deck display case were compared side-by-side over a three month period. Average evaporator fan power, current and power factor are shown in Figure 1. It can be seen that the two PMS motors consumed 79% less power while drawing 82% less current than the two shaded pole motors. In addition, the power factor for the PMS motors was 20% higher than that of the shaded pole motors. Data from the other test sites show similar trends.

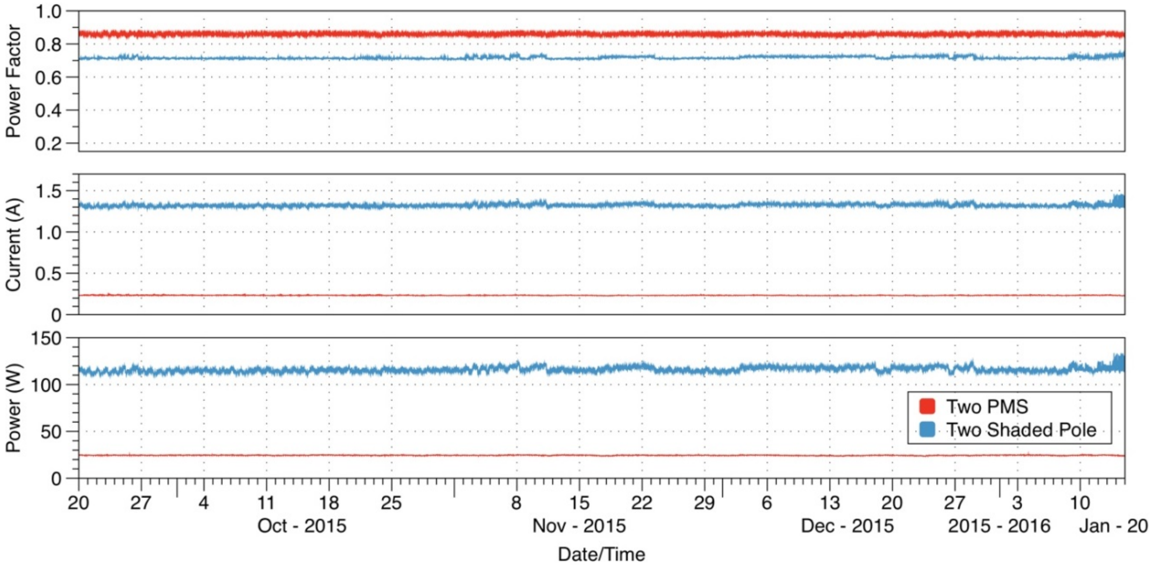

Figure 1: Shaded-pole and PMS evaporator fan motor performance, including fan power, current and power factor, Kansas City, MO Test Site #1

A summary of evaporator fan motor performance data for all the test sites is given in Table 3. From Table 3, it can be seen that, on average, a PMS motor consumes 79% less power and draws 82% less current than a shaded pole motor. Also, the PMS motor consumes on average 34% less power and 50% less current than an EC motor. In addition, the PMS motor exhibits an average power factor of approximately 0.83, which is on average 40% greater than that of existing evaporator fan motors. Power factors for San Antonio, TX Site #1 are not reported because the evaporator fan motors were on the same circuit as the door heaters, which skewed the data.

Table 3: Summary of evaporator fan motor energy performance

Fan Motor Type	Average Power, per motor (W)	Average Current, per motor (A)	Average Power Factor	Site Location
Shaded-Pole	58.0	0.661	0.717	Kansas City, MO Site #1
PMS	12.3	0.117	0.860	
Difference (%)	-78.9	-82.4	+20.0	
EC, type A	9.8	0.136	0.602	Kansas City, MO Site #2
PMS	7.4	0.086	0.724	
Difference (%)	-24.2	-37.0	+20.4	
EC, type B	24.3	0.324	0.618	Lee's Summit, MO
PMS	13.2	0.126	0.867	
Difference (%)	-45.5	-61.1	+40.3	
EC, type B	20.9	0.380	0.459	San Diego, CA
PMS	12.7	0.122	0.865	
Difference (%)	-39.1	-67.8	+88.6	
EC, type C	23.6	0.256	--	San Antonio, TX Site #1
PMS	13.9	0.148	--	
Difference (%)	-40.8	-42.1	--	
EC, type C	16.4	0.228	0.619	San Antonio, TX Site #2
PMS	13.0	0.138	0.811	
Difference (%)	-21.0	-39.6	+30.9	

Table 4 summarizes the average discharge and return air temperatures and their difference, ΔT, for the refrigerated display cases. The effect of evaporator fan motor type is negligible on the discharge and return air temperatures, which do not vary by more than approximately 2°C between PMS and shaded-pole or EC motors. This is an indication that the airflow rate and refrigerating effect within the display cases is not affected by replacing the incumbent fans and motors with the PMS fans and motors. The discharge air temperature sensor at the San Antonio, TX Site #1 failed to report data.

Table 4: Summary of display case discharge and return air temperatures

Fan Motor Type	Average Discharge Air Temperature (°C)	Average Return Air Temperature (°C)	Average ΔT (°C)	Site Location
Shaded-Pole	0.94	4.82	3.88	Kansas City, MO Site #1
PMS	1.12	5.05	3.93	
Absolute Difference (°C)	0.18	0.23	0.05	
EC, type A	2.16	6.90	4.74	Kansas City, MO Site #2
PMS	2.18	6.31	4.12	
Absolute Difference (°C)	0.02	0.59	0.62	
EC, type B	2.48	8.69	6.21	Lee's Summit, MO
PMS	1.72	6.51	4.78	
Absolute Difference (°C)	0.76	2.18	1.42	
EC, type B	1.91	6.34	4.43	San Diego, CA
PMS	2.22	7.95	5.73	
Absolute Difference (°C)	0.31	1.61	1.30	
EC, type C	--	1.07	--	San Antonio, TX Site #1
PMS	0.13	1.15	1.02	
Absolute Difference (°C)	--	0.08	--	
EC, type C	-0.77	0.11	0.89	San Antonio, TX Site #2
PMS	-0.59	1.68	2.27	
Absolute Difference (°C)	0.18	1.57	1.39	

5. CONCLUSIONS

In this paper, various evaporator fan motor technologies were reviewed. This paper also presented the results of field demonstrations consisting of side-by-side measurements of the power consumption of PMS versus shaded-pole, PSC, or EC evaporator fan motors in identical refrigerated display cases. Measured quantities included fan motor power, current, and power factor, as well as display case discharge and return air temperatures and ambient store temperature. The field demonstrations were conducted at six supermarkets and commissaries located in Missouri, Texas and California, with the duration of these tests ranging from approximately two months to four months. Results from the field demonstrations indicate that the PMS motor is approximately 34% more energy efficient than existing EC motors and nearly 79% more energy efficient than shaded-pole motors. In addition, the new motor exhibits an average power factor of approximately 0.83, which is on average 40% greater than that of existing evaporator fan motors. Furthermore, the increased energy efficiency of the PMS fan motor results in less energy being dissipated as heat within the display case, thus reducing the refrigeration load.

NOMENCLATURE

AC	alternating current
BTO	Building Technologies Office
DC	direct current
DOE	U.S. Department of Energy
EC	electronically commutated
EIA	Energy Information Administration
NCI	Navigant Consulting, Inc.
ORNL	Oak Ridge National Laboratory
PMS	permanent magnet synchronous
PNNL	Pacific Northwest National Laboratory
PSC	permanent split capacitor
RTD	resistance temperature detector

REFERENCES

de Almeida, A., & Greenberg, S. (2004). Electric Motors, In Cleveland, C. J. (Ed.), *Encyclopedia of Energy* (191-201). San Diego, CA: Elsevier Academic Press.

Deru, M., & Torcellini, P. (2007). *Source Energy and Emission Factors for Energy Use in Buildings* (NREL/TP-550-38617). Golden, CO: National Renewable Energy Laboratory.

Department of Energy. (2011). *2010 Buildings Energy Data Book*. Washington, DC: U.S. Department of Energy.

Energy Information Administration. (2015). *Electric Power Monthly with Data for March 2015*. Washington, DC: U.S. Department of Energy.

Flynn, C. J., & Tracy, C. N. (2014). *U.S. Patent Application US 2014/0152228 A1*. Washington, DC: U.S. Patent and Trademark Office.

Flynn, C. J., & Tracy, C. N. (2016). *U.S. Patent No. 9,300,237*. Washington, DC: U.S. Patent and Trademark Office.

Fricke, B. A., & Becker, B. R. (2015). *Q-Sync Motors in Commercial Refrigeration: Preliminary Test Results and Projected Benefits* (ORNL/TM-2015/466). Oak Ridge, TN: Oak Ridge National Laboratory.

Hughes, A., & Drury, B. (2013). *Electric Motors and Drives—Fundamentals, Types and Applications* (4th Ed.). Oxford: Elsevier.

Navigant Consulting Inc., & Pacific Northwest National Laboratory. (2011). *Preliminary Technical Support Document (TSD): Energy Conservation Program for Certain Commercial and Industrial Equipment: Commercial Refrigeration Equipment*. Washington, DC: U.S. Department of Energy.

Navigant Consulting Inc. (2013). *Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment*. Washington, DC: U.S. Department of Energy.

Wilson, T. G., & Trickey, P. H. (1962, October). *D-C Machine with Solid-State Commutation* (AIEE paper CP62-1372). Paper presented at the American Institute of Electrical Engineers (AIEE) Fall General Meeting, Chicago, IL.

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