Exploring the Customer Benefits of Permanent Magnet Motors: Test Results and Opportunities for Next Generation Motor Programs

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ABSTRACT

State and utility energy efficiency programs have historically supported incrementally more efficient general purpose, induction motors as a measure to help achieve energy savings goals. Over time, federal minimum efficiency standards have been raised to the level of premium efficiency® (IE3) motor specifications and the benefits from administering programs for slightly more efficient motors no longer outweigh the costs. Advanced technology motors, such as permanent magnet (PMAC) motors, may provide program administrators with the opportunity to continue to capture significant energy savings from motor programs.

Bench and field tests of small horsepower permanent magnet motors, following CSA 838-13 or the input-output model from IEC 60034-2-1 and IEEE 112, indicate they are 2%-26% more efficient than the same size induction motor across the same operating load range. Typically, the lower the loading or speed of the motor the higher the percent energy savings. The tests demonstrate energy savings from PMAC motor technology. Combined with estimates for industrial motor and drive efficiency potential of 30 - 70 TWh by 2020, the savings opportunity appears substantial.

In 2013 and 2014, CEE members BC Hydro, Pacific Gas and Electric, and the Sacramento Municipal Utility District tested the saving opportunity and market potential for permanent magnet motors. This paper summarizes test results with emphasis on measured energy savings and efficiency program potential. The paper further uses the results of the tests, preliminary market research and CEE member experience with PMAC motors to explore program implications and opportunities for the next generation of energy efficient motor programs.

Introduction

Rising federal minimum energy efficiency levels for motors has made it difficult for energy efficiency program administrators to maintain programs that support the installation of premium efficiency motors[1]. Motor and drive efficiency programs are of interest to program administrators due to the substantial energy savings available in the market. According to the US Department of Energy, industrial motors systems use over 20% of all electricity sold in the US, nearly 680 TWh per year (DOE 1998, 1). In 1998 the US DOE estimated motor system energy savings to be 75 - 122 TWh per year, and more recent reports from McKinsey and Company (2009, 78) and the Electric Power Research Institute (2009, 4-29) estimate savings of 30 - 70 TWh per year. The range is wide, but even at the low end of the estimate the impact to total energy use is significant.

[1] With energy savings attributable to the program rather than federal codes and standards.

US and Canadian motor energy efficiency incentive programs had been based upon the Consortium for Energy Efficiency (CEE) Premium Efficiency Motor Specification, which CEE and NEMA aligned under the NEMA Premium® label in 2001. Since the Energy Independence and Security Act of 2007 (EISA 2007) went into effect in late 2010, federal minimum efficiency levels for many motor types were raised to premium efficiency levels. As a result, CEE retired the Premium Efficiency Motor Specification in 2011. Subsequent federal rulemaking, which goes into effect June 2016, has expanded the scope of motor types covered by these federal minimum efficiency levels to most motors sold in the market (DOE 2015). It is difficult for program administrators to claim savings for new or replacement motors with efficiency levels equal to federal minimums. Program administrators have been pushed to look beyond general purpose line start induction motors for market-based energy savings opportunities.

The CEE Motors and Motor Systems Committee, which is comprised of program administrators with an interest in motor system efficiency opportunities, is exploring motor program options that maximize achievable industrial energy savings through market transformation programs for motors and drives. Given time, the market may adopt more efficient products and practices, but industrial energy users may be less aware of emerging technologies and may be averse to the risk of adopting new technologies like PMAC motors. CEE Committee work helps program administrators to raise collective awareness of new motor system efficiency measures, and develop resources like performance specifications that increase comfort with these measures for programs and their customers.

The Committee member case studies discussed in this paper explored the potential opportunity presented by advanced technology motors such as electronically controlled permanent magnet AC (PMAC) motors. Manufacturers claim PMAC motors are more efficient than premium efficiency motors. The PMAC motors referenced in this paper require a variable frequency drive (VFD)[2] to operate. The combined motor-drive package is claimed to provide substantially more energy savings when used in applications with variable load, as is typical in fans, pumps and air compressors.

The PMAC motor technology, and the potential energy savings opportunity presented by motor-drive packages, are new to program administrators[3] and their industrial customers. The following case studies describe the results of bench and field tests from Pacific Gas and Electric, Sacramento Municipal Utility District, both in California, and BC Hydro in British Columbia, Canada. These three CEE members sought to better understand the energy savings potential and characterize the market opportunity for PMAC motors. BC Hydro and PG&E both estimate potential energy savings in their service territories at over 35GWh per year, which is a substantial market transformation opportunity to replace and upgrade older motors with PMAC motor-drive packages.

Case Study 1: BC Hydro

During an energy efficiency feasibility study of multiple fans at an industrial processing plant in Vancouver, British Columbia, a 10-foot diameter cooling tower was identified as a

[2] Variable frequency drives are used with motors to vary motor speed. As the motor load ramps up and down, the VFD speeds up or slows down the motor, using more or less electricity. This can result in significant energy savings, based on reduced motor speed, if the motor serves a load that consistently varies over the course of its duty cycle.
[3] Programs historically offered incentives for motors and drives separately. After EISA 2007 raised federal minimum efficiency levels for most motors, many programs chose to focus on VFD-only incentives. Programs combining the two are relatively new.

potential candidate for a demonstration project. The existing baseline was a two-speed (1750/875 rpm) induction motor with rated horsepower of 40/10 HP respectively. The speed was controlled manually by an operator who would switch the speed to high in the summer and low in the winter. BC Hydro replaced the two-speed induction motor with a 30 HP PMAC motor in 2010 and completed measurement and verification of the pilot project impacts in 2012 (CEATI 2014).

The PMAC motor and accompanying drive was designed to be interchangeable with many popular fan and gearbox bolt hole mounting configurations, allowing for quick and relatively easy installation of the new motor. In addition, no tuning of the system was required due to the matched performance of the motor and control built into the design package. The drive was designed exclusively for the cooling tower industry and can be easily set to always operate at the optimum speed point and maximize energy savings while meeting the variable process load conditions. This low speed direct drive cooling tower fan with speed control is a good example of the system approach to efficiency optimization rather than efficiency improvements of individual components only. Figure 1 demonstrates the physical changes to the system.

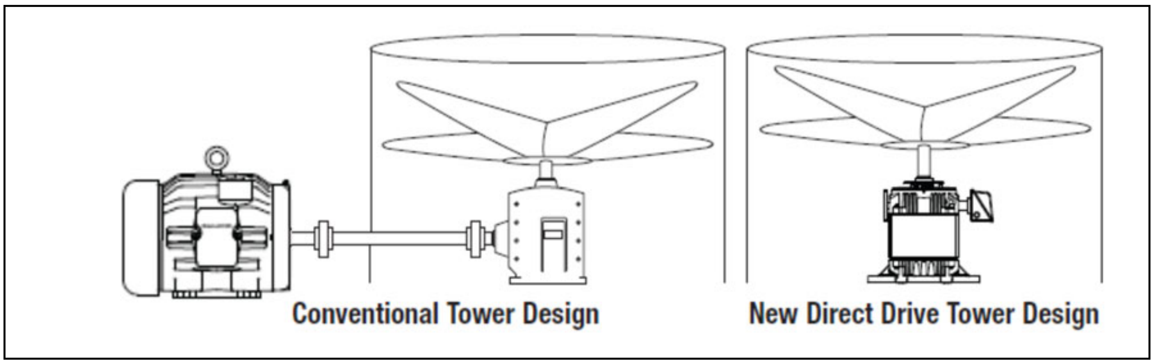

Figure 1. Direct drive PMAC motor system set up. The smaller PMAC motor coupled directly to the fan, eliminating the gearbox and providing additional system efficiency gains. *Source:* BC Hydro unpublished.

Prior to the retrofit, power was measured at the fan's high speed (350 rpm) and low speed (175 rpm). Sets of measurements were taken when the process was running and water was flowing through the cooling tower. An additional set of measurements was taken when the process was offline and no water flowed through the cooling tower. Table 1 shows the results of the energy savings available by replacing a two-speed induction motor, driven through a right-angle gearbox, with a direct drive PMAC motor and variable speed drive (tested at the two fixed speeds).

Table 1. Energy savings demonstrated by the PMAC motor for the BC Hydro pilot project

Fan Speed Setting	Fan Speed (rpm)	Pre-Motor Speed	Pre-Input Power (kW)	Post-Motor Speed	Post-Power (kW)	Power Saved (kW)	Energy Savings (%)
High	350	1750	28.8	350	26.2	-2.6	-9%
Low	175	875	4.6	175	3.4	-1.2	-26%

The average energy reduction with this technology depends largely on the load profile of the application. The lower the fan speed the greater the energy savings with this integrated motor system technology. The energy savings achieved in the demonstration facility with 6900 operating hours per year are 87% or 110,000 kWh per year for converting to a direct drive cooling tower fan with variable speed. For a typical cooling tower fan load profile, the total savings are between 65 and 85%, which translates to approximately 2750 kWh/yr per installed HP. The results were run against a simulation of a premium efficiency motor with a VFD and gear box, and show that over 85% of the PMAC motor system energy savings are achieved with the introduction of variable speed control and the remaining 15% of the energy savings are due to the permanent magnet motor (CEATI 2009).

The direct drive permanent magnet motor and drive has a three-year simple payback when using the original two-speed motor as the baseline. With the BC Hydro Power Smart incentive, the payback is reduced to one year, as seen in Figure 2, for a 10-year cumulative cost of $14,750. If a premium efficiency induction motor with VFD and gearbox were used instead of a PMAC motor, the simple payback is estimated at 1.5 years, which could be reduced to a one year payback with the Power Smart incentive and a 10-year cumulative cost of over $28,000 (not shown in figure). The payback of the direct drive permanent magnet motor using a VFD and induction motor with gearbox as the baseline, both with a Power Smart incentive, is 7 years.

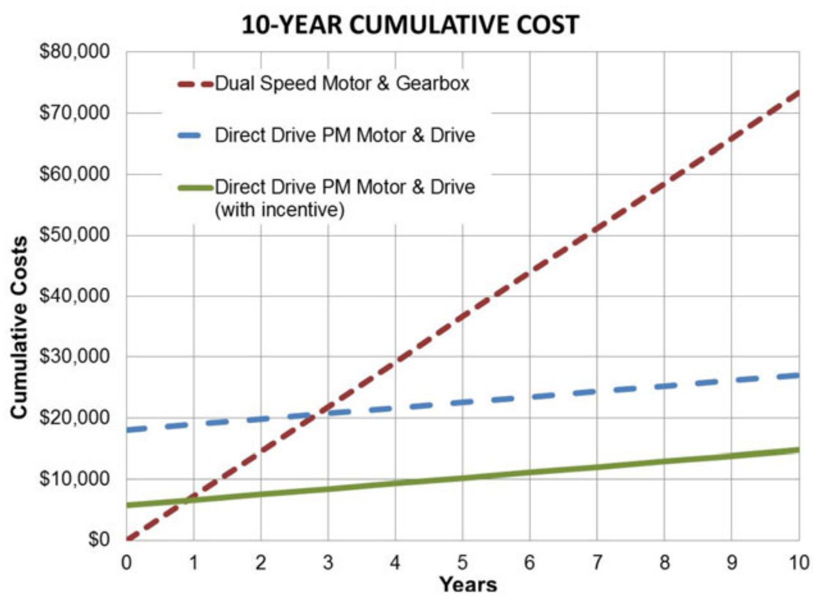

Figure 2. BC Hydro pilot project cumulative cost and payback estimates.
Source: BC Hydro unpublished.

The energy savings potential for variable speed control in cooling towers alone is between 50 to 100 GWh per year in British Columbia. After this successful demonstration project, a pulp mill in BC has expressed interest in applying PMAC motor technology to their four 200 horsepower cooling tower fans for potential savings of 2.2 GWh per year.

In more general terms, the technical and market energy savings potential for permanent magnet motor and drive technology over induction motor and variable frequency drives is 77 GWh per year in British Columbia. The technical potential is estimated from 35 GWh per year being achieved for the 3% incremental efficiency improvement of this motor technology, with the remaining energy savings resulting from the additional elimination of a gear reduction device due to the smaller footprint of PMACs. In other words, this project was only possible because the installed PMAC motor is physically smaller than the same horsepower induction motor. The

PMAC motor plus VFD integrated motor system technology is supporting the shift in programs from energy efficient components to system energy performance.

Case Study 2: Pacific Gas and Electric (PG&E)

In 2013, the PG&E Emerging Technology program within its Customer Energy Solutions department engaged with the company's independent Applied Technology Services facility in San Ramon, California to perform lab-based motor testing of 3 and 5 HP Permanent Magnet AC (PMAC) motors with variable frequency drives and 3 and 5 HP premium efficiency induction motors (PEIM) with variable frequency drives (PG&E 2013). PMAC motors are of interest to PG&E for possible energy efficiency incentive programs given the potential for motor driven machines to be improved with variable frequency drives. PMAC motor manufacturer literature claimed significantly superior efficiency in variable speed applications.

PG&E's test methodology used the same sort of technology that is currently being used in electric vehicles. This uses a special variable frequency or speed drive (VFD or VSD) that can control a normal induction motor as a generator/absorber. A matching VFD was used to control the motor. Power generated by the generator/absorber was fed back into the motor VFD, reducing the overall system power required to just what was required to make up losses in the overall motor/generator system.

The test system setup used a 10 HP inverter-duty rated induction motor, allowing for a total test range of between 1 HP and 10 HP, a speed range of 0 to 5000 RPM, a maximum rated torque range of 40 Nm, and power limit of 7.45 kW. The results for the 3 HP and 5 HP PMAC motors were similar and indicate that in both cases, under identical full or part loads, PMAC motors operate about 4% higher efficiency at full speed, 7-12% higher efficiency at ½ speed and about 24% higher efficiency at 1/6th speed. A key finding is that these results closely matched the motor manufacturer's published literature. Figure 3 summarizes of the comparative efficiencies of the 5 HP PMAC and PEIM at two load points.

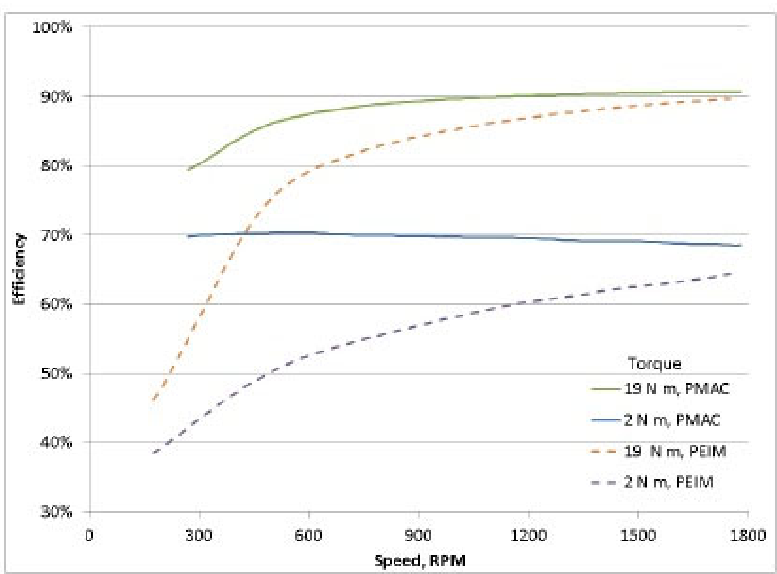

Figure 3. PG&E bench test motor efficiencies. *Source:* PG&E 2013.

In the second part of the project, PG&E estimated the savings potential for various sized motor applications within the utility's service territory. Table 2 shows the PG&E estimated energy savings potential for various motor sizes, based on motor shipment data collected by the survey. The lab tests and technical potential analysis results indicate a significant energy and demand savings opportunity for PMAC motor technology

Table 2. PG&E estimated annual energy savings potential by motor horsepower range

Size Range (HP)	Estimated Annual Potential Energy Savings in PG&E Territory (MWh)
1 - 5	3,273
7.5 - 20	9,635
25 - 50	7,960
55 - 100	5,977
125 - 200	5,103
250 - 500	3,461
Total	35,409

In response to this data, PG&E has implemented a variable speed PMAC HVAC fan motor retrofit add-on rebate called Enhanced Ventilation Control for Packaged HVAC Units, and is developing additional PMAC information and incentive offerings. Additional details are provided in the Discussion section below.

Case Study 3: Sacramento Municipal Utility District (SMUD)

The Sacramento Municipal Utility District (SMUD) conducted bench and field tests of PMAC motors to determine their operating efficiency over a range of conditions. The results were intended to help inform future motor efficiency program design.

For the bench test, SMUD contracted with ADM Associates to test a 3 HP PMAC motor system (SMUD 2013). The motor can be used in the compressor of a typical residential or small commercial air conditioning system, or for pumping chilled water in a larger system. The bench test was conducted using a dynamometer test stand. The PMAC motor was tested alongside two typical induction motors to compare its efficiency at various torque and speed settings. The control motors were new motors selected and purchased by ADM to represent "standard" and premium efficiencies. The PMAC motor manufacturer provided the variable frequency drive (VFD) by which all three motors were driven during the testing. The control motors were rated at 3 HP and 1800 RPM. All motors were totally enclosed and fan cooled.

Figure 4 compares the bench test efficiencies of the three motor systems (including the VFD) at different torque and speed settings. As expected, all motors show a reduction in efficiency at lower speeds and torques. The PMAC motor had the highest efficiency of the three, especially at part load.

To estimate likely energy savings in practice, the efficiency data from Figure 4 was combined with hourly annual load profiles for an air handler fan and a chilled water pump, both generated in eQuest for a simple building model. Tables 3 and 4 show the resulting estimated annual savings when compared against a standard induction motor.

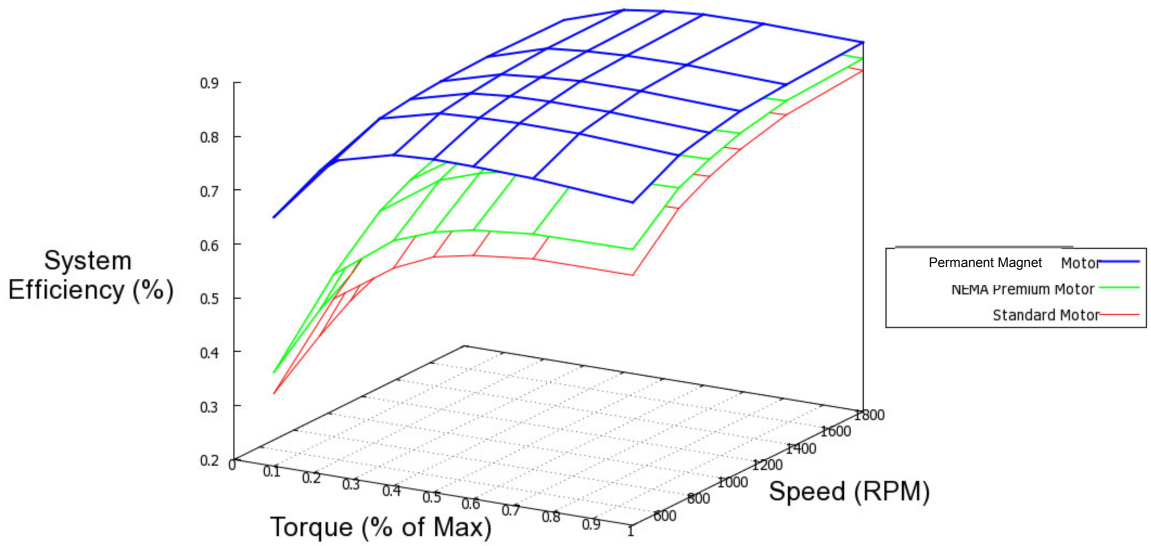

Figure 4. Motor efficiencies measured during SMUD bench tests. *Source:* SMUD unpublished.

Table 3. Estimated Annual Savings of PMAC Motor When Compared Against Control Motors in a Supply Fan Application

	Supply Fan (3 HP)		Supply Fan (5 HP)	
	Premium Motor	Standard Motor	Premium Motor	Standard Motor
Annual Estimated Savings (kWh)	276	396	565	800
Annual Estimated Savings (kWh/HP)	92	132	113	160
Annual Est. Energy Cost Savings ($)	$27.60	$39.60	$56.50	$80.00
Estimated Savings (%)	7.1%	9.9%	8.2%	11.2%

Table 4. Estimated Annual Savings of PMAC Motor When Compared Against Control Motors in a Chilled Water (CHW) Pump Application

	CHW Pump (3 HP)		CHW Pump (5 HP)	
	Premium Motor	Standard Motor	Premium Motor	Standard Motor
Annual Estimated Savings (kWh)	174	363	480	1070
Annual Estimated Savings (kWh/HP)	58	121	96	214
Annual Est. Energy Cost Savings ($)	$17.40	$36.30	$48.00	$107.00
Estimated Savings (%)	7.3%	14.1%	11.6%	22.4%

For the field test, SMUD again contracted with ADM to verify the performance characteristics measured in the bench test, and to estimate annual energy savings in a typical application (SMUD 2014) . The field test compared a 5HP PMAC motor to a 5HP premium efficiency induction motor, driving identical loads. Both motors used variable frequency drives (VFDs), driving fans operating in parallel in an air handling exhaust application. Power monitoring of each motor VFD combination was conducted in conjunction with the site's Building Energy Management System, which also monitored air flow rates of each fan. The resulting data were normalized to the volume of air flow. After one month of monitoring, the two motors were swapped and monitored for an additional month in order to compensate for any instrumentation accuracies or operational differences. The results were extrapolated to estimate annual energy use, based on the assumption that operating conditions remain the same throughout the year. Modeled in this way, the PMAC motor provides an 8.5% reduction in annual energy use over the premium efficiency control motor, as shown in Table 5.

During the field test, the PMAC motor showed an 8.5 percent reduction in demand when compared directly to the induction motor. The demand normalized to airflow showed a savings of 8.7 percent in average W/cfm, due to the slightly higher air flow rate produced by the NovaTorque motor. Savings in other applications may vary as the average speed and speed range vary.

Table 5. Summary results from the SMUD field test

	Premium Induction Motor	PMAC Motor	Difference	Reduction
Average Demand (kW)	1.09	1.00	0.09	8.5%
Average Airflow Rate (cfm)	4,355	4,384	-30	-0.7%
Normalized Demand (W/cfm)	0.249	0.227	0.022	8.7%
Estimated Annual Energy (kWh)	4,104	3,754	350	8.5%

Ultimately, the SMUD bench and field tests demonstrate the ability of electronically controlled PMAC motor technology to achieve greater energy savings than a standard premium efficiency induction motor operated with a drive. Energy savings found in the field test were in the middle of the range suggested by bench tests results. This supports the fact that savings are dependent upon application specific load curves. SMUD is continuing to explore PMAC motors through its Emerging Technology work, and expects to include PMAC motors in future program offerings.

Discussion

The three case studies presented in this paper demonstrate the energy saving potential of PMAC motors operated in conjunction with variable frequency drives. Capturing the savings will require a shift from a focus on motor efficiency and drives (separately) to a focus on motor system efficiency for specific applications. Table 6 summarizes the case study results. In each test, PMAC motors were shown to be more efficient than induction motors operated with a VFD, but the largest energy savings impact was associated with the use of a variable speed drive to match variations in motor load during the duty cycle.

Table 6. Summary case study results

PA	Tested Motor	Control Motor	Size (HP)	Test Type	Test Standard	Motor End Use	Recorded Savings	Est. Potential Savings
BC Hydro	PMAC	Two-speed induction	33	Pilot Project	CSA 838	Cooling Tower Fan	9% - 26%	35GWh
PG&E	PMAC	Premium Efficiency	3 & 5	Bench	CSA 838	N/A	4% - 24%	35GWh
SMUD	PMAC	Premium Efficiency	3 & 5	Bench	Custom (49 data points)	Fan & Pump	7% - 22%	N/A
SMUD	PMAC	Premium Efficiency	5	Field	Custom (49 data points)	Fan	8.5%	N/A

The energy savings benefit of the PMAC motor and VFD combination increases as the load decreases. The technology package will provide the most motor system savings for applications in which the load varies over a certain range, such as with the ventilation fans or cooling tower fans discussed above. Ongoing CEE Committee work will involve collecting sufficient data about load variability for specific applications, in different building types and climate zones, to develop a robust data set that will allow for the development of statistically robust load curves. Program administrators need this data to justify and prove the energy savings impact to state regulators. The data will also allow program administrators to define criteria to screen for applications that are appropriate for PMAC motors, and other motor technologies that work with VFDs and have efficiencies greater than premium levels. Additionally, in order to design prescriptive motor programs, program administrators must demonstrate to regulators that the amount of energy saved justifies the use of efficiency program funds, whether funds are used for education and guidance or financial incentives like equipment rebates.

Recognizing the value of PMAC motors for certain applications, PG&E has already developed a prescriptive incentive program for PMAC motors and drives for commercial HVAC (PG&E 2015). The incentive program is tiered, as shown in Table 7, providing the highest incentive for the installation of a PMAC motor with a drive.

Table 7. PG&E enhanced ventilation control prescriptive rebate table

Description	Rebate/Unit Measure
CO2 Sensor + VFD	$155/ton
CO2 Sensor + VFD + Premium Efficiency Motor	$190/ton
CO2 Sensor + VFD + PMAC Motor	$194/ton

PG&E was able to demonstrate to regulators that the PMAC motor and drive combination will provide more energy savings than a drive alone or a drive paired with a premium efficiency level motor. The HVAC application supported by the program has a predictable load curve, which in combination with the PMAC test results can be used to accurately estimate the energy savings that will be achieved through the PG&E program.

As described in this paper, motor system energy savings from PMAC motors and drives have been established as a real possibility by the work of individual program administrators.

Both BC Hydro and PG&E estimate approximately 35 GWh of energy savings per year in their service territories. PG&E is already running a prescriptive program that includes PMAC motors for commercial HVAC, with plans to expand offerings to other applications based on the estimated savings potential. Work is underway to identify the applications that will provide reliable prescriptive program savings. Meanwhile, the BC Hydro pilot demonstrated substantial energy savings in a real world cooling tower application, and demonstrated a relatively short payback period. BC Hydro plans to continue to offer incentives to PMAC motors through its custom project pathway. Given the large number of cooling tower fans operating across the US and Canada, one can easily recognize a substantial energy savings opportunity of replacing those systems with direct-drive PMAC motors.

However, no one program can transform the market across the US and Canada on its own. By working together in the CEE Motors and Motor Systems Committee, program administrators can collectively examine new opportunities for their programs, avoid duplication of effort and come to consensus on how best to pool their resources and influence to accelerate the introduction and adoption of energy saving technologies at a national market level. In turn, program administrator support for the industry gives motor and drive manufacturers confidence to make investments, sooner than they otherwise might, in plant and equipment updates needed to manufacture and distribute new products. At the same time, this program support helps to address market barriers such as new technology risk, product availability, and higher incremental costs at the consumer and distributor end of the market.

The test results presented in this paper are the foundation for much work to come, to gather data and develop robust energy savings numbers for specific motor system applications with variable load (like cooling tower fans). The next steps for broader program design will include defining the characteristics of applications that are appropriate for motor-drive packages (such as statistically robust load curves) and demonstrating for regulators the achievable energy savings for these applications. As discussed above, prescriptive programs are a likely program outcome, but CEE and its members will explore broader options for market transformation including targeted outreach and guidance to communicate and promote the energy savings potential of advanced technology motors in combination with drives.

Conclusion

PG&E, BC Hydro, and SMUD are active participants in the CEE Motors and Motor Systems Committee and are actively engaged in current Committee discussions about the next generation of efficiency program opportunities for motor systems. These program administrators share their test results and work with other Committee members to develop a shared understanding of best practices for the design of standardized motor and drive efficiency programs. Based on the results of these tests and the BC Hydro pilot, programs are beginning to collect the data needed to promote energy savings goals that capture motor system savings for those applications that lend themselves to variable speed motor technology.

Bench tests and field tests have demonstrated that, as one example of advanced motor technology, PMAC motors offer significant savings over industry-standard induction motors in a wide range of commercial and industrial applications. Key benefits include:

- 2-26% savings compared to industry-standard induction motors with variable speed drives.

- Highest savings are in applications where very low-load or reduced speed operation is common, such as HVAC (including compressors, air handlers, chilled water pumps, and cooling tower fans) and industrial fan and pump systems.
- Same size or smaller than existing induction motors, making them suitable to retrofit projects.
- Smaller motor size sometimes offers increased savings by mounting the motor closer to the load, reducing mechanical drive losses.

Advanced Technology Motors Are a Promising Opportunity for Programs

Advanced technology motors, such as PMAC motors, are a promising opportunity for efficiency programs to achieve performance-based, energy savings for the following reasons:

- PG&E has developed deemed savings for PMAC motors for commercial HVAC applications.
- Approximately 90% of program savings will be achieved with motors of 1-200HP with variable speed requirements, according to estimates for the PG&E service territory.
- Significant savings can be achieved by OEMs integrating PMAC into the design of packaged motor systems for improved energy performance. These packages are agnostic to motor technology and how improved energy performance is achieved, but PMACs allow higher efficiency in a smaller package than induction motor technology.
- PMAC retrofit projects can achieve especially high savings when the existing motor has no VFD control. In these cases, savings can be in excess of 50% due to the variable speed control.
- Within the class of PMAC motors there is a wider range of performance and efficiency characteristics than with induction motors, which programs should consider when communicating about PMAC motors and developing PMAC motor resources.
- PMAC motors, and other advanced technology motors, are starting to be more widely available from multiple manufacturers and across a broad size range. Program support will help to further transform and expand the market.
- When comparing the energy savings of an induction motor with a VFD to a PMAC motor-drive package, the PMAC package provides additional savings over the induction motor with a VFD. PMAC motors are more efficient than the same horsepower induction motor at all load points, and are particularly better at low load points (see Figure 3).

The CEE Motors and Motor Systems Committee recognizes a new direction for non-custom industrial motor programs: application-specific motor system packages that contain better-than-premium motors, such as PMAC motors, for applications that demonstrate consistently variable loads. The PMAC motor work described in this paper is an early step toward designing performance-based, technology neutral programs for motor-drive packages, based on technology neutral standards. Sources including the US DOE, McKinsey and Company, and the Electric Power Research Institute have estimated the potential for substantial energy savings from industrial motor system efficiency measures. Committee members are working together to explore the program opportunity associated with motor-drive performance across the US and Canada, to support market transformation and realize the benefits of better industrial motor system efficiency.

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