NovaTorque
Brushless Permanent Magnet Motor
Bench Test

Final Report

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Sacramento Municipal Utility District
6301 S Street
Sacramento, California

Submitted by

ADM Associates, Inc.
3239 Ramos Circle
Sacramento, CA 95827-2501
Phone: (916) 363-8383
Fax: (916) 363-1788
Website: http://www.admenergy.com/

Introduction

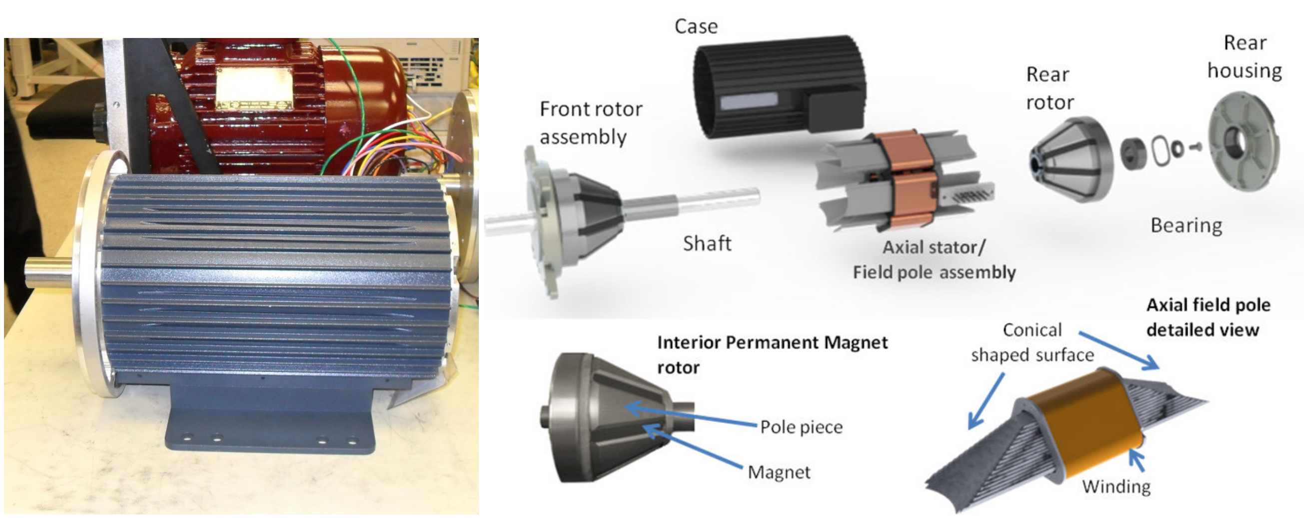
ADM Associates, Inc., under a contract with the Sacramento Municipal Utility District, conducted an evaluation of a new high efficiency motor. SMUD provided funding under its Customer Advanced Technologies (CAT) program to evaluate a new 3 HP brushless permanent magnet motor (conventionally known as an *Electronically Commutated Motor*), developed by NovaTorque (see Figure 1). The NovaTorque Premium Plus+™ 3 HP Motor System includes a motor and a variable speed drive. The motor's performance as an energy efficiency technology was evaluated using laboratory testing. This was done in order to quickly provide SMUD with an initial technology assessment.

NovaTorque claims that their motor saves energy when compared against standard induction motors in variable speed applications. This is primarily due to their claim that the motor's efficiency does not degrade as quickly as a 'typical' induction motor as it is unloaded or the speed reduced. NovaTorque supplied ADM with the following description of their motor technology.[1] Figure 1 illustrates the motor and its various components.

The rotor in the NovaTorque motor design consists of a pair of conical hubs mounted on opposite ends of the motor shaft. The rotor hubs use an interior permanent magnet (IPM) arrangement which allows the flux to concentrate. An IPM design has both mechanical and adhesive magnet retention, which allows for higher speed motor operation than a surface permanent magnet design. The surface area available for magnetic flux transmission is maximized by giving the motor's stators and rotor hubs matching conical shapes. By making the rotor/stator surface area interface twice the perpendicular cross-sectional area of the stator field pole, the motor's geometry also concentrates the magnetic flux density.

The NovaTorque motor uses an axial flux path, flowing straight (parallel to the shaft) through the axially-oriented field poles of the stator. The axial orientation of the NovaTorque motor stator field poles allows the use of bobbin-wound coils, which creates a thermal path, as one face of the coils is next to the external motor case, instead of being inside the lamination stack as is found in an induction motor.

Figure 1 The Premium Plus+™ Brushless Permanent Magnet Motor and Exploded View



[1] The description has been edited for length and content by ADM to fit into this report.

Monitoring Approach

ADM visited NovaTorque's facility in Sunnyvale, California in order to evaluate their motor's performance using a dynamometer test stand. The 3 HP NovaTorque Premium Plus+™ motor was tested alongside two "typical" control motors to compare its efficiency at various torque and speed settings. The control motors were new motors selected and purchased by ADM. NovaTorque provided the variable frequency drive (VFD) by which all three motors were driven during the testing. The following tables illustrate all test points at which data was collected (Table 1), as well as the list of parameters recorded at each data point (Table 2):

Table 1 List of Motor Loading Points at Which Performance Data was Collected

Cells give Horsepower output									No Drive*	
		15%	25%	40%	50%	60%	75%	100%	100%	% Speed
% Load	Load (Nm)	270	450	720	900	1080	1350	1800	Actual	RPM
10%	1.19	0.04	0.07	0.12	0.15	0.18	0.22	0.30	Actual	
25%	2.97	0.11	0.19	0.30	0.37	0.45	0.56	0.75	Actual	
40%	4.75	0.18	0.30	0.48	0.60	0.72	0.90	1.20	Actual	
50%	5.94	0.22	0.37	0.60	0.75	0.90	1.12	1.50	Actual	
60%	7.12	0.27	0.45	0.72	0.90	1.08	1.35	1.80	Actual	
75%	8.90	0.34	0.56	0.90	1.12	1.35	1.69	2.25	Actual	
100%	11.87	0.45	0.75	1.20	1.50	1.80	2.25	3.00	Actual	

** Since the NovaTorque motor requires a VFD drive to operate, only the two control motors were tested at these points.*

Table 2 List of Motor Performance Parameters Recorded at Each Loading Data Point

#	Description Of Parameter
1	Speed (RPM)
2	Motor Output (Brake) Power (W)
3	Torque (Nm)
4	Volts (phase to phase for each combination of phases)
5	Amps (Read for each phase)
6	System Input Power (W)
7	Motor Input Power (W)
8	System Efficiency (%)
9	Motor Efficiency (%)

Measurement Equipment

The dynamometer 5 HP automated test system stand setup has a torque range of 0 to 20 N-m, a speed range of 0 to 5000 RPM, and power limit of 3.7 kW. The setup contains the following equipment and is shown in Figure 2.

- Magtrol TM308 20 N-m torque head and Magtrol 3410 torque display
- Magtrol AHB-12 air-cooled hysteresis brake
- Yokogawa WT1600 power meter
- Dell Latitude E6400 notebook computer
- Tests that can be performed:
  - Motor and system efficiency

Figure 2 Dynamometer Test Bench Used to Test Motors

Control Motors

ADM purchased two new induction motors that were used as controls against which the NovaTorque motor was compared. The two control motors were purchased from the same manufacturer, and were rated at two different efficiencies (89.5% and 87.5%). The control motors were rated at 3 hp and 1800 RPM. Both were totally enclosed and fan cooled. Henceforth, the 89.5% efficient motor will be referred to as the *NEMA Premium Efficiency Induction Motor*, and the 87.5% efficient motor will be referred to as the *Standard Efficiency Induction Motor, although the manufacturer had it marked as a "high efficiency" motor*.

Verification of Primary Instrumentation

While onsite, ADM made several independent measurements of System Input Power, and Motor RPM in order to validate the primary instrumentation. System Input Power was measured using a handheld AEMC F05 true RMS power meter, while Motor RPM was confirmed using a Pocket Strobe™ PK2 strobe light. ADM found no discrepancies between the independent measurements and those of the primary instrumentation.

Monitored Data

The following graphs (Figures 3 & 4) illustrate the monitored performance for all three motors. Since the NovaTorque motor must be operated using a VFD; ADM used the motor-drive *system* efficiency to compare motor performance as well as to estimate motor savings. Thus, the efficiency values shown in each of the figures is the motor-drive *system* efficiency. Figure 3 shows a three-dimensional plot in which each plane represents the monitored efficiency of a motor at various speed and torque settings. Each intersection in the x-y plane (Torque, Speed) represents a motor brake power output, and the color and height (z-axis) of that point represents the monitored *system* efficiency for that brake power output. As expected, the monitored efficiencies for equivalent brake powers at lower speeds were slightly lower.

Figure 3 Monitored System Operating Efficiency for Each Motor

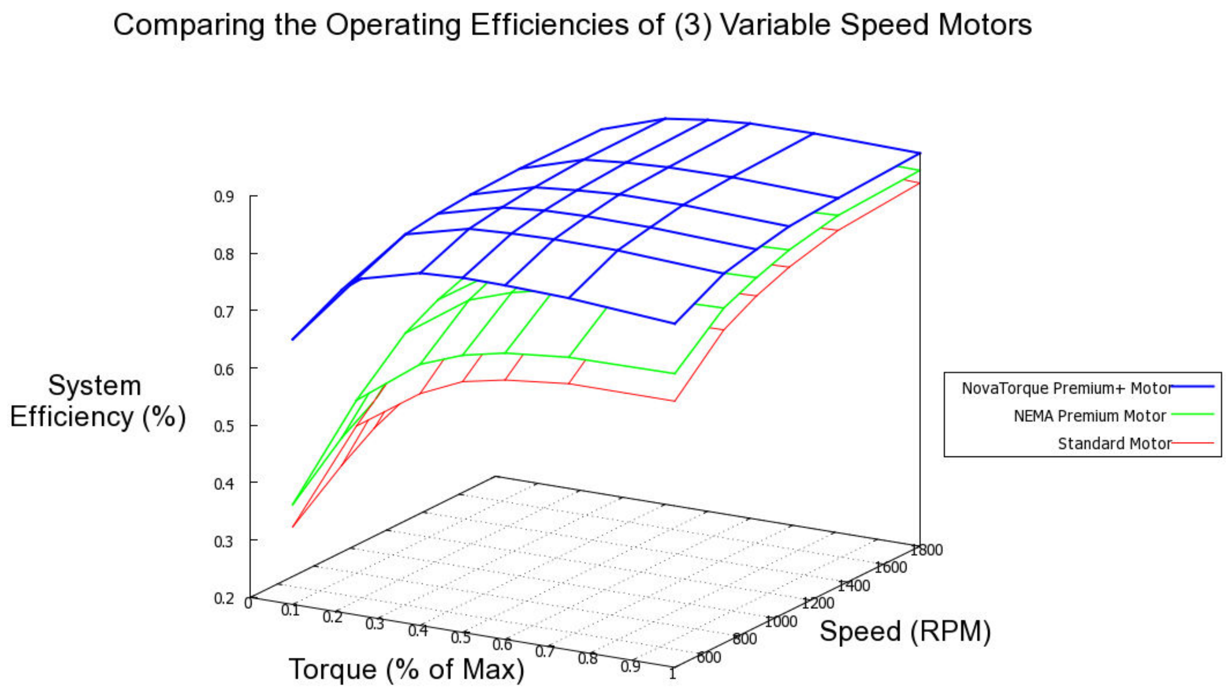
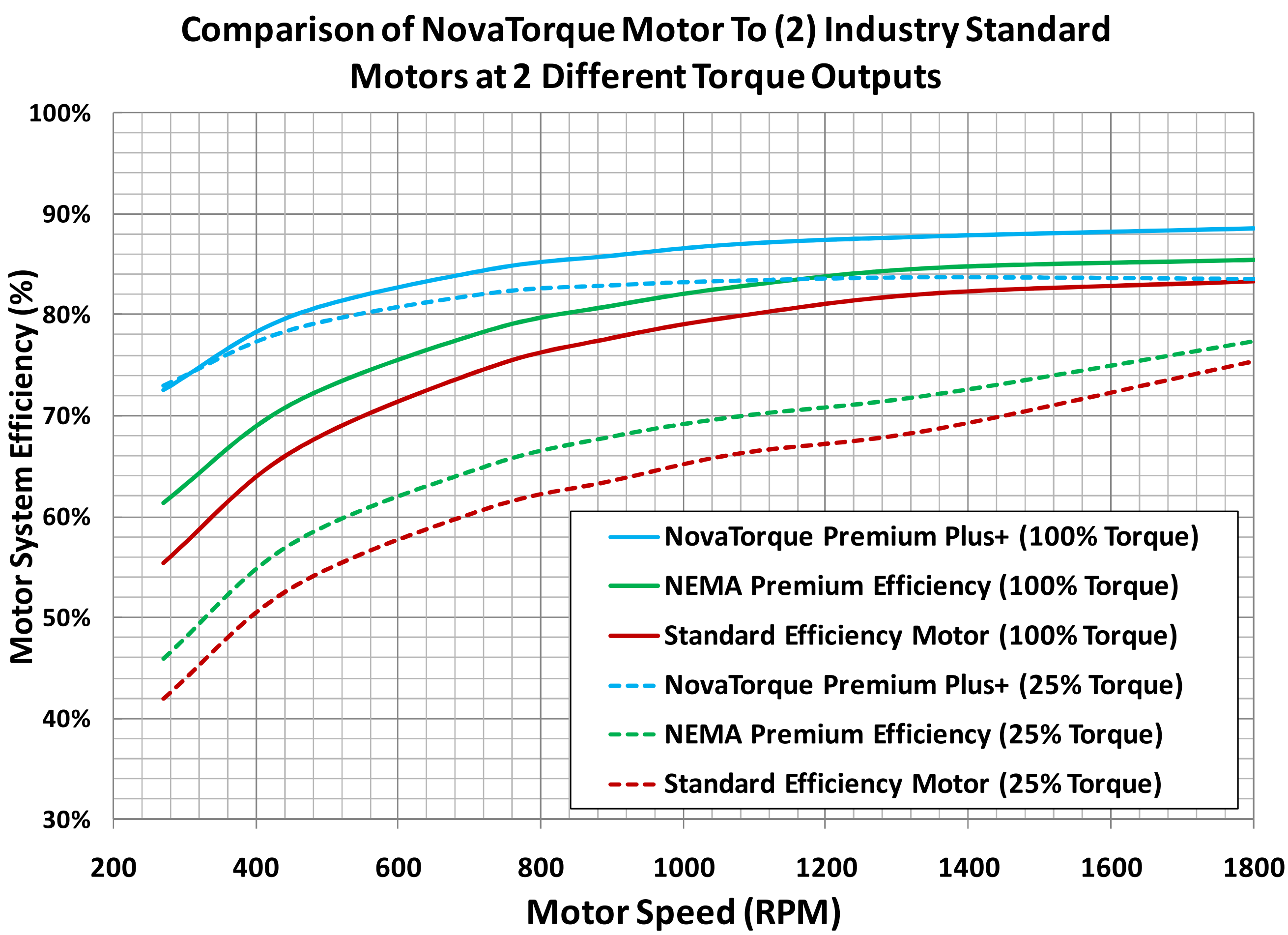


Figure 4 compares each of the motors' monitored efficiencies versus its speed (RPM), holding torque constant. The solid lines in Figure 4 represent the motors monitored performance at 100% of the rated torque output at 1800 RPM (~12 Nm), while the dotted lines represent monitored performance at 25% of the rated torque at 1800 RPM (~ 3 Nm). Each line color represents a particular motor.

At full torque (solid lines) the system efficiency fell off with speed in a similar fashion for all three motors. The slopes for all three are relatively parallel down to about 1200 RPM, after which the standard and premium motors begin to fall off a bit faster. This can be seen in the gap between the lines at various speeds. Down to 1200 RPM the gap between each of the solid lines is relatively constant. Below 1200 RPM the gap gradually widens. This trend indicates that the NovaTorque system is able to better maintain its operating efficiency at reduced speeds. This trend is much more pronounced at 3 Nm torque (dotted lines). Here the NovaTorque system efficiency remains constant down to about 1000 RPM while the standard and premium motor system efficiencies begin to degrade immediately as the speed is reduced. Notice that the gap between the NovaTorque and the control motors is much wider at lower loads (dotted lines) than at full loads. This indicates that the

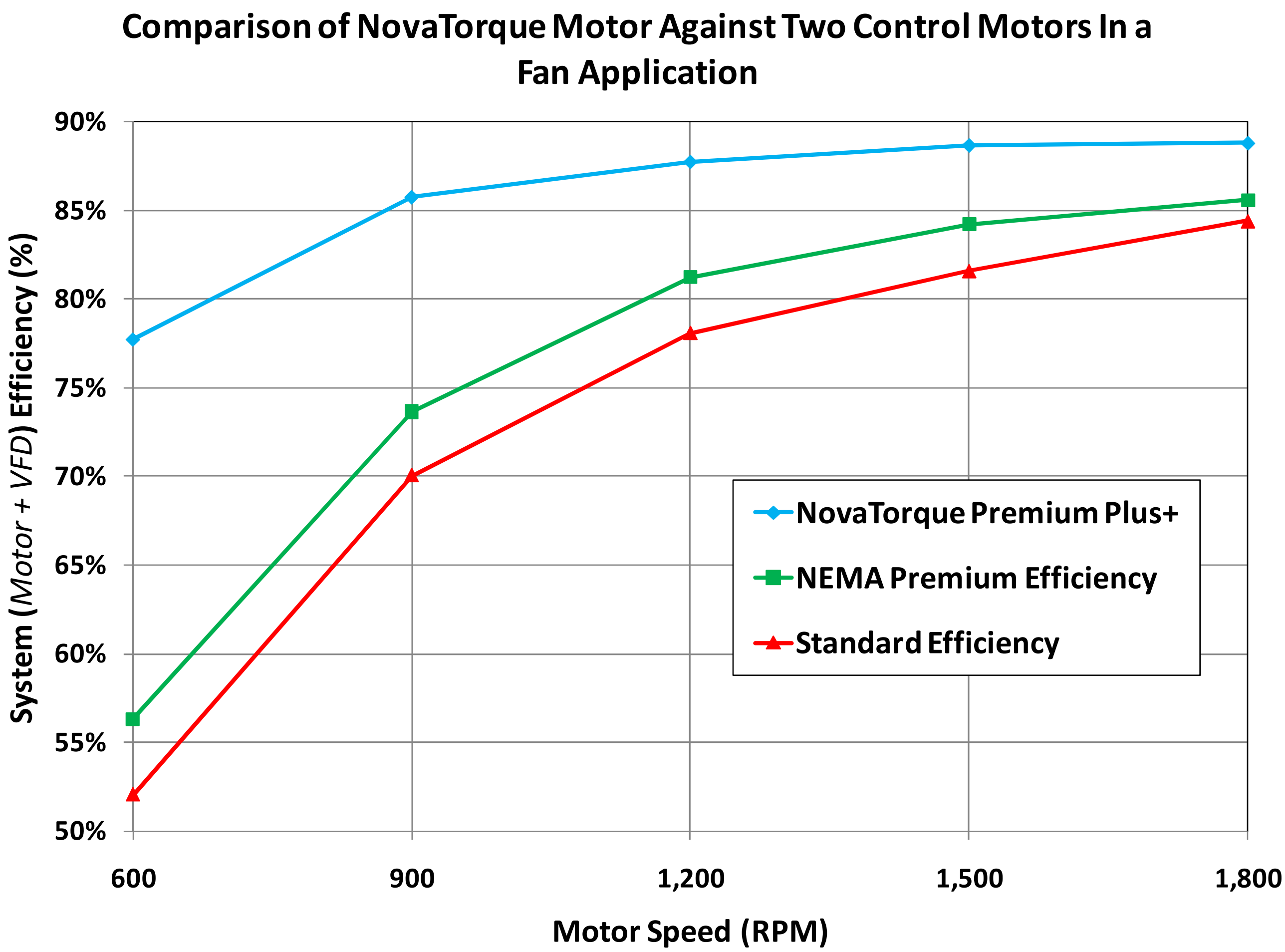
NovaTorque would save energy, when compared against a typical induction motor, in applications in which the motor spends considerable time at lower loads.

Figure 4 Monitored Motor System Efficiency Vs Speed (RPM) at Two Different Torque Outputs



The lab data was used to generate performance curves comparing the NovaTorque motor system to two induction motor system efficiencies for a fan application. The chart in Figure 5 is based on a typical fan curve. The efficiency of the NovaTorque Premium Plus+™ motor system remains high while the induction motor system efficiencies drop off as the speed is reduced. For example at 50% speed the NovaTorque is at 86% efficiency while the standard motor is at 70% efficiency.

Figure 5 Monitored Motor System Efficiency Vs Speed (RPM) for Typical Fan Application



Energy Savings

Based on the monitored data in the previous section, it is expected that the NovaTorque motor would garner energy savings when used to supplant a *typical* premium or standard efficiency motor with variable speed drives. ADM estimated such energy savings by applying the monitored motor data to a simulated annual load profile for (2) typical variable speed motor applications – an HVAC supply fan and a chilled water pump.

In order to use the monitored data in a predictive capacity, each data set was fitted with a curve of the form:

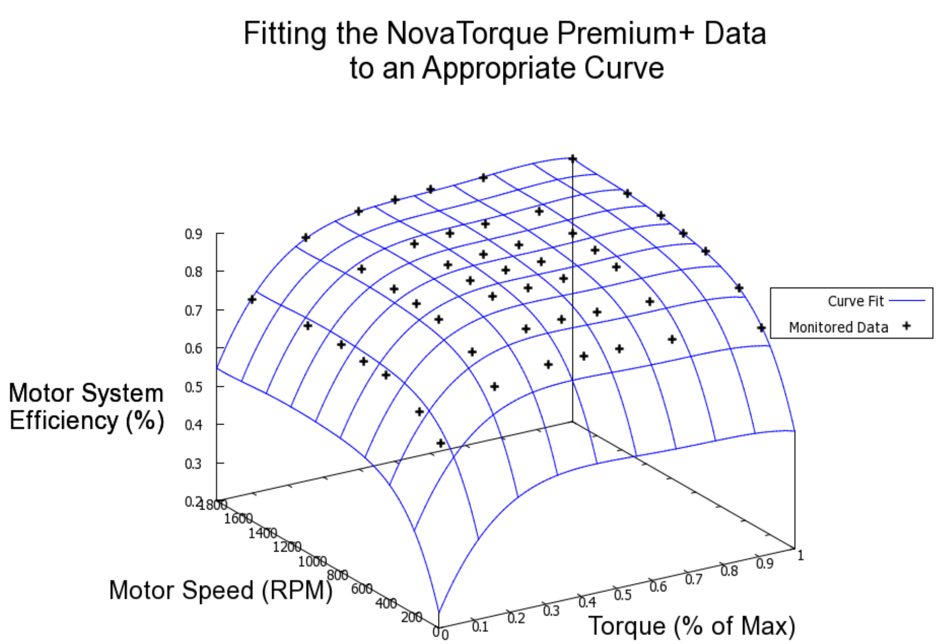
$$\eta = a + bx + cx^2 + dx^3 + ex^4 + fy + gy^2 + hy^3 + iy^4 + jy^5 + kxy$$

Where:

η	=	Motor-Drive System Efficiency	[*%*]
x	=	Motor Torque	[*% of Maximum Rated at 1800 RPM*]
y	=	Motor Speed	[*RPM*]
a,…,k	=	Curve Fit Parameters	[Unitless]

Figure 6 illustrates a comparison between one fitted curve and its monitored dataset. By fitting a curve to the monitored data, its equation can then be used to predict the performance of the motor at any conceivable operating point within its range - even points not directly monitored. Given a set of motor loads (hourly torque and speed setting for a 24 hour period for example) the curve fit equations can be used to compare motor system energy use, and identify potential energy savings.

Figure 6 Comparison of the Fitted Curve (Blue) and the Monitored Data-Points (Black)



For the purposes of this study, eQuest was used to simulate the load profiles used to compare motor energy performance. These hourly load profiles are depicted in Figure 7 and Figure 8. Two different profiles were created because potential motor energy savings will vary considerably depending on motor's application and its sizing (e.g. how much larger the motor is compared to the minimum size that could possibly be installed). This paper examines potential NovaTorque savings in supply fan and chilled water pump applications. In order to predict potential savings due to motor sizing, this study estimated savings for two possible scenarios for each simulated profile; 1) a 3 HP right sized motor, and 2) a 5 HP oversized motor. These scenarios are summarized in Table 3 below.

Table 3 Summary of Motor Placement Scenarios Considered in this Study

	Supply Fan Motor	Chilled Water Pump Motor
Right Sized Motor	3 HP	3 HP
Oversized Motor	5 HP	5 HP

When the load profiles were created, the 3 HP motor was designed to be *right sized* by making the peak brake-power[2] requirement 3 HP (2.2 kW). These load profiles were combined with the fitted efficiency curve illustrated in Figure 6 to estimate the motor-drive system's efficiency for each hour of the year.

Figure 7 Annual Load Profile Used to Predict Motor Savings for the Variable Speed Supply Fan Application

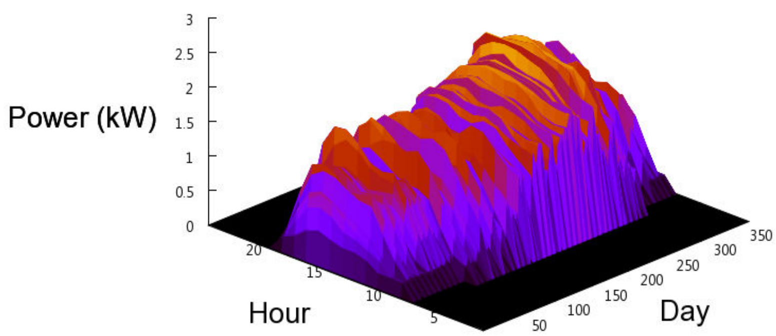
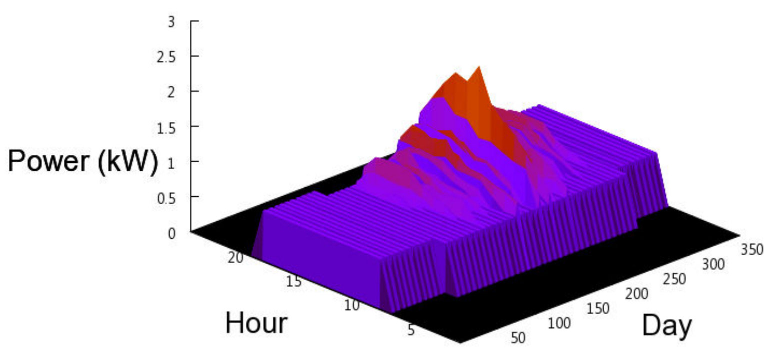


Figure 8 Annual Load Profile Used to Predict Motor Savings for the Variable Speed Chilled Water Pump Application



[2] Brake power (usually in horsepower, but in this case illustrated in units of kW) is the mechanical power output by the motor. This is different from the electrical power (kW) which is always larger than the brake power and is equal to the brake power divided by the system efficiency.

Potential energy savings were estimated using the following formula:

$$E_{Sav} = \sum_{h=1}^{8760} P_{Brake_h} \left(\frac{1}{\eta_{c_h}} - \frac{1}{\eta_{NT_h}} \right)$$

Where

$\eta_{c\ h}$	=	Hourly Control Motor-Drive System Efficiency	[%]
$\eta_{NT\ h}$	=	Hourly NovaTorque Motor-Drive System Efficiency	[%]
$P_{Brake\ h}$	=	Hourly Predicted Brake-Power by Profile	[*kW*]

All savings are normalized to rated motor horsepower. The estimated savings for the supply fan and chilled water pump are listed in Tables 4 & 5 respectively and show both the right sized and over sized motor simulations.

Table 4 Estimated NovaTorque Annual Savings When Compared Against Control Motors in Supply Fan Application

	Right Sized Supply Fan (3 HP)		**Oversized Supply Fan (5 HP)**	
	Premium Motor	Standard Motor	Premium Motor	Standard Motor
Estimated Savings (kWh/HP)	90	136	137	200
Estimated Savings (%)	7%	10%	10%	14%

Table 5 Estimated NovaTorque Annual Savings When Compared Against Control Motors in CHW Pump Application

	Right Sized CHW Pump (3 HP)		**Oversized CHW Pump (5 HP)**	
	Premium Motor	Standard Motor	Premium Motor	Standard Motor
Estimated Savings (kWh/HP)	69	105	116	162
Estimated Savings (%)	8%	11%	12%	16%

As expected, NovaTorque motor shows more savings compared to the 5 HP oversized motor than the right sized (3 HP) motor. This happened because the difference in operating efficiency between the NovaTorque and (both) control motors becomes greater as percent motor load decreases. The oversized motor operates at much lower loads than the right sized motor, exaggerating this effect. Figure 9 and Figure 10 are time series plots showing each motor's simulated demand (kW) over an average summer day.[3]

[3] Average summer day is defined here as the average of all days from June through September.

Figure 9 Simulated Demand for a Right Sized Supply Fan for a Typical Summer Day

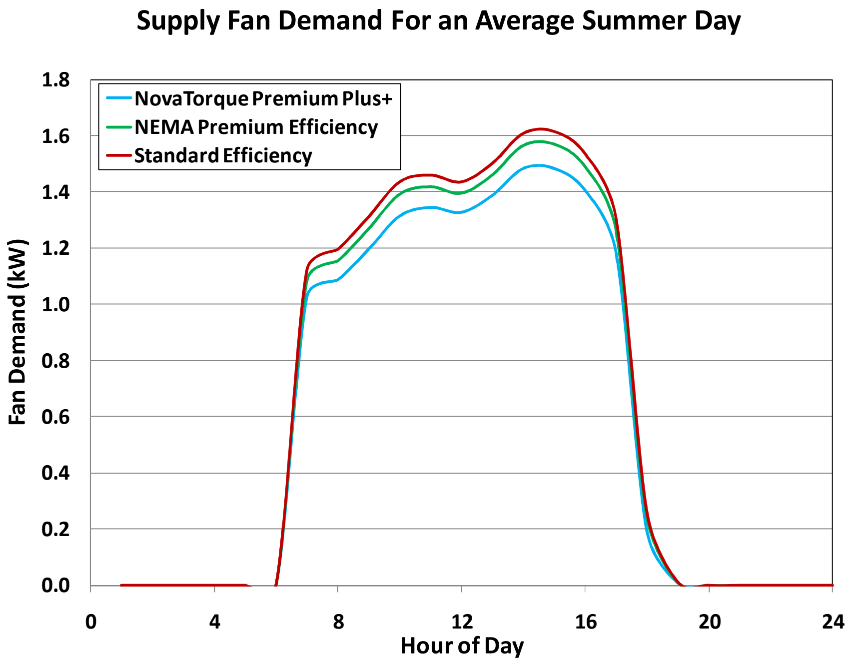
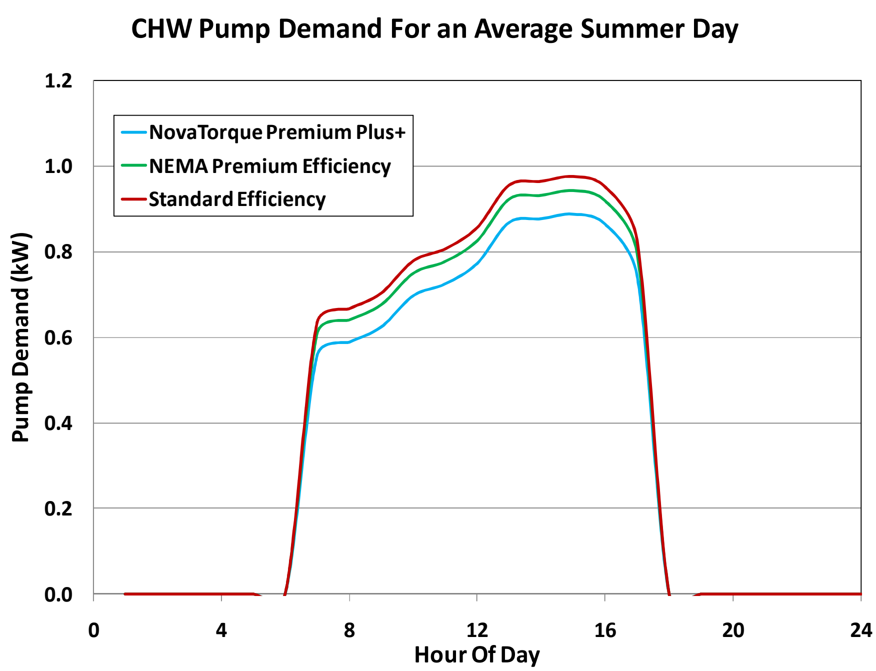


Figure 10 Simulated Demand For a Right Sized CHW Pump for an Average Summer Day



Conclusions

The findings presented in this report indicate that the NovaTorque Premium Plus+™ motor has the potential to save energy in variable speed applications where it supplants a 'typical' NEMA Premium efficiency or standard efficiency induction motor. The NovaTorque motor system maintains efficient operation under variable speed, and part load, more effectively than a NEMA Premium Induction motor. Savings are dependent on motor sizing of existing motor and speed distribution the motor operate over the course of a year. The savings will increase for oversized existing motors and motors that spend a considerable amount of time at low speeds. The savings compared to the two motor and two applications presented in this report ranged from 7% to 16%. Comparison with an existing in-situ motor would likely show more savings if the existing motor has a lower rated efficiency and whose performance has most likely degraded over time. Since neither of the two control motors were rated at the same nominal efficiency as the NovaTorque, it is difficult to quantify to what extent the NovaTorque would save versus a comparably rated motor. ADM suggests that SMUD supplement these findings with an additional in-situ study in which the NovaTorque motor's performance is evaluated in an actual variable speed application.